Quantifying the effects of anthropogenic heat sources on the water temperature in the drinking water distribution system

By

L. van den Bos

4617894

A thesis submitted in partial fulfilment of the requirements for the degree of

Master of Science
in Civil Engineering
Water Management

at the Delft University of Technology,
in collaboration with Evides Waterbedrijf

Assessment committee:

Prof.dr.ir. J.P. van der Hoek	TU Delft, CiTG, Professor in Sanitary Engineering
Dr.ir. E. Abraham	TU Delft, CiTG, Assistant Professor in Water Resources
Dr.ir. L. Zlatanović	TU Delft, CiTG, Postdoc Researcher in Sanitary Engineering
Dr. B.M. van Breukelen	TU Delft, CiTG, Assistant Professor in Sanitary Engineering

2020

Abstract

The temperature of drinking water is an important parameter, affecting physical, chemical, biological and aesthetic properties of the water. Currently, measurements exceeding the legal limit of 25°C at the tap are exceptional. However, there are reasons to believe that the number of exceedances will increase due to climate change and urbanization. So far the effects of sunlight hours and soil coverage on drinking water temperature have already been quantified quite well. Still lacking is the exact effect of anthropogenic heat sources on these temperatures. In this study more insight is given in the extent of this effect for Rotterdam, and measures are discussed to mitigate or to prevent drinking water warming.

First, potential anthropogenic heat sources are identified. By analyzing data on tap temperatures and old soil temperature measurements, several anthropogenic heat sources emerged. A map of the statistically warm drinking water temperatures in Rotterdam, appears to have a lot of resemblance to the city heating system whereabouts. Furthermore, smaller indications point at high voltage power cables and metro lines to be important anthropogenic heat sources.

Soil temperature measurements around these potential heat sources confirm some of the expectations. Around high voltage power cables, a limited elevated temperature of 0.6°C is found. Much more alarming results were encountered around the city heating mains. In autumn, primary heating mains warm-up the soil by 4.9 – 5.3°C and secondary heating mains do so by 2.9°C. A temperature elevation of 1°C is measured to a distance of 3.8 - 5.25m and 2.3m, respectively. However, these results are highly dependent of several parameters, like the temperature differences between the air and soil, the thermal properties of the soil, and the depth and state of the anthropogenic heat sources themselves.

Several strategies to mitigate the warming of drinking water in the distribution system are applicable. In a general sense, it is most sensible to create a distance between any heat source and the distribution system. By placing drinking water mains in the shade, below grass and away from anthropogenic heat sources, warming of the drinking water can be prevented in a relatively inexpensive manner. Measures targeted at temporary local hotspots can be focused on restraining the heat flux from the heat source to the soil, the heat flux through the soil, and the heat flux from the soil to the drinking water.

Acknowledgements

I would like to thank a number of people that helped me during my research. First of all my company supervisor, Henk de Kater. Henk is the expert on drinking water temperatures in the distribution system of Evides. Aside from guiding me through my time at the company, it was really interesting to exchange thoughts on the topic from time to time. Together with many other employees he made my time at Evides into a fun and a very educational experience.

In addition, I would like to thank my assessment committee, who helped me to create the best possible final result. Not only did they give me feedback on my report, but during out meetings they came up with interesting additions to improve the completeness of the study. In my opinion, our collaboration was good and professional.

I would also like to thank all people that provided materials that were used in for the measurements. Jan Hofman of the University of Bath who gave me 6 high quality sensors. Claudia Agudelo-Vera and Mirjam Blokker who provides the other sensors and who gave me an opportunity to present my research at a workshop among experts. Wim Noordhof and Henk van der Maas, for sharing data on infrastructure depths from the municipality of Rotterdam. Rob ten Boden form VattenFall, for being very helpful and open about their city heating net. And last but not least, mechanics William Romijn and Jurriaan Jansen. They helped me to place and remove the sensors at the measuring sites and they have shown me what it is like to work in the field.

On another note, I want to express my gratitude to my parents and my girlfriend. By supporting me where needed, but also by not interfering too much in my study process, they found the perfect balance for me to achieve my bachelor’s and master’s degree in just over 5 years. Thank you.

Laurens van den Bos
13-01-2020

Content

Abbreviations

AHS = Anthropogenic heat source(s)

ATES = Aquifer thermal energy system(s)

BGL = Below ground level

DWDS = Drinking water distribution system(s)

Evides = Evides Waterbedrijf

IPCC = Intergovernmental Panel on Climate Change

RDC = Rijksdriehoekscoördinaten

STM = Soil temperature model(s)

SUHI = Surface urban heat island effect

SSUHI = Subsurface urban heat island effect

TST = Tap sample temperature(s)

UHI = Urban heat island effect

HVPC = High voltage power cable(s)

LVPC = Low voltage power cable(s)

Introduction

Problem statement

The World Health Organization states that in 2017, 29% of the world's population did not have a continuously available water source on their premises, free from contamination (WHO, 2019). In the Netherlands, drinking water is of a very high quality and the supply is much more reliable than average. The water quality is among the best of the world, and drinking water companies own a nationwide supply network in which only 3-7% non-revenue water leaves the system (Rosario-Ortiz, Rose, Speight, Von Gunten, & Schnoor, 2016; Beuken, Lavooij, Bosch, & Schaap, 2008). Still, distributing high quality drinking water at the treatment facility, gives no guarantee for the same water quality at the customers tap (Peterson, Pratt, Neapetung, & Sortehaug, 2006). Despite good asset management of the drinking water distribution system, water temperature is hard to control throughout the network.

The Dutch drinking water act captures all the rights and obligations of the nation's drinking water companies, concerning both water quantity as quality. The act states that distributed drinking water should not exceed 25°C at the costumers tap, and this number is supported by the world Health Organization (Ministerie van VROM, 2011; WHO, 2011). The water quality risks that become greater with temperatures above 25°C are not unilateral. A number of physical, chemical, biological, and aesthetic reasons make temperature such an important parameter (Blokker, & Pieterse-Quirijns, 2013). Physically, temperature affects the viscosity of the drinking water, causing transport and thereby sedimentation processes to change (Uber, & Boxall, 2010; Pothof, & Blokker, 2012). Chemically, reaction rates and the speed of the disinfection processes are influenced. Corrosion increases with temperature, and if chlorine is used more carcinogenic disinfection byproducts are formed with higher temperatures (Volk, Dundore, Schiermann, & Lechevallier, 2000; Sadiq, & Rodriguez, 2004; Li, & Zhao, 2006). Khamnei, Hosseinlou and Zamanlu (2011) and the Safe Drinking Water Foundation (n.d.) concluded the preferred water temperature according to the consumer is 16°C. Furthermore, they investigated that most complaints come in when temperatures are higher than 19°C, also making it an aesthetic problem. And lastly, temperature has an important effect on microbial activity. Microorganisms will create biofilms in drinking water mains, having consequences for the water quality over time (Lehtola, Juhna, Miettinen, Vartiainen, & Martikainen, 2004). Warm temperatures are favorable for the growth of bacteria like: *Legionella Pneumophila,* and *Aeromonas,* the fungi *Aspergillus Fumitagus* and the amoeba *Naegleria fowleri* (van Bel, 2017; van der Wielen, 2017; WHO, 2011).

Reassuring to know is that temperatures at the costumers tap above 25°C seem to be exceptional. Evides Waterbedrijf (Evides) has documented these water temperatures for a long time. In the last 19 years almost 30,000 samples were taken in the area of Rotterdam and only 11 of those turned out to be over the 25°C threshold. Even in the warm year 2006, nationwide only 21 samples at the tap exceeded the threshold, representing 0.01% of all the tap samples (Versteegh, & Dik, 2007). However, these samples are taken randomly in space and in time. Thus, there is a reasonable chance that hotspots (locations with temperatures over 25°C) are missed. An increase in data variability in space and time, makes it easier to identify hotspots at the tap and in the drinking water distribution system (DWDS) itself. Agudelo-Vera (2018) expects that measurements targeted at warm areas during heat waves, would increase the number of exceedances drastically.

Right now the findings of temperatures at the tap and in the DWDS may not be alarming, but there are reasons to believe that the number of hotspots in the future will increase. Causes of warm drinking water can be of a climatic nature, an anthropogenic nature, or a combination of the two. Both climate change and urbanization show clear upward trends, and will aggravate the number of hotspots in the future (Agudelo-Vera, Blokker, van der Wielen, & Raterman, 2015). The latest assessment report of the Intergovernmental Panel on Climate Change (IPCC) projects global temperatures to rise, and heat waves to occur more frequent and become longer (IPCC, 2014). Different climate scenarios predict a global mean temperature rise between 1°C and 5°C, which locally can even be higher (NASA, 2019). Furthermore, the density of anthropogenic heat sources (AHS) in urban areas is likely to increase due to urbanization and modernization. Subsurface infrastructure like geo- and aqua thermal energy systems, power cables, city heating, etc. likely contribute to higher soil temperatures now, and even more in the future (Agudelo-Vera, 2018).

Research aim

With these expectations in mind, the knowledge on the causes and effects of hotspots in the drinking water distribution network needs to be extended. Knowledge could help to deal with elevated risk of hotspots in the future. Feasible measures may be found to either mitigate the warming effects of AHS, or to adapt the DWDS in such a way that the water remains cool enough. Depending on the results, actual implementation throughout the entire system may take decades. Therefore, the adaptation process must begin as soon as possible.

In the past several years, the Dutch water research institute KWR dedicated multiple studies to hotspots in DWDS. The next chapter, tries to capture the existing relevant knowledge on the topic of hotspots in the DWDS. Very early on in the process, the strong relation between soil temperatures and drinking water temperatures is indicated (Blokker, & Pieterse-Quirijns, 2013; Agudelo-Vera et al., 2015). For this reason most subsequent hotspot studies use the soil temperature at one meter below the surface as a proxy for the water temperature in the DWDS. Up until now, the most extensive research has been done on the effect of climatic influences, soil coverage and soil properties on the soil temperature. The effect of AHS on soil temperature has gotten less detailed attention so far. This presents a knowledge gap, that will partially be filled by this study. In addition, an effort is made to link the preliminary results to ways to limit the warming of drinking water in the DWDS.

Research questions

As mentioned, an important knowledge gap steers the research towards a better understanding of AHS. Insight in the temperature magnitude and the effect radii of potential AHS will be increased by means of measurements. The following research question and sub-questions were setup to guide and provide a clear framework for the proposed research.

> "To what extent do anthropogenic heat sources have an effect on drinking water temperatures in the drinking water distribution system of Rotterdam, and how can warm temperatures, as an effect of anthropogenic heat sources, be mitigated or prevented in the future?"

1. What anthropogenic heat sources are identified to have the most influence on the drinking water temperature?
2. Can earlier soil temperature measurements, performed by Evides and KWR, provide useful information on the identification of AHS?
3. How can the radiated heat from the sources be measured?
4. What would be the best location to perform measurements?
5. What are existing ways to prevent hotspots, and can new ideas be based on the first results of this study?
6. What broader conclusions can be drawn outside of the Rotterdam case study?

As sub-question 6 indicates, this research will partially be performed as a case study. Evides is the second largest drinking water company of the Netherlands, in terms of customers served. The drinking water and industry water sections combined produced 253.9 million m^3 of water in 2018 (Evides Waterbedrijf, 2019). Infrastructure summing up to 14,811 km of piping, delivers drinking water to 2.5 million customers in Zeeland, southwestern Zuid-Holland, and southwestern Noord-Brabant

(Evides Waterbedrijf, 2019). This study focusses on Rotterdam, the second most populated city in the Netherlands, first in the distribution area of Evides (CBS, 2019). Analysis and measurements will be done for and in the city of Rotterdam, but conclusions can be drawn wider for other urban areas. Results will help in hotspot localization, they might help to improve future soil temperature models (STM), they will help to think about solutions efficiently, and lastly they may also be used in the prevention of future hotspots.

This document consists of a state of the art literature review. All relevant background information is described and evaluated, creating a coherent basis for the practical part of the study. The practical part is structured in three phases. In the first phase the most important AHS are identified. An analysis of tap sample temperatures (TST), supplemented with the evaluation of measurement results of a preceding study by Evides and KWR, should indicate significantly warm areas in Rotterdam. Connecting these warm areas with the whereabouts of potential heat sources finalizes the AHS identification phase. In the second phase, targeted soil temperature measurements are done around the identified AHS. The right measurement locations and sensor placements are selected in this phase. And lastly, in the third phase, the measurement results are retrieved and visualized. The first conclusions can be drawn from these results. They form the basis for the last theoretical part of this study, in which measures to mitigate and prevent warm water temperatures are discussed.

The methodology of the three practical phases is described in more detail after the literature review. Steps leading to the results, as well as all materials and costs are elaborated upon. What follows is the results and discussion sections of the practical part. The data analysis and measurement outcomes are visualized and interpreted. Each AHS is reviewed individually, and connections are made to existing literature. At the end of this section, most research questions should already have been answered. Creating a framework for the last substantive part, another literature review on the measures to reduce warming of the drinking water in the DWDS. Using the feedback from the preliminary results, general measures applicable over the entire DWDS and measures targeted at local temporary hotspots are discussed separately. The last sections of this paper describes the conclusions and recommendations for further research. All research questions are answered in a concise and clear way, effectively summarizing the most important aspects of this paper. Recommendations for further research in the future, point at an extension of this research and other remaining knowledge gaps.

State of the art literature review

As mentioned, multiple studies have already been dedicated to causes of high drinking water temperatures in the distribution network. The vast majority of the relevant literature is written in Dutch, and is conducted by KWR in collaboration with several drinking water companies. International literature about the relation between drinking water and temperature, mainly focusses on the effect of temperature on the water quality, and hardly ever on the causes of high temperatures.

Heating time versus residence time

Crucial for the understanding of hotspot studies, is the conclusion that the temperature of drinking water in the DWDS is strongly related to the ambient soil temperature (Blokker, & Pieterse-Quirijns, 2010; Smulders, 2006; van Daal & Slaats, 2008). This is one of the reasons why soil temperatures at 1 m below ground level (bgl) are often used for drinking water temperature studies. However, this conclusion only holds under the assumption that the heating time of water is shorter than the residence time of the water in the DWDS (Blokker, & Pieterse-Quirijns, 2010). The residence time indicates the time the drinking water stays in (a certain part of) the DWDS. The heating time is the time it takes for the water inside the mains, and the soil around the mains to reach a uniform temperature. Often there is a continuum in soil temperature that varies in space around the DWDS. Though, if the water is practically stagnant, or the soil temperature is homogeneous over a long section along the

DWDS, the water will reaches an equilibrium temperature, the surrounding soil temperature. I.e. the heating time should be seen as the time it takes for water in the mains to reach an equilibrium, as if the residence time of the water would be infinite at that location.

Both heating time and residence time are variable throughout the system. In general, the assumption of a shorter heating time than residence time holds. Making the soil temperature a useful proxy for water temperature. However, when using this proxy, the relation between these parameters must be considered.

The diameter of a pipe, the pipe material, and the temperature difference (driving force), tell a lot about the heating time of the water, as can be seen by the modeled graphs in Figure 1 (Blokker, & Pieterse-Quirijns, 2010). Figure 1 shows the heating time for PVC piping, which has a low thermal conductivity (Engineering ToolBox, 2003). This means that the water in pipes of other materials would warm even faster. The residence time of the water depends on the water velocity in the mains, which is a function of the downstream demand and again the pipe dimensions. At the distal ends of the distribution system, diameters are relatively small, and downstream demands can also be next to nothing. Making them the most vulnerable parts for high temperatures around the DWDS.

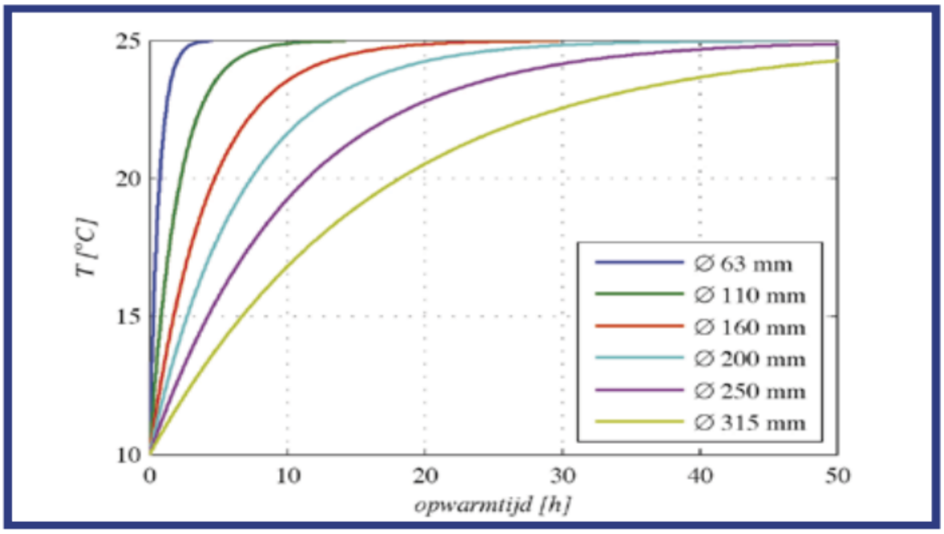


Figure 1: Modeled heating time of water [hr] in PVC piping for different diameters [mm]. A initial water temperature of 10°C and an ambient soil temperature of 25°C are used for these graphs (Blokker & Pieterse-Quirijns, 2010).

Van Daal & Slaats (2008) argue that water temperature at the pumping station is an important parameter for water temperature at the customers tap. At the point of distribution, drinking water produced from surface water, annually fluctuates much more in temperature than drinking water produced from ground water. This would mean that in summers, surface drinking water companies are more likely to have hotspots in the DWDS. A reduction in heating time is created, thus the theory holds for the first part of the DWDS. Still, the residence time will exceed the heating time when the distribution system branches out to smaller consumption areas. Agudelo-Vera, et al. (2015) even state that tap water temperatures are not at all influenced by the temperature at the pumping station. In their study, pumping station Berenplaat (surface water) and pumping station Halsteren (ground water) provide the same range of temperatures at the tap in Schiedam (surface water) and Tholen/Halsteren (ground water). Figure 2 presents their results, it may look like there is a small difference, but no statistical significance was found. Thus, soil temperature measurements at 1 m bgl still provide the best proxy, in absence of actual water temperature measurements.

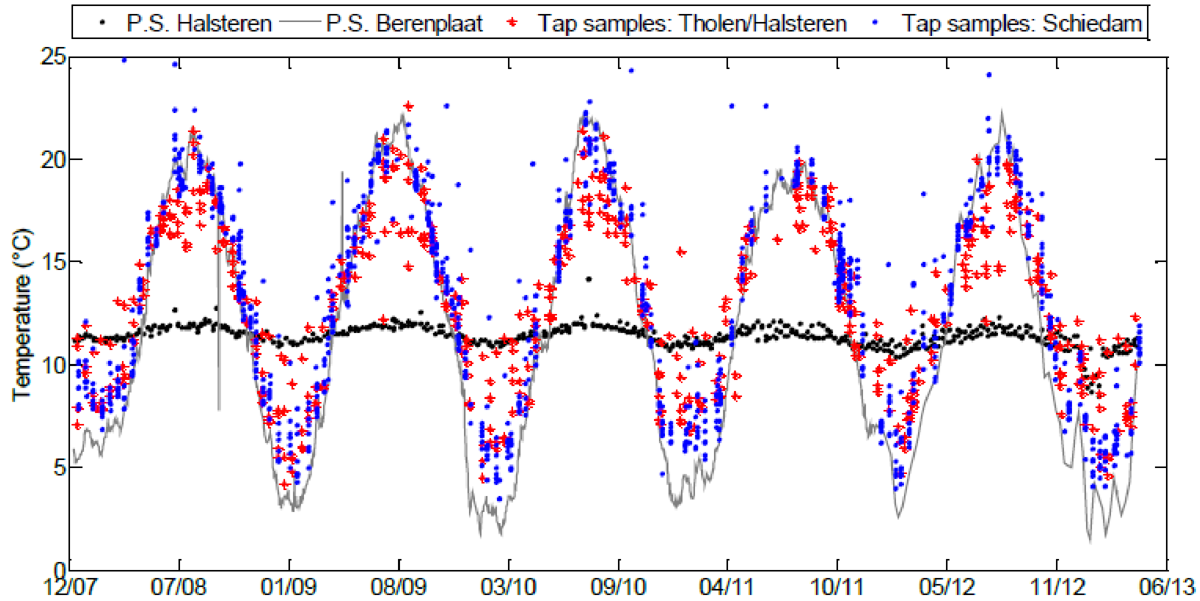


Figure 2: Comparison of the measured water temperature at the pumping stations Halsteren (ground water) and Berenplaat (surface water); the drinking water temperature at the tap at Tholen/Halsteren supplied by P.S. Halsteren, and Schiedam supplied by P.S. Berenplaat (Agudelo-Vera et al., 2015).

As seen in Figure 2, some studies use TST to indicate drinking water temperatures in the DWDS. These temperatures are collected after letting the tap run for approximately a minute, with the idea of subtracting the water from the DWDS instead of from the domestic piping. Despite this run time, there is an uncertainty in this way of measuring (Moerman, Blokker, Vreeburg, & Van der Hoek, 2014). Moerman et al. (2014) shows that there is a change in temperature between the house connection (the water meter) and the different tap locations in a house. The cause for this uncertainty again is the ambient temperature around the piping. This temperature can be caused by parallel warm heating mains, but also just by the room temperature. Especially in winters when using a kitchen tap, the error margin of tap measurements is significant (Moerman et al., 2014). In this period the difference between the soil temperature, and the indoor building temperature is biggest, leading to a bigger driving force; and the kitchen tap has a small discharge, leading to a relatively long residence time in the domestic mains. Moerman et al. (2014) modelled water temperatures in the domestic system for different scenarios. Temperatures can rise between 2-4°C in Dutch domestic water systems, even after flushing the system to a stable temperature. Figure 3 shows the distribution functions for four different scenarios: a warm day, an average day, and two scenarios in which the system is partially heated. The scenarios are described in Table 1. The model is statistically analyzed and validated by Zlatanovic et al. (2017), and was proved to be adequate.

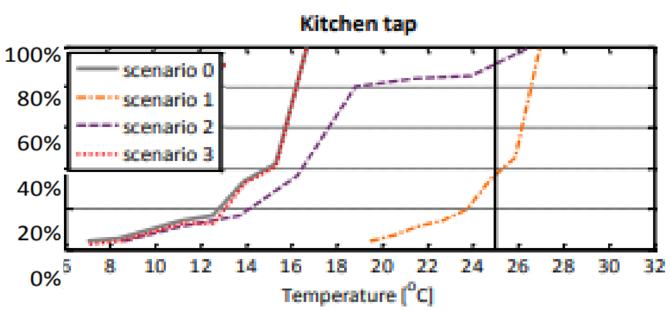


Figure 3: Cumulative cold-water distribution graphs at the kitchen tap for four scenarios described in Table 1. The tap temperature stays approximately 1.5°C above soil temperature, even after stabilization (Moerman et al., 2014).

Table 1: scenario description (Moerman et al., 2014)

Scenario #	Scenario	Specification
0	Reference	Soil Temp. (T_0)= 5°C, Inside Temp. (T_∞) = 18°C
1	Summer day	T_0 = 18°C, T_∞ = 28°C
2	A warm section	T_0 = 5°C, T_∞ = 35°C for a section
3	A warm pipe	T_0 = 5°C, T_∞ = 35°C for a small pipe

To prevent temperature changes in the domestic system to have an effect on the research quality, it could be helpful to install temperature logging water meters at house connection. These water meters prevent temperature changes in the domestic system to have an effect on study results. Another reason for installing these kind of water meters, is to make a clear division in legal responsibilities. The drinking water company is responsible for the DWDS as far as the meter. Behind the water meter, any emerging problems are the legal responsibility of the property owner. Lastly, these meters could save man-hours and money. One step further awaits the intelligent water meter. By adding functionality to the regular water meter, via sensors and ICT, more data could be collected. If processed correctly it could even provide a framework for action (Blokker, & Albert, 2017).

So far, a widely applied, accurate measuring device for water temperatures in the DWDS does not exist. The different proxies, like TST and soil temperature measurements, could all provide useful information on water temperatures in the DWDS. The important thing when using any proxy is to remember what is actually measured, and to keep in mind in what way it relates to what you want to know. Good knowledge of the DWDS is key in any study on the cause of drinking water temperature.

Weather and climate

The most important factors that influence soil temperature on the big scale are weather and climate. Parameters like air temperature, solar radiation, and evapotranspiration have a direct effect on the soil temperature. Especially the top soil layers react fast on weather fluctuations (Tsilingiridis, & Papakostas, 2014). The deeper the soil layer, the slower it reacts on weather fluctuations. Only if temperatures hold on for longer times, results will be visible in deeper soil layers (Jacobs, Heusinkveld, & Holtslag, 2011). Jacobs et al. (2011) visualized this effect for a grassland area in the Netherlands. Figure 4 shows that the graph for the 1 m deep soil layer reaches less extremes, is smoother, and has

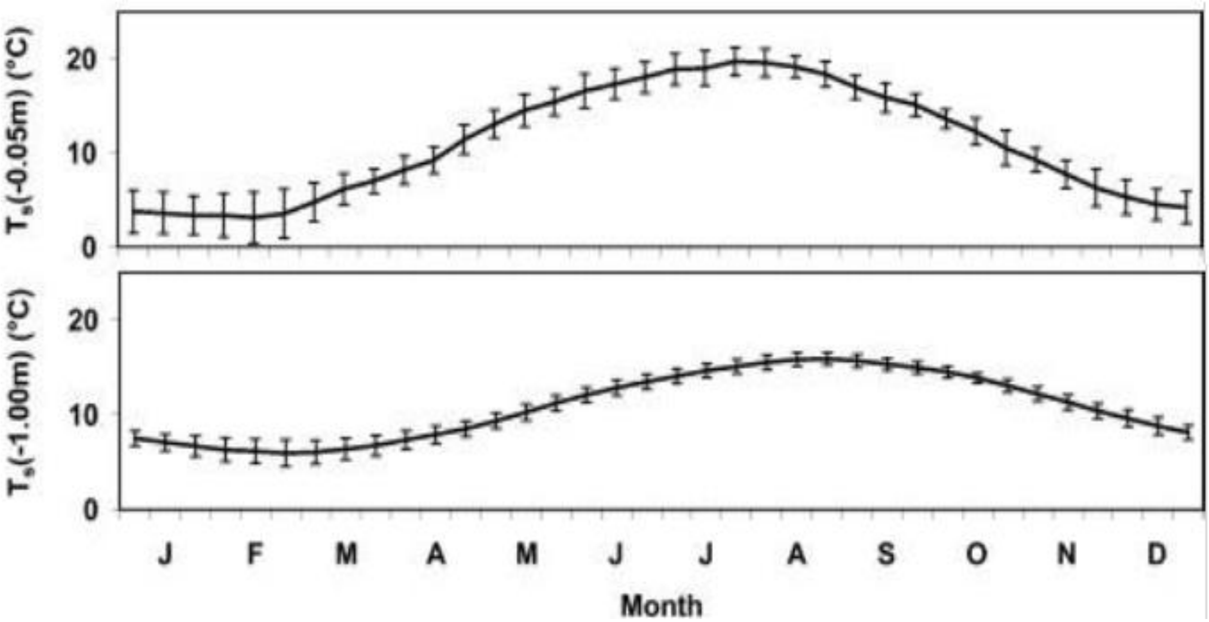


Figure 4: Annual mean distribution of soil temperatures below grassland areas in the Netherlands (Jacobs et al., 2011).

smaller standard deviations than the graph for the 0.05 m deep soil layer. Figure 4 is just an example of the heat penetration through the soil. For an exact temperature relationship between the soil layers, soil properties, surface cover, and boundary conditions are important (Jacobs et al., 2011).

The temperature of deep soil layers is not influenced by short-term weather fluctuations. When deep enough, soil temperature becomes a result of only climate. The depth at which even annual variations are not visible is called the neutral zone. It is estimated to lie at approximately 15 m bgl in a climate similar to that of the Netherlands (Henning, & Limberg, 2012). However, different soil properties can affect the precise depth of the neutral zone. Henning, & Limberg (2012) determined the temperature of the neutral zone for Berlin to be between 8.4°C and 11.3°C. Due to the similar climate it is likely to be comparable to that of Rotterdam. Because of the slow reaction of deeper soil layers on weather variations, soil temperature profiles can be complicated. In Figure 5 temperatures are plotted for depths down to 10 m bgl for every month. Note that this profile is a presentation of a warmer climate than in the Netherlands. Still, it correctly shows that soil temperatures at 1 m bgl can have different values than primarily expected, especially at the end of a hot summer and a cold winter.

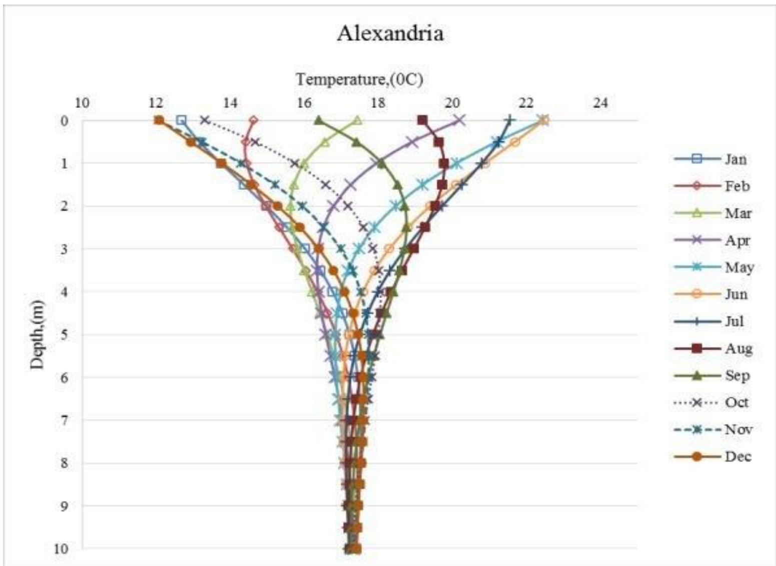


Figure 5: Soil temperature profile for different months on the northern hemisphere (Egypt) (Serageldin, Abdelrahman, Ali, & Mohamed, 2015).

Because drinking water temperature and the soil temperature are closely related, logical reasoning tells us that placing drinking water mains in deeper soil layers, makes them less susceptible for temperature fluctuations. In general the placement depths of mains depend on a few factors: carrying load, protection against excavation damage, construction and operation costs, and protection against freezing and heating (Meerkerk & Beuken, 2017). However, instead of weighing these factors for each location, standards are often used. Most distribution mains in the Netherlands are located at a depth of approximately 1 m bgl, transport mains lie about 0.2 m deeper, and home connections are on average covered by 0.8 m of soil (Agudelo-Vera, & Fujita, 2017; Blokker, & Pieterse-Quirijns, 2010). In practice, it turns out that most network operators can give no certainty about the actual depths of their subsurface infrastructure. Even if installment was performed as planned, improper documentation, subsidence, and interference of other parties in the subsoil could have changed the depths of the infrastructure. Still most studies use the soil temperature at 1 m bgl, because distribution mains tends to have the longest retention time and it is assumed that these lie at 1 m bgl (Agudelo-Vera, & Fujita, 2017; Blokker, & Pieterse-Quirijns, 2010; Agudelo-Vera, 2018; Van Summeren, Vries, Albert, & Verbree, 2017).

As mentioned, research has already been done on the effects of the soil cover, and sunlight on temperatures in the DWDS (Agudelo-Vera, & Fujita, 2017; Van der Molen, Kooi, Smulders, & Heijman, 2008). These factors affect the incoming solar radiation and the amount of evapotranspiration (i.e. latent heat). Agudelo-Vera, and Fujita (2017) showed that in summer locations in direct sunlight are about 2.5°C warmer, in comparison to locations in the shade; and that a paved soil coverage leads to a temperature rise of about 2ºC, in comparison to grassland. Unfortunately, both of these factors are often not taken into account during the design of a DWDS. Mains are often laid below the pavement, at any side of the road, not considering shade. In this study the raw data obtained by Agudelo, and Fujita (2017) is again used in the process of AHS identification.

Anthropogenic heat

The way humans influence soils, and thereby drinking water temperatures, are multifold. We affect the climate, and make alterations to the environment that can directly and indirectly (via climatic factors) cause the soil to warm up. Urban soils are generally warmer, due to all the anthropogenic causes. From now on, human influences that directly affect soil temperature are referred to as AHS.

First of all, urban activity influences the climate on the long term. It is well know that humans have been emitting greenhouse gasses in the atmosphere, inducing global warming (IPCC, 2014). This process has been taking place for a long time, but this section is not meant to address this issue. More important in this case is the way that urban areas have their own local climate. The phenomenon that densely populated urban areas are warmer than rural areas is called the urban heat island effect (UHI). In these areas a combination of limited evaporation, low albedos (less sunlight reflection), changing wind patterns, and a lot of electrical devices cause a warmer local climate (Albers et al., 2015). There are uncertainties about the exact effects, as they are difficult to measure directly. Still, studies have estimated elevated air temperatures in urban areas to be 11.3°C higher (Wang, Berardi, & Akbari, 2016).

Secondly, humans influence soil temperature by changing the environment, aggravating the warming weather effects. Soil coverage, described in the previous section, is one of those alterations. Another is placing buildings, creating shade in some areas, but additional reflection in others (Agudelo-Vera et al., 2015). On average, those alterations cause a hotter soil surface, also penetrating into

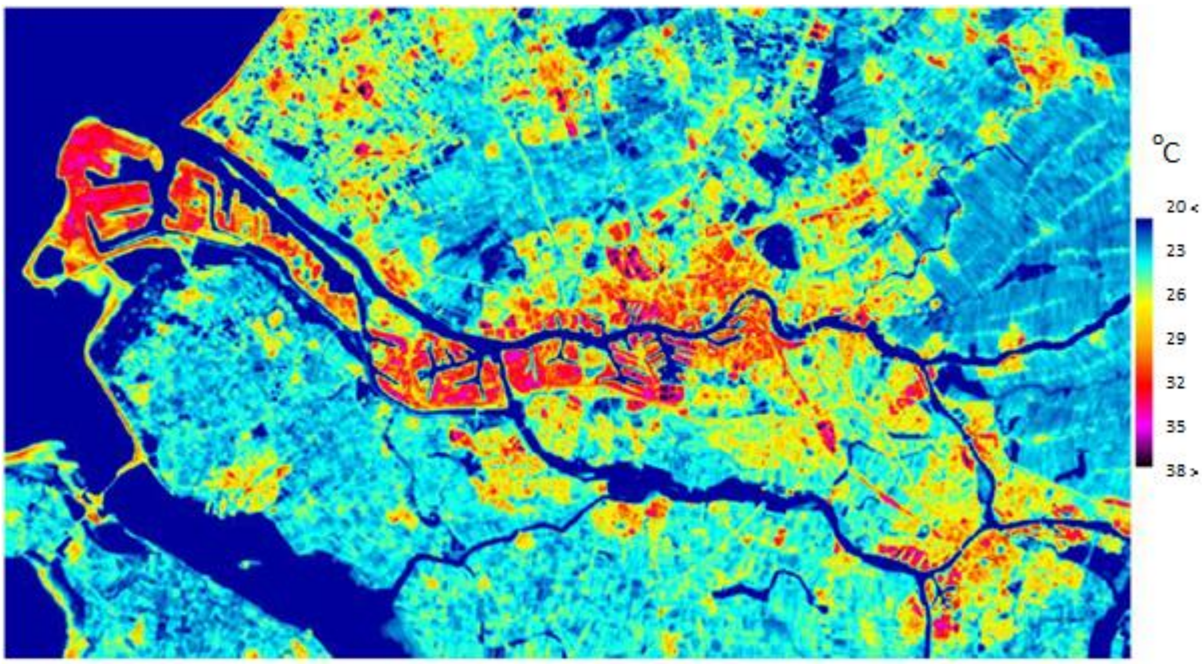


Figure 6: The SUHI in Rotterdam and surroundings. Average surface temperature in °C (Klok, et al., 2012).

deeper soil layers. This effect is called the surface urban heat island effect (SUHI). Klok, Zwart, Verhagen, and Mauri (2012) used Landsat images of Rotterdam to show the magnitude of this effect as shown in Figure 6. This article points out that Nieuw-Mathenesse and Spaanse Polder are the two areas in Rotterdam with the hottest average surface temperature.

Lastly, the urban environment contains more and more heat radiating objects. Especially AHS below the soil surface have the potential to make hotspots in DWDS (Agudelo-Vera, Blokker, Kater, & Lafort, 2017). The heat sources can be categorized in point, line and diffuse sources (Agudelo-Vera, & Fujita, 2017). Examples of point heat sources are an electrical substation, or a single car charging station; line heat sources can be subsurface power cables, metro lines, sewer systems, or city heating mains; and diffuse sources can for instance be a cluster of charging stations, or underground parking garages (Menberg, Blum, Schaffitel, & Bayer, 2013; Revesz et al., 2016; Agudelo-Vera et al., 2017; Agudelo-Vera, & Fujita, 2017). For warming of the drinking water, the line sources are expected to be the most relevant ones for two reasons. First of all, drinking water mains often run parallel with these heat sources for long stretches, making the relation between the heating time and the residence time more disadvantageous. And secondly, a hypothesis is that line sources radiate heat in an infinite number of 2 dimensional planes in a row, while point sources radiate heat in a sphere like 3 dimensional space, leading to believe that the heat of line sources reaches further. Table 2 shows many potential AHS above and below the surface. The table is made using the experience of Dutch drinking water companies and several literature studies.

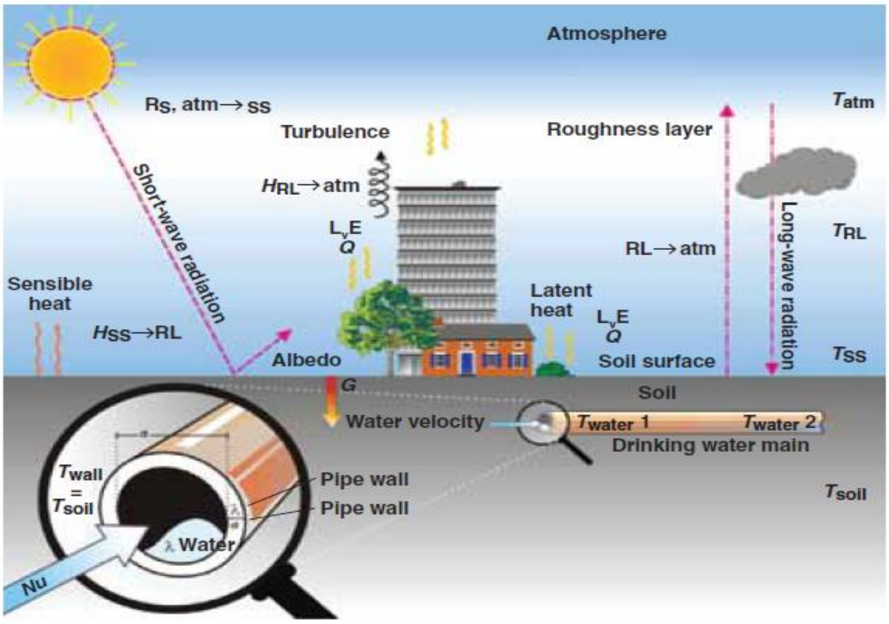
Table 2: Potential AHSs (Menberg, Blum, Schaffitel, & Bayer, 2013; Revesz et al., 2016; Agudelo-Vera et al., 2017; Agudelo-Vera, & Fujita, 2017).

Potential AHS	Point	Line	Diffuse
Above ground	Electrical substation Charging station Laundry facility Swimming pool Industrial source	Road	Building reflection Multiple charging stations High density of buildings Hospital Parking garage
Below ground	Basement Geothermal energy system Aqua thermal energy system	Metro line Power cables City heating system Sewer networks Tunnels	Parking garage

The research that has been done on subsurface heat profiles is hardly ever linkable to drinking water temperature studies. These studies mainly focus on the subsurface urban heat island effect (SSUHI) for sizable areas. In those cases the resolution of data is of a different order, making it impossible to draw conclusions for small scale areas. As mentioned, drinking water temperature studies did try to involve the effects of AHS, but detailed results were not found because of insufficient data. More information on the exact location of AHS and a more comprehensive dataset of drinking water and soil temperatures in space and time is needed.

Modeling soil temperature

Initially, KWR made a 1 dimensional soil temperature model (STM), used to estimate drinking water temperatures (Blokker and Pieterse-Quirijns, 2010; Blokker and Pieterse-Quirijns, 2013; Van der Molen et al., 2008; van der Molen, Pieterse-Quirijns, Donocik, & Smulders, 2009). The STM is based on findings in the field of micrometeorology (Arya, 2001). Figure 7 represents the processes described by the model, which makes use of an energy balance and a heat balance (Blokker and Pieterse-Quirijns, 2013).



atm—atmosphere, DWDS—drinking water distribution system, λ—thermal conductivity, G—heat flux into the ground, H_{RL}—height of the air column representing roughness layer, H_{SS}—heat flux of soil surface, L_vE—latent heat for evaporation, Nu—dimensionless number of Nusselt, Q—energy to heat vegetation, RL—roughness layer, R_S—short-wave radiation, SS—soil surface, T_{RL}—temperature in the roughness layer, T_{soil}—temperature of soil, T_{SS}—temperature of soil surface, T_{wall}—wall temperature, T_{water}—water temperature

Figure 7: Schematic representation of the model, as described by Blokker and Pieterse-Quirijns (2013).

Figure 7 shows the two processes. First the warming of the soil. Secondly, the heating of the water in the DWDS, emphasized by the magnifying glass. Blokker and Pieters-Quirijns (2013) concluded that in most cases using just the STM will suffice for determining drinking water temperatures. To support this conclusion, they used two test cases. Despite the fact that one case contains a scale factor systematic error, and the other case contains a considerable random error, both cases show a high correlation between the modeled and measured results (Blokker, Vreeburg, Beverloo, Klein Arfman, & Van Dijk, 2010). The errors are easily explained by the measuring methods, thus do not mean a flaw in the STM. Still, for reasons explained in the first paragraph of this chapter, certain assumptions are made when using this STM for studies.

In a more recent report, the 1 dimensional STM is expanded to a 2 dimensional model STM. This model includes urban properties. Factors like anthropogenic heat, heat storage of buildings, and urban evaporation are added (Agudelo-Vera et al., 2015). This renewed model, involves information on the UHI and SUHI described in the previous paragraph (Agudelo-Vera, & Fujita, 2017). Scenarios for peri-urban neighborhoods, the average city, and hotspots are predefined in the model. With these scenarios, a lack of detailed knowledge on AHS will not obstruct the composition of a decent average soil temperature estimation in urban areas. Figure 8 shows that most tap sample temperature measurements are captured by these model scenarios. Inspecting the locations of the samples that still fall above these graphs, could prove to be helpful in hotspot research (Agudelo-Vera et al., 2015).

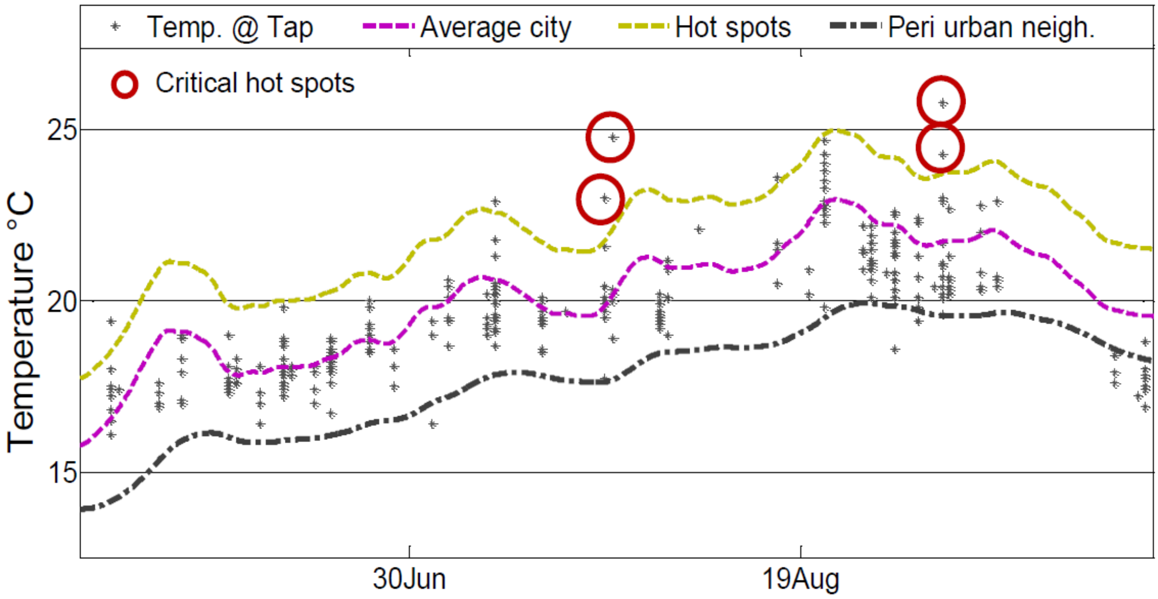


Figure 8: 2D STM simulations and tap measurements for the city of Rotterdam (Agudelo-Vera et al., 2015).

Methodology

The practical part of this study consists out of three phases. In the first phase, AHS are identified. Both a dataset of TST collected by Evides, and the raw data of an earlier study by KWR and Evides are evaluated. Statistically warm areas in the city of Rotterdam are identified for different times of the year, with the intention to link them to the whereabouts of potential AHS. Once the most important AHS are identified, the second phase commences. In the second phase, soil temperatures are measured around the identified AHS. The best measuring sites are determined for each AHS based on influential environmental factors. Lastly, the measurement results are collected and visualized. The second and third phase are intertwined. In this way, the measurement setup can be optimized for the later measurements if needed. When all results are retrieved and visualized, the practical part of this study is finalized and the first conclusions can be drawn. This section describes the three phases of the practical part in more detail, and elaborates on the materials used in this study.

Anthropogenic heat source identification

Analyzing tap sample temperatures

Tap sample temperatures (TST) have been logged for a long time in and around Rotterdam. Evides has given access to a dataset containing temperatures, measurement dates, and measurement addresses in Rotterdam. First inspection of the data shows that the measured temperatures before 2002 are rounded values, and the data before 2012 contain a lot of easily spotted outliers. For these reasons only the measurements from the 1st of January 2012 to the 1st of July 2019 are used in this study. Figure 9A shows the spread of the remaining 10,500 measurements over time.

First step in data preparation, is converting the addresses to coordinates. A Google spreadsheet tool is combined with a Python script to geocode the documented addresses into 'Rijksdriehoekscoördinaten' (RDC), a coordinate reference system which is commonly used by Dutch companies (Appendix 1, line 45). The few addresses not recognized by the tool are corrected or removed manually. Consistency checks in the longitude and latitude columns are used to check for faulty data. Figure 9B shows all left over sampling points plotted over a map of Rotterdam.

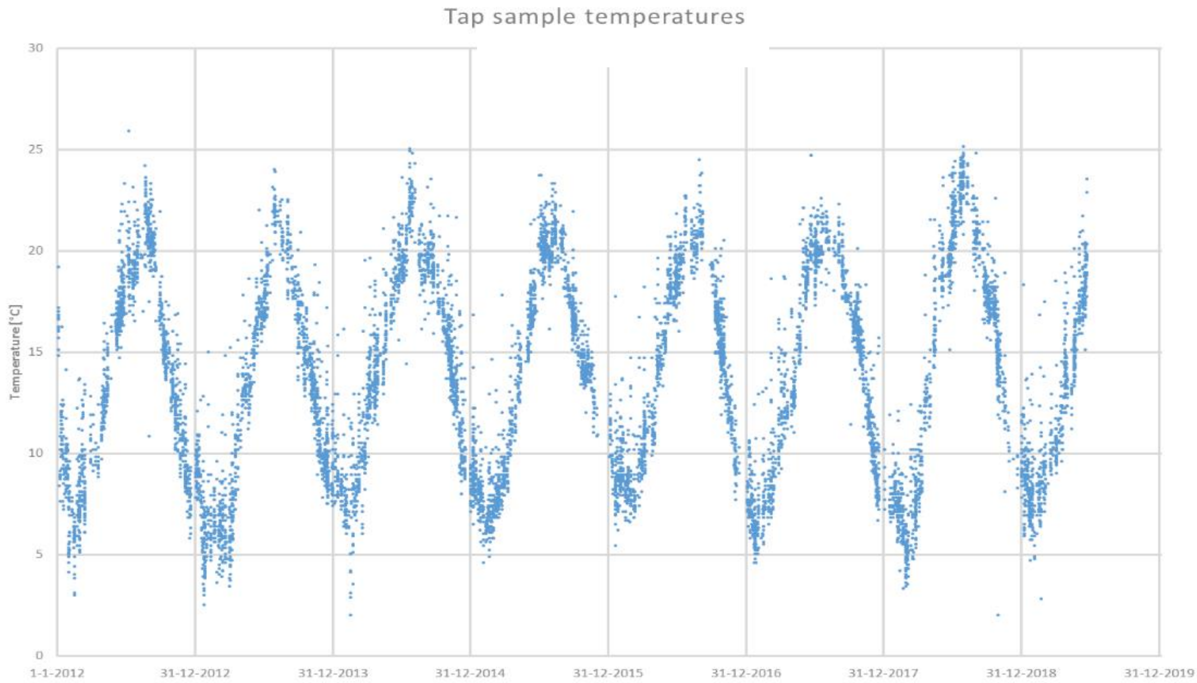


Figure 9A: Time series of tap sample temperatures in Rotterdam, since January 2012.

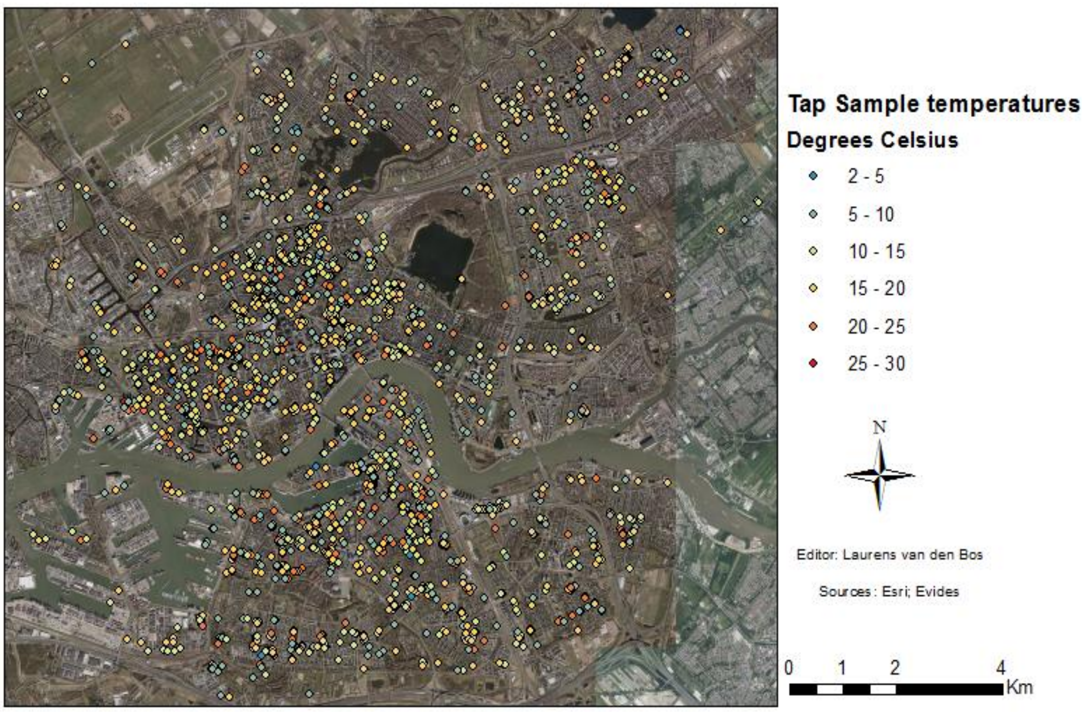


Figure 9B: Locations of tap sample temperatures in Rotterdam, since January 2012.

The next step is to correct the TST for periodical temperature variations. KWR ran the "Average city" STM from January 2012 to July 2019. These results were subtracted from the TST with corresponding dates. A small seasonal trend remained in the data, because of the changing calibration parameters of the STM throughout the year. This trend is also removed in Python, along with the outliers in the remaining dataset. The script of Appendix 1 (lines 57 – 85) shows all the correction steps described.

Subsequently, the TST are spatially and temporally clustered. Rectangular grids of overlapping circles, split the study area in grid cells with radii of 1396m, 698m, and 349m (carried out in the way shown by Figure 10). The different radii should identify different AHS. Some warming the drinking water of only a few streets, whilst others affect a whole district. Initially smaller grid cells were preferred, but the spatial spread of the TST turned out to be insufficient to give reliable results. The temporal clustering is done to check if different seasons show different dominating AHS. Clustering the data in four seasons and three different grid cell sizes, creates 12 scenarios for the TST analysis. The Python script of Appendix 1 shows the clustering steps, partially in a function to call on any of these 12 scenarios (lines 88 – 159).

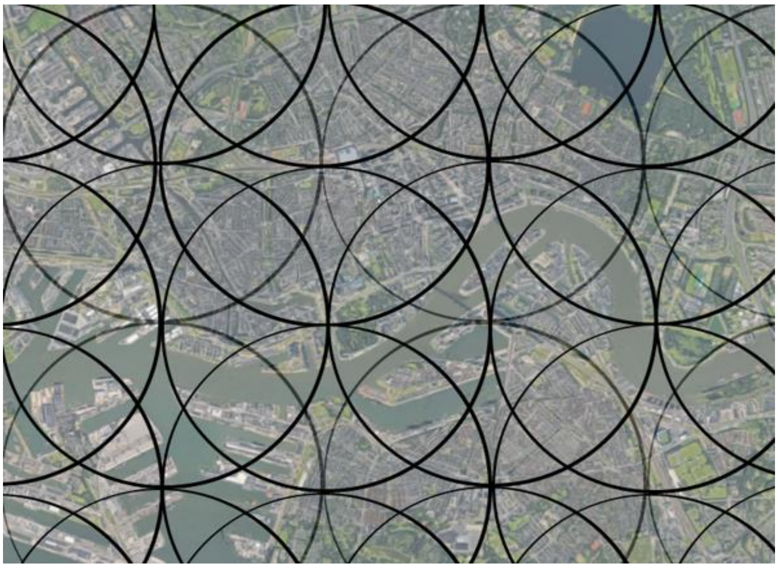


Figure 10: Example of the grid cell distribution for the clustering of the TST.

The same function returns the grids that are statistically warmer than the mean of all grid cells for a scenario. A one-tailed, one sample statistical student t-test determines the significantly warm grid cells based on the sample mean, the number of measurements in the grid cell and the values of those measurements (Encyclopaedia Britannica, 2005). The coordinates of the warm cells are automatically stored in a .csv file, making them easy to import into ArcGIS. In ArcGIS buffers are created having radii that correspond to the grid cell size. By using a distinct colors per season, the results of the TST analysis are clearly visualized. Areas with statistically warm drinking water temperatures compared to the rest of Rotterdam are colored.

Evaluating soil temperature measurements carried out by KWR and Evides in 2016

The TST dataset has the advantage of size. A large spatial and temporal spread, make it useful to create an elaborate image of relatively warm areas over Rotterdam. However, as the literature review explains, measuring soil temperature can in some cases be a better way of determining drinking water temperatures in the DWDS. For this reason, soil temperature measurements from an earlier study are also evaluated. In the summer of 2016, KWR and Evides measured hourly soil temperatures at 42 locations in Rotterdam for 3 months. Figure 11A and 11B show the measurement results and the measuring locations of that study.

The main goal of the study was to determine the effect of solar radiation and soil coverage on soil temperatures at a depth of 1 m. Therefore, the results are not directly linkable to the warming effects of AHS. In fact, the distances to AHS varies a lot making it impossible to draw conclusions about the effects of AHS on soil temperatures. Still, the measurements show additional warming of soil temperatures in some areas, possibly related to AHS. Therefore, inspecting these old measurements in relation to AHS whereabouts, is a supplementary step to improve the identification of potential AHS.

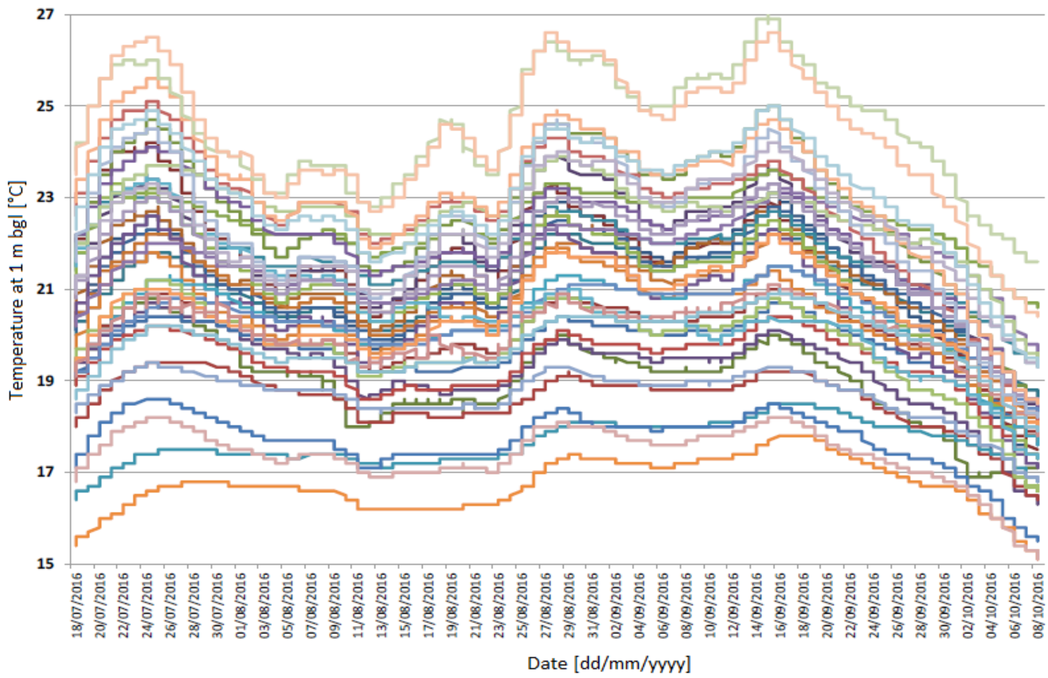


Figure 11A: Soil temperature measurement results of the earlier study by KWR and Evides (Agudelo-Vera, & Fujita, 2017)

Figure 11B: Soil temperature measurement locations of the earlier study by KWR and Evides (Agudelo-Vera, & Fujita, 2017)

Retrieving external datasets

Aside from the temperature datasets, information on the location of potential AHS needs to be collected. Many different sources are used for this localization. First and foremost, the companies that own the heat radiating structures are contacted. Think about Eneco for city heating mains, TenneT for high voltage power cables (HVPC), RET for tracing of the metro lines, etc. Several companies operate transparently and share datasets without any problems; others are willing to help but do not have all the requested information; and some fail to respond at all. If the information is not obtained, ArcGIS possesses a database which may proves to be valuable. All sorts of maps can be collected from this online database. However, one must be cautious in using these maps, because anyone can create them. It is sensible to check the author, a description, and any reviews.

Despite the transparency of some of the companies, it turns out that practically no network operator has information on the depth of their subsurface infrastructure. Guidelines exist about the organization of the subsoil, but no one dares to ensure exact depths. After meeting with the municipality of Rotterdam and discussing this problem, they were willing to help as much as they could. The department “Stadsbeheer Ondergrond LBBO” (subsurface mains and cables), shared information in 3 dimensions on subsurface infrastructures. This information is partially based on the design guidelines of Appendix 2, but it also includes knowledge obtained from test slots that have been dug at certain locations, design blueprints, etc.

Determining measurement locations and setups

On the basis of the hotspot identification process described in the previous paragraphs, it is expected that patterns are found that relate elevated temperatures to AHS. To confirm the suspicions of potential AHS, soil temperatures are measured at locations around these sources. Suitable sites need to be determined on the basis of several factors.

- Because measurements are done in October and November, AHS that are associated with autumn are selected.
- Locations at which the AHS are relatively isolated are preferred, to make sure that the warming effects can be assigned to one specific source exclusively.
- The accessibility of the site must be good. It is not realistic to brake open an asphalt road to temporarily place some sensors.
- Factors like soil coverage, solar radiation, and other influential parameters need to be as uniform as possible at the site.

Once a site seems fit to measure at, a KLIC-request (Kabels en Leidingen Informatie Centrum) is done, to exclude unexpected information about subsurface infrastructure, and to obtain permission to place and remove sensors in this subsoil. Based on the KLIC-request, a line transect perpendicular to the potential heat source is selected to install the measurement equipment along.

Most temperature sensors are placed at 1 m bgl, and some at 0.5 m bgl. 1 m because this is the depth of most drinking water mains in the Netherlands, and the additional sensors at 0.5 m should tell us more about the heat profile in a 2 dimensional plain. In total, 14 sensors are placed spread out over the perpendicular transect. They are placed in a vertical pit, and buried to keep soil properties as intact as possible. Two types of sensors have been made available. 8 Sensors owned by KWR which are placed along a wooden beam, and 6 sensors owned by Jan Hofman of the University of Bath, which are hung in the pit by an iron wire. For each measuring location a specific setup is made on the basis of expectations and experiences of preceding measurements. The sensors stay in the soil for approximately 5 days, to make sure temperatures are not influenced by any soil disturbances during installation. Aside from the 14 sensors, additional information on water and air temperatures at set time are collected from the Evides and KNMI databases. The closest weather station of the KNMI is used, just north of Rotterdam The Hague airport.

At the sensor placement, multiple parameters are noted. The main reasons for collecting these records are proper data storage, and result interpretation. Unexpected results can sometimes be explained by parameter values, which are hard to recover when not documented instantly. Appendix 3 is an installation form which is completed at sensor placement; preferably by the main researcher, otherwise by the main installer. The form is partially derived from the installation form used by Agudelo-Vera et al. (2019).

Visualizing measurements

Once the equipment is recovered from the soil, good visualization of the data is key. In excel the datapoints are linked to depth and horizontal orientation coordinates. An interpolation is made between all measurements at 1 m bgl, using the best polynomial fit between several points. The same is done for the points at 0.5m bgl. In addition, the KNMI air temperature is used as a constant at the soil surface. The data behind these results is saved and exported to construct a 2 dimensional profile of the soil temperature in python.

This phase concludes the practical part of this study. These results should offer sufficient information for the first part of the conclusions, answering most of the research questions. However, the study is supplemented by a literature review giving insight in ways to mitigate warming of the drinking water in DWDS and thereby preventing hotspots.

Materials

Software

In the first few weeks of the study, data handling is the main objective. The raw data is supplied in .csv or .xlsx type files. The TST were not provided with coordinates, but merely with addresses. A Google spreadsheet geocoding tool is used, called Awesome Table. For confidentiality reasons the data is clipped to solely addresses before using the online software. Daily, 1000 addresses are geocoded to a very high precision. In addition, scripts written in Python programming language make the data manageable. Both Jupiter Notebook and Spyder are used for all the programming steps of this study.

The subsequent step consists of data analysis and AHS identification. Again this is partially carried out in Python, but also in ArcGIS. This program is not only used for data analysis and AHS identification, but the program also plays an important role in the visualization of data. As earlier mentioned, the final python script for the data analysis and AHS identification phase is presented in Appendix 2.

After selecting measuring sites based on data analysis, accurate knowledge of the infrastructure in the subsoil must be available. KLIC-requests provide a tool to check if no unexpected subsurface infrastructure is present. The data collected from these KLIC-requests is read out using the free downloadable KLIC-viewer (zakelijk.kadaster.nl/klic-viewer). In addition, the municipality of Rotterdam aided by locally providing information on the depth of the mains and cables. DWG TrueView 2018 is used to see this 3 dimensional information.

The last programs used for the practical part of this study, are used to read out the temperature sensors. The sensors retrieved from Jan Hofman use the software programs Diver-Office and Diver-Field. These programs are specifically used to program and start the devices before placement and to stop and read out the divers after removing them. The other 8 temperature sensors use RC-4H. Software specifically made for this type of thermometers, containing similar functions as the Diver software packages.

Measurement devices and auxiliary material

The temperature sensors made available by Jan Hofman are Van Essen divers. 5 Cera-Divers, 22mm in diameter and suitable for aggressive environments; and 1 Baro-Diver, which has similar functions relevant for this study. All divers have a measurement range between -20°C to 80°C, a resolution of 0.01°C, and a typical- and maximum accuracy of approximately 0.1°C and 0.2°C, respectively.

The thermometers furnished by KWR are called RC-4H Temperature Data Loggers. The logger itself is stored in a waterproof plastic box, and is connected to a needle by a 2 meter long cable. The temperature range of these sensors is -20°C to 40°C. The manual describes an accuracy of approximately 0.5 °C. These devices have a lower resolution, but a resolution of 0.1°C is still expected to be sufficient for this research.

For placing the sensors, some extra equipment is used. A long measuring tape is essential to accurately navigate through the predefined measurement locations. In office, sensor placement is determined, but these places must be related to aboveground landmarks to implement them in practice. Furthermore, a well shovel or a manual auger is needed to create narrow vertical wells. The sensors are placed either at the end of a wooden beam, or along an iron wire. In this way the sensors can easily be placed on the right depth and retrieved after the measurements.

There are some costs involved in this study, all covered by Evides. These are actually limited to the measurement phase. Appendix 4 gives an overview of the costs of the entire study. A KLIC request at Kadaster costs €16.50 per request. Using the services of the employees at Evides, for installing and retrieving the equipment, also indirectly brings costs. The fee of €80.- per hour is actually the price for an external party to use their services. Lastly, KWR requested that their sensor preparation was done by their own personnel. This accounted for 55% of the total costs of this study, as can be seen in Appendix 4.

Results

Anthropogenic heat source identification

By splitting the TST analysis 3 different grid cell sizes and four seasons, 12 different scenarios are created. Figure 12 shows the relatively warm areas of Rotterdam for every season. In Appendix 5 – 8 these maps are enlarged. The first thing standing out, is the similarity between the 3 scenarios within each season. Smaller grid cell sizes show more details, but bigger grid cell sizes often overlap the same general areas on the maps.

Scenarios do differ when different seasons are compared. If the largest grid cell sizes are used, only one cell is warm in all seasons. It accurately covers Rotterdam Center, containing districts

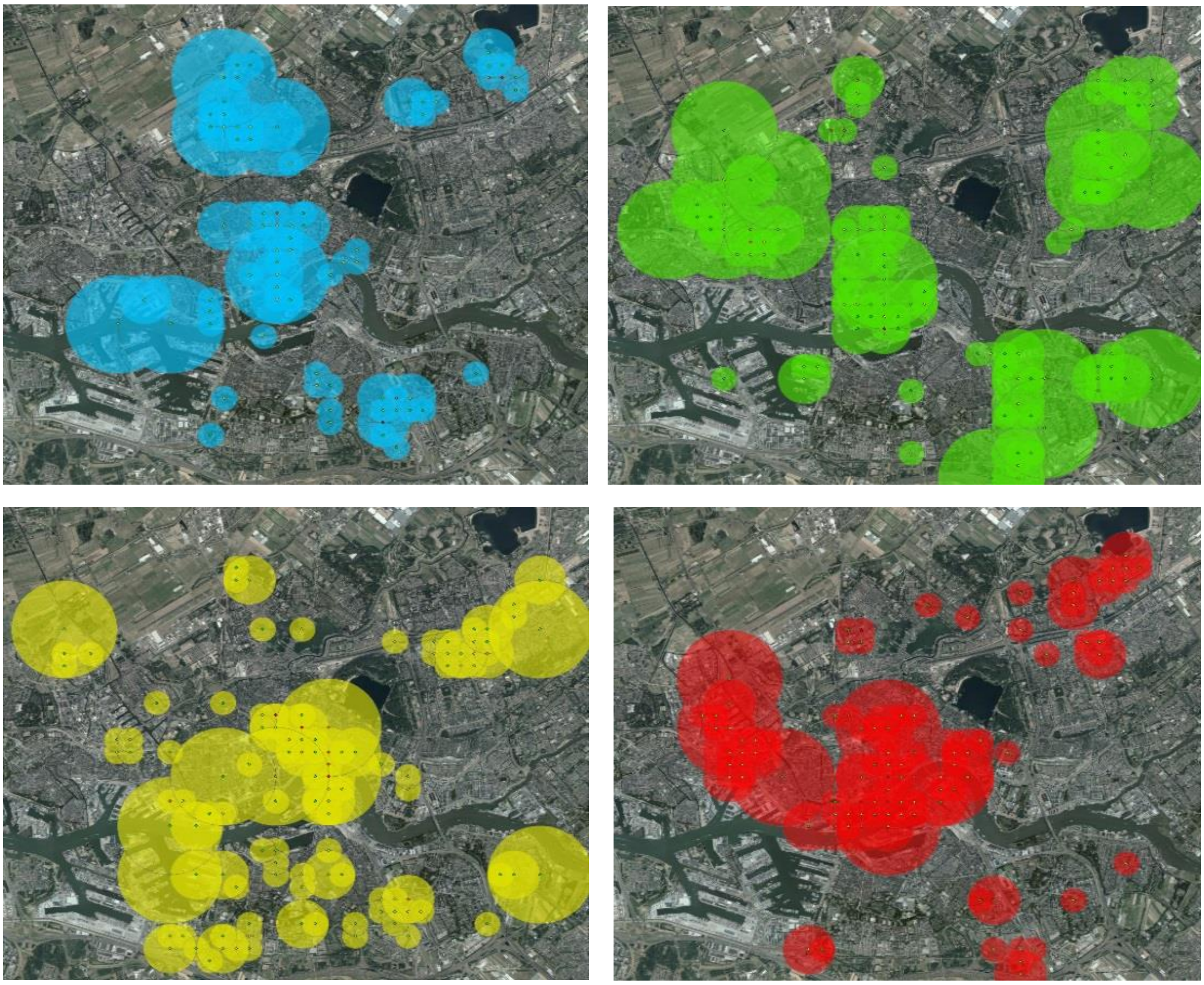


Figure 12: Statistically significant warm grid cells ordered by season. Blue: winter, green: spring, yellow: summer, and red: autumn.

Stadsdriehoek, Cool, Oude Westen, Dijkzicht, and Nieuwe Werk. When the second largest grid cell size is selected, all seasons again only have one area in common. This cell partially overlaps the north of the previously described cell and it contains part of Rotterdam central station and the city archive. For the smallest cell size, again some cells in the north of the center appear to be significantly warm throughout the year. Nevertheless, this cell size shows the vast differences between seasons. Table 4 shows the number of warm cells that scenarios have in common with each other, and the number of unique warm cells.

Table 4: Resemblance between the four seasons at the smallest grid cell size.

Cells matching at the smallest grid cell size	**Winter: In total 57 100%**		**Spring: In total 65 100%**		**Summer: In total 91 100%**		**Autumn: In total 75 100%**	
	#	**%**	**#**	**%**	**#**	**%**	**#**	**%**
Winter	-	-	11	17%	17	19%	17	23%
Spring	11	19%	-	-	12	13%	22	29%
Summer	17	30%	12	18%	-	-	16	21%
Autumn	17	30%	22	34%	16	18%	-	-
Unique	25	44%	33	51%	57	63%	30	40%

Summer shares the least amount of warm grid cells with other seasons. This can be explained by weather factors causing hotspots in summer. Despite the correction of the TST using the STM, the hot weather locally causes very high temperatures via indirect anthropogenic influences (Agudelo-Vera, & Fujita, 2017). These anthropogenic influences, like paved surfaces, are not bound to certain areas, explaining the spread of warm areas. On the contrary, more clustered warm areas are common in winter and spring. Soil temperatures at 1 m bgl are lowest in these seasons, making the absolute temperature increase in the indoor piping system the biggest. For this reason, areas with a large indoor water system, like industrial areas, are shown as warm clusters on the winter and spring maps. Following this logic, the method used to identify potential AHS in this study is most suited for autumn, the measuring period of this study.

When each warm grid cell is inspected individually, all of them can rationally be linked to a cause for an elevated tap temperature. Not just because of weather factors or large domestic water systems, but some can also be linked to AHS. City heating using residual heat is by far the most suspected cause of warm temperatures at the tap. Neighborhoods Rotterdam center and Prins Alexander possess highly branched networks, which closely correspond to warm clusters occurring in every season. The primary mains of the city heating network operate at temperatures of 120°C (feed) and 70°C (return), and the secondary mains at 70°C (feed) and 40°C (return). In Figure 13 the city heating network within 250 meters of any of the included TST measurements is displayed in blue (OverMorgen, 2017).

A less evident but still probable cause of some warm areas, is the presence of HVPC nearby. Figure 13 shows how in autumn the cables appear to have an effect on water temperatures in Rotterdam west. Because the measurements are done in October and November, the HVPC are included in the study.

It is more difficult to state if metro lines or aqua thermal energy systems (ATES) influence soil and drinking water temperatures. The Rotterdam metro line only runs underground between the station in and around the center, which makes it hard to discriminate between the metro lines and city heating to be causing hotspots in those areas. ATES do not seem to correlate specifically with warm cells. The ones that do, are located in the city center again, as are the metro lines and the city heating mains. Furthermore, no data about specific routes is available for these installations. Moreover, these are mainly vertically oriented in contrast to the drinking water mains, thus are less likely to cause warming of the drinking water.

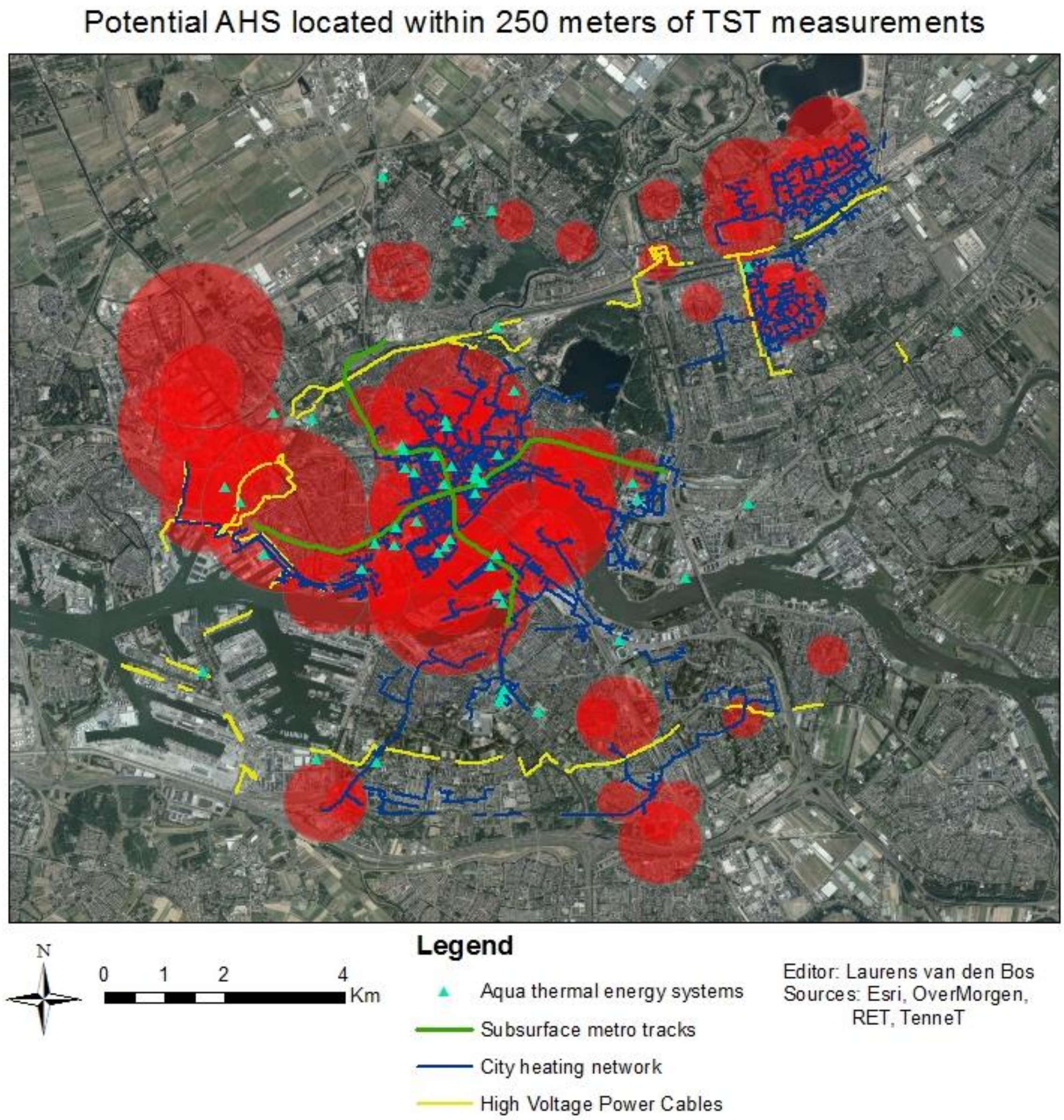


Figure 13: City heating, HVPC, ATES, and subsurface metro lines within 250 m of all TST, overlain with the warm temperatures in autumn

The methodology already described the spread of the TST to form an issue for AHS identification, when creating smaller grid cells. The resolution of the results is too low to identify smaller heat sources. For this reason the study shifts its focus, solely measuring around line heat sources. Still, not all line sources are included in the measurements. Roads, low voltage power cables (LVPC), and sewer networks, run throughout the whole study area. In some areas these networks are even more abundantly present than the DWDS. This also results in the fact that these potential AHS do not particularly correlate to the warm areas.

Evaluating the raw data of the 2016 study by KWR and Evides does not add new insights in identifying AHS. It does however, confirm suspicions raised by the TST analysis. For this data a lot of parameters need to be taken into account. Samples were taken either under grass or pavement, they received different amounts of solar radiation during the day, and their distance from potential AHS varied a lot. Furthermore, not all documented coordinates match the photos that were taken at the corresponding measuring sites. This inaccuracy needs to be kept in mind. In the end, only the measurements in and around Nieuw-Mathenesse can help to identify AHS.

Of the four warmest measurements, three are located within ten meters of city heating mains, and one overlays multiple metro lines. Of those locations near city heating, two are also near HPVC, however, the warmest of all four is only near the city heating system. When looking at relatively cool measuring points, it stands out that they are all located at a fair distance of both city heating and metro lines.

Measurements and visualization

The potential AHS that are identified through the first phase of this research affect relatively large areas. By far the most evident AHS is the city heating system, using residual heat. Especially in autumn, the whereabouts of the system correspond very well to the map of warm areas. Both the primary and secondary mains, are likely to cause hotspots in the DWDS. In addition, HVPC in the west, and metro lines and ATES in the center also possibly cause hotspots. However, less evidence points at these potential AHS. ATES are not included in the measurements, because the exact design of these systems is not known. For the other potential heat sources four locations are selected to clarify the warming effects in autumn. Below, the findings of those locations are described in chronological order.

Location 1: Mevlanaplein

The first measurements were done at the Mevlanaplein, from 11 to 16 October. The sensors were placed near three parallel 150kV power cables owned by network operator TenneT. Appendix 9 shows the exact measurement set-up. This location was determined to be the best measuring site. The AHS

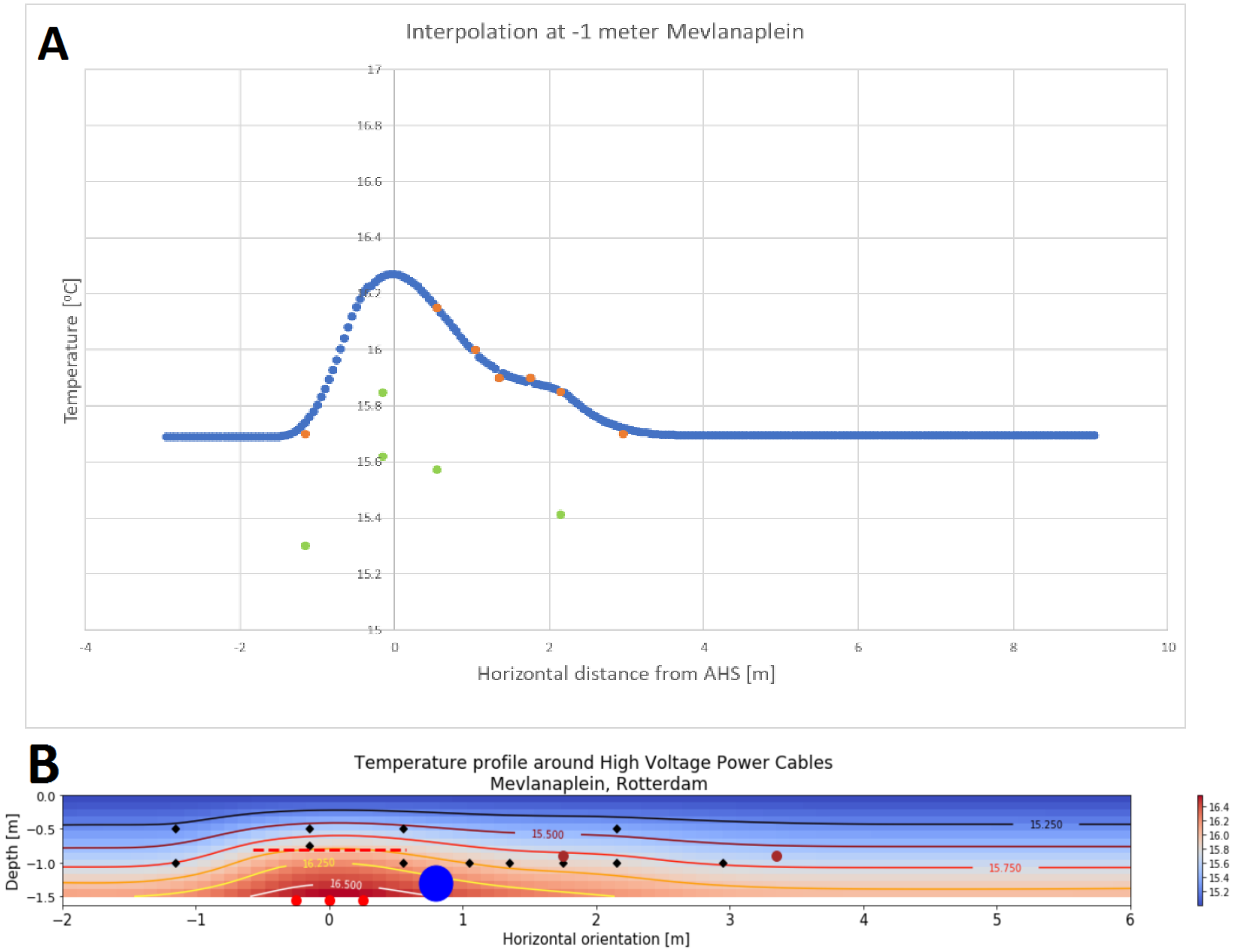


Figure 14A: Measurement results at 1 m bgl (orange dots), measurement results at other depths (green dots), and an interpolation of the temperature at 1 m bgl (blue); Figure 14B: 2 dimensional temperature grid based on sensors (black dots) and air temperature as boundary condition at depth = 0m. Included in the grid are LVPC (brown), HVPC and cover plate (red) and drinking water main (blue).

is relatively isolated and the soil is accessible. Furthermore, the effect of the heat source on the drinking water temperature could perhaps be seen. Also important, the sun, soil, and soil coverage conditions are the same over the transect. The groundwater level fluctuated several centimeters around 1 m bgl during the measuring period, probably related to rain showers.

At placement, 1 sensor was damaged. Another turned out to give weird and unpredictable results. This sensor gave a hunch that sewer lines would radiate a lot of heat, but after multiple measurements, it turned out to be a faulty sensor. The rest of the sensors showed a very constant temperature at 1 m bgl, as can be seen in Figure 14. Sensors at 0.5 m bgl, showed a bit more variations, as expected. In Appendix 10, for all working sensors the temperature is plotted over the 5 days in the soil. Figure 14A shows the interpolated temperature at 1 m bgl perpendicular to the HVPC, combined with the measurements at 1 m bgl in orange, and the other measurements in green. What stands out is an elevated measured temperature of just 0.5°C, and the fact that shallower soil layers are clearly colder than the deeper layers. The bump in the graph, to the right of the peak, may be there for one of two reasons. Either one of the LVPC warmed up the soil by 0.1°C (rounded off); or it is only a measuring flaw, because the sensor precision is less than the size of the bump.

In Figure 14B the 2 dimensional soil temperature profile perpendicular to the HVPC is shown. Animated within the picture are the HVPC with a cover plate at a depth of 0.75 meter, a transport drinking water main, two LVPC marked with brown dots, and all the sensor locations from which the image is created as black dots. These features are also shown in the schematic measurement setup of Appendix 9. The location of the HVPC can easily be traced back from the temperatures in Figure 14B. However, if the temperature scalebar is inspected, it can be seen that the heating of the soil is limited.

Location 2: Hogenbanweg

At the second site, measurements were done from 18 to 23 October, at the intersection of the Hogenbanweg and the Engelsestraat. At this location a city heating main with an inside diameter of 700mm, and six 150kV HVPC are present. After the results of the first location, the potential heat sources were deemed to be far enough from each other to use this location for measurements. Water temperatures in these primary city heating mains should lie around 120°C in the feed pipe and 70°C in the return pipe. No ground water table was encountered at a depth of 1 m. Appendix 11 schematically presents the measurement setup.

The measurement results, shown in Appendix 12, indicate considerably more variation in temperatures at this location. However, only around the city heating mains. At a short horizontal distance from the HVPC, there initially was no elevated temperature exceeding the sensor precision. Only in the last few days an elevation of 0.4°C was measured. Again an indication of limited heating of the soil near HVPC.

Directly above the city heating mains, a pronounced temperature rise is found. The temperature above this infrastructure is 4.9°C higher than the uninfluenced soil temperature of 16.7°C. Furthermore, 5.25 m from the hottest point at a depth of 1 m, the soil temperature was still 17.7°C. The blue line of Figure 15A shows the interpolated temperature at 1 m bgl for the entire measuring transect. The orange and green dots indicate the measured temperature values at depths of 1 and 0.5 m, respectively. The graph is not symmetrical top both sides, probably because of the drinking water transport main at 10 m from the AHS, which likely cools the soil a bit.

The meshgrid of Figure 15B shows the soil temperature profile perpendicular to both AHS. As in Appendix 11, Figure 15B displays a drinking water transport main (blue), the city heating mains (purple), the HVPC incl. cover plate (red), and the sensors (black). Both Figure 15A and 15B, and Appendix 12 indicate a much more thermally influenced soil, in comparison to location 1.

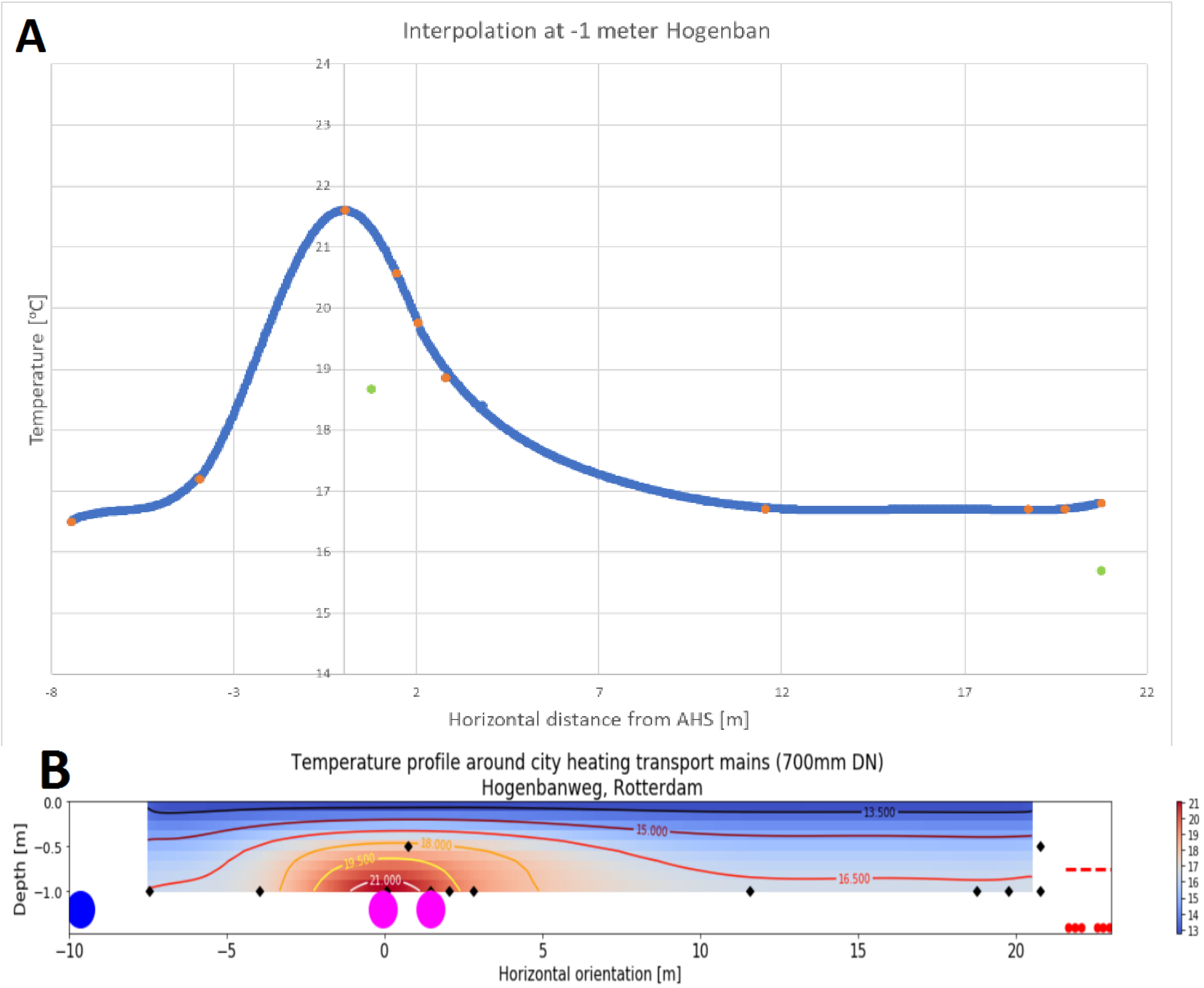


Figure 15A: Measurement results at 1 m bgl (orange dots), measurement results at other depths (green dots), and an interpolation of the temperature at 1 m bgl (blue); Figure 15B: 2 dimensional temperature grid based on sensors (black dots) and air temperature as boundary condition at depth = 0m. Included in the grid are HVPC and cover plate (red), drinking water transport main (blue), and primary city heating mains (purple).

Location 3: Hofdijk

The third measuring site was in the city center, at the intersection of the Hofdijk and Katshoek. From 28 October to 1 November the temperature was measured around secondary city heating mains with an inside diameter of 150mm. The water temperature inside these mains lies around 70°C in the feed pipe and 40°C in the return pipe. Instead of vertical pits, a small trench was dug directly above the city heating mains to locate their position more accurate. The 3 dimensional information provided by the municipality of Rotterdam placed them at only 0.7 m bgl. The trench however, proved that the mains actually were covered by 1.3 meters of soil. At this same depth, the groundwater table was encountered. The complete measurement setup is shown in Appendix 13. It shows that most sensors were placed around the city heating mains, and some sensors were placed around the 160 mm PVC drinking water main at a distance of 14 m.

Again, the soil temperature was elevated around the city heating mains. The highest measured temperature at 1 m bgl was 18.2°C, 3°C higher than the temperature of the uninfluenced soil. At a horizontal distance of 2.3 meter, the soil was still 1°C warmer than the uninfluenced soil temperature of 15.2°C. Only one side of the profile is plotted in Figures 16, because something went wrong with the placement of the sensor at the other side. Still, it is expected that the temperature profile will be practically symmetrical, as no other warm or cold sources are around.

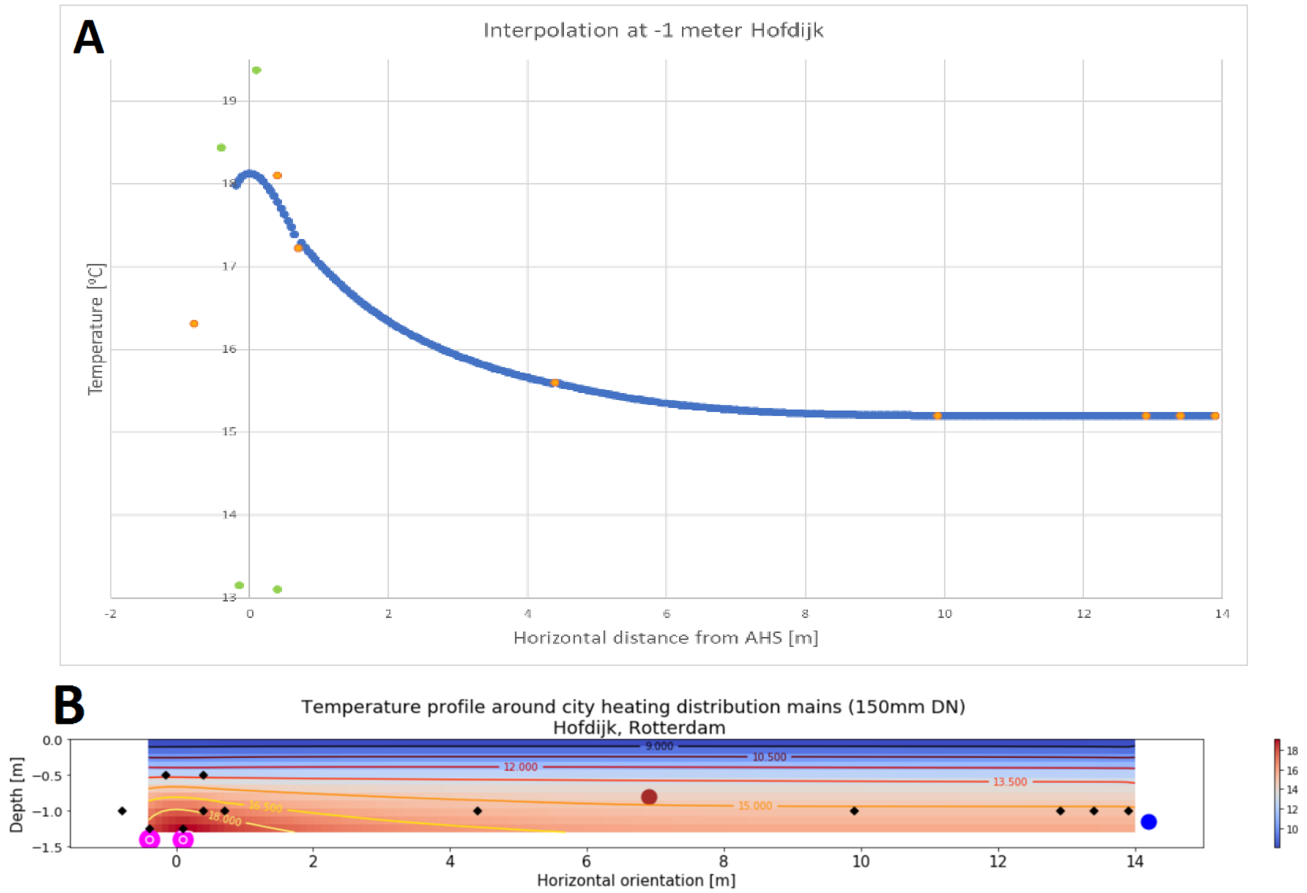


Figure 16A: Measurement results at 1 m bgl (orange dots), measurement results at other depths (green dots), and an interpolation of the temperature at 1 m bgl (blue); Figure 16B: 2 dimensional temperature grid based on sensors (black dots) and air temperature as boundary condition at depth = 0m. Included in the grid are a drinking water main (blue), a LVPC (brown) and secondary city heating mains (purple).

The drinking water main does not have any measurable effects on the soil temperature. Probably because the water temperature in the pipe already reached the soil temperature upstream from the measuring site. When looking at the results in Appendix 14, it shows that some sensors start the measuring period with an arch. This arc is explained by the dug trench. When the trench was closed, the sand was exposed to the air temperature for about an hour, and the sand layers were mixed. This effect faded out towards the end of the measuring period. The interpolated results at 1 m bgl in Figure 16A show a clear temperature peak around the AHS. Compared to the primary heating mains of location 2, these secondary mains provided a less elevated temperature, also reaching less far. In Figure 16B, the 2 dimensional soil temperature profile perpendicular to the AHS is shown. This image includes the whereabouts of the city heating mains (purple), the drinking water main (blue), the LVPC (brown) and the sensor locations (black).

Location 4: Prinsenlaan

From 7 until 13 November, the last measurements were done at the Prinsenlaan. Aside from primary city heating main with an inner diameter of 500mm, a pressurized sewer system is present at this location. Based on the identification phase, there is no reason to believe that a pressurized sewer system acts as an AHS. However, unexpected results at the first measuring location, made it necessary to include pressurized sewer systems as a potential AHS. Aside from the Prinsenlaan, two other sensors are placed at the Gerdesiaweg over the metro lines. Based on the TST analysis, there was a slim chance that the metro would be a relevant AHS. These two sensors should indicate if additional measurements around metro lines were needed. Appendix 15 schematically presents the measurement setup of the sensors at the Prinsenlaan.

Both the pressurized sewer system and the metro line showed no measurable elevated temperature. As the drinking water main at the Hofdijk, the sewer system appears to have the same temperature as the surrounding soil. The measured temperature difference at the Gerdesiaweg fell within the sensor precision.

On the other hand, the city heating system again showed an elevated temperature. The highest temperature directly above the mains is measured to be 5.3°C warmer than the unaffected soil temperature. Figure 17A shows that the highest measured temperature was almost 17°C. This elevation is actually bigger than the temperature increase over the 700mm city heating mains. However, the heat did not reach as far at this site. 1°C warming was measured at a horizontal distance of 3.8 m from the highest measured temperature. Figure 17A shows the interpolated results of the measurements at 1 m bgl, including the measurement results at 1 m bgl, and the results at different depths in orange and green respectively. In Figure 17B, the subsurface soil temperature profile, including the whereabouts of the city heating mains (purple), the sewer system (brown), and the sensor locations (black), is shown for the results at the Prinsenlaan.

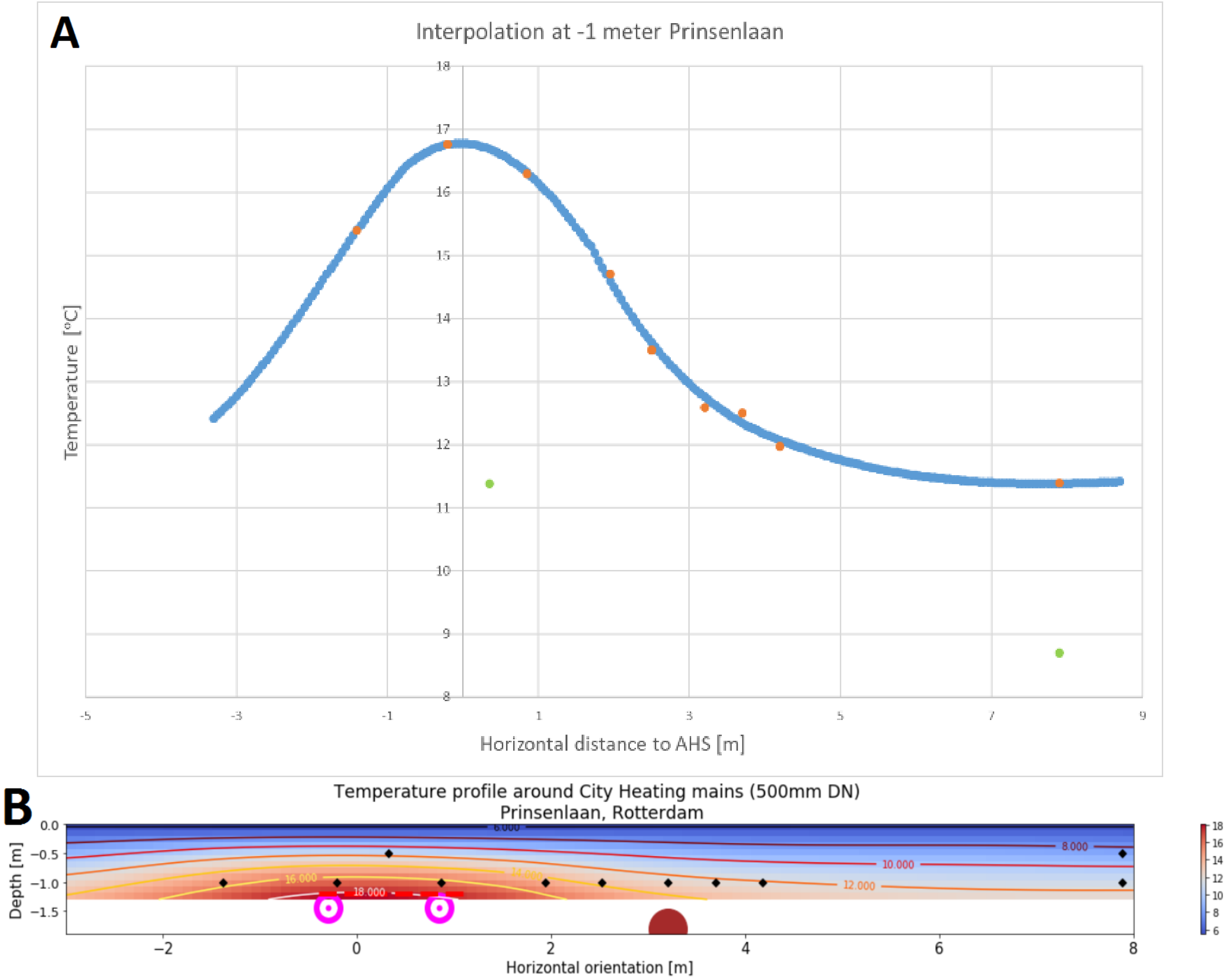


Figure 17A: Measurement results at 1 m bgl (orange dots), measurement results at other depths (green dots), and an interpolation of the temperature at 1 m bgl (blue); Figure 17B: 2 dimensional temperature grid based on sensors (black dots) and air temperature as boundary condition at depth = 0m. Included in the grid are a pressurized sewer system (brown) and primary city heating mains (purple).

Discussion

The measurements have both confirmed and invalidated some of the expectations that came forth from the initial analysis. The TST analysis only gave a strong suspicion towards city heating as the most important AHS. Furthermore, HVPC and metro lines turned out to be worth measuring around. These expectations were endorsed by the evaluation of the raw dataset of KWR from 2016. In addition, the first measurement location gave a reason to include sewer mains as a potential AHS. Despite this selection of potential AHS, some additional networks that could influence soil temperature were automatically measured as well, due to their presence at some of the measuring sites. In fact, the only potential subsurface line AHS identified in Table 2 that was not measured in this study are tunnels.

Low voltage power cables

While not showing up in the analysis of this study, theoretically there was still a chance that LVPC could have a small warming effect on the soil. Some studies mention power cables as a potential heat source, however, the expectation is that they only mean the HVPC. Agudelo-Vera et al. (2019) already placed a sensor right next to this potential AHS, which did not detect any warming. The same holds for the measurements performed for this study. No measurable temperature rise was observed. Thus, an expected and convenient result. Convenient because taking matters to prevent warming from LPVC would be an immense job, based on the extent of both networks.

Sewer mains

The temperature of wastewater when generated in households varies between 30°C and 35°C (Pochwała, & Kotas, 2018). However this substance drops in temperature once it enters the sewerage. Just as drinking water, the temperature within these mains quickly drops to the ambient soil temperature. The heat that is transferred to the soil, is not expected to form a serious problem for drinking water temperatures. There are certain standards to keep the drinking water and waste water apart, because of contamination risks (Slee, & Tjan, 2015). However, these standards are also favorable for the drinking water temperature near house connections.

The temperature that KWR sensor 15 measured at location 1 was unexpected. Not only the relatively high temperature was unpredicted, but also the pattern over 5 days did not make sense. The sensor was checked and calibrated twice before being placed in the soil, thus the results were taken very serious. But afterwards the sensor proofed to be faulty, and its measurements were removed from all the results. As a double check, extra sensors were placed around a pressurized sewage at the fourth location. No elevated temperature was documented at that location.

Metro lines

The typical source temperature of metro tunnels is described to be 20°C to 30°C (Revesz et al., 2016). Different than sewers, the temperature does not approach the surrounding soil temperature. Like with most AHS, the source temperature does not by definition decrease over length of the route. RET, the operator of the metro lines of Rotterdam, owns 17.7 kilometers metro tracks in the subsurface (RET, n.d.). The depths of these tracks is no public information, and RET is also not willing to share this information. In online literature the depth ranges from less than 16 meter (deepest station according to ZJA (2019)), to 20 - 25 meter (depths of a tunnel through the Pleistocene sand layer according to van Haastrecht (2005)).

Two sensors placed just behind station Gerdesiaweg, measured no elevated temperature over the metro tunnel exceeding the sensor precision. For this reason no extra measurements were included in the study. Even if the temperature would have been significantly higher, an alternative measuring method should have been made. The big tunnel diameter and varying unknown depths would make it hard to select an appropriate measuring site.

High voltage power cables

On forehand, literature identified HVPC as important potential AHS. The temperature range of HVPC can reach up to as high as 90°C (Agudelo-Vera, & Fujita, 2017). However, this is depends on the voltage and current over the cable. In and around Rotterdam, the power cables with the highest voltage are 150kV cables (TenneT, 2019). A concept modelling study of Eneco uses a maximum source temperature of 45°C for these kind of cables (Dijkstra, 2013).

The fact that HVPC produce residual heat is nothing new. Therefore, limitations on thermal soil influence are documented in the NEN3654 (NEN, 2014). Broadly this NEN states: a soil temperature rise of 5°C must be avoided, no temperature rise should be noticeable further away than 10 m, and the soil temperature should not exceed 20°C. This third statement however, is quiet arbitrary. After a hot summer period, it is possible that soil temperatures become 20°C, without any AHS present. Favorable is that HVPC usually lie deeper than drinking water mains and under a cover plate, as can be seen in Appendix 2 (Slee, & Tjan, 2015).

The analysis of TST showed no strong correlation between the whereabouts of the HVPC and the warm water temperatures. Some warm areas have a subsurface HVPC network, but the network is not restricted to the warm areas. However, a reason to include HVPC in the measurements comes forth from the visual evaluation of the data from the earlier study of KWR and Evides (Agudelo-Vera, & Fujita, 2017). Some very warm measurements were located just several meters away from the high voltage power net.

The expectations on the basis of preliminary research, were not matched by the measurements. The thermal influence of HVPC depends on multiple factors, among which the electric current (NEN, 2014). This dimension changes as a result of the energy demand of the underlying area. The demand shows daily and annual fluctuations. However, no daily pattern was encountered in the soil temperature measurements. In general, the electricity demand in Dutch cities is lower in summer, decreasing the temperature risk for drinking water companies (De Cian, Lanzi, & Roson, 2007). Only in very hot summers, the electricity demand could increase a bit due to all sorts of cooling devices (De Cian, Lanzi, & Roson, 2013). Still, this small demand increase is not expected to hold on for a long time. Therefore, the temperature effect is not expected to be much bigger than those of the measurements in October. Probably more important are varying soil properties around HVPC. This aspect will be discussed in the last paragraph of this chapter.

The soil temperature measurements show limited heating of the soil. The whereabouts of the HVPC at the measuring sites can be retrieved from the figures, but the absolute temperature rise is minimal. The trendline through the measurements at 1 m bgl indicates an increase in temperature of 0.6°C directly above the AHS, at the Mevlanaplein. However, due to a cover plate above the HVPC, the nearest sensor at 1 m bgl measured a soil temperature rise of 0.5 °C at a horizontal distance of 0.55 m from the warmest point. As expected, the measurements at 0.5 m bgl roughly show a similar pattern, but at a temperature closer to the air temperature. At placement, the groundwater table was encountered at 1 m bgl at one of the vertical pits. The same is measured by the Van Essen divers. Fluctuations of centimeters occurred after rain showers. The importance of water in the soil is described later on in this chapter. The results of the measurements close to the HVPC at the Hogenbanweg only confirm the idea that heating of the HVPC is very limited. No groundwater table was encountered at this location, and the temperature rise only just exceeded the measurement accuracy during the last few days.

City heating

There are several types of district heating systems in use. Systems that use residual industrial heat, ATES, geothermal energy systems, etc. Rotterdam has an extensive and growing city heating network that uses residual industrial heat. Furthermore, there is a number of ATES installed. In 2016, 60 authorities were licensed to use ATES (OverMorgen, 2018). In this study no measurements were done around ATES for multiple reasons. First of all they are not expected to cause as high soil temperatures as other district heating systems. Water temperature in these systems is much lower than in systems using residual heat (Sommer, 2015). The ATES do also not strongly come forth as a potential AHS in the TST analysis. And secondly, exact locations of the underground infrastructure of these systems is not public information. Moreover, the mains of these systems are predominantly vertically orientated, so they act as point sources in the (almost) 2 dimensional plane of drinking water infrastructure.

In contrast to the ATES, the city heating system of Rotterdam proves to be an important AHS. Especially in autumn, the statistically warm areas based on the TST measurements, strongly correlate to the whereabouts of the city heating system. The network is actually a double network of primary and secondary mains, which transport warm water to the customer. Vattenfall (Rotterdam south), and the municipality of Rotterdam, have declared the water temperatures in the distribution system generally to be as follows: in a primary feed pipe between 120 °C and 130 °C; in a primary return pipe approximately 70 °C; in a secondary feed pipe 70 °C; and in a secondary return pipe 40 °C (H. Van Der Maas, personal communication, 9-12-2019; Rob ten Boden, personal communication, 2-12-2019). Despite the changing heat demand throughout the year, these temperatures remain the same.

This does not mean that these high temperatures are passed directly to the soil. To retain their heat, all city heating mains have an insulation layer, often made of polyurethane (PUR) (Kręcielewska, & Menard, 2015). Kręcielewska and Menard (2015) describe that insulation layers are produced to keep thermal conductivity at or below 0.033 W/m·K, working for 30 years at constant temperature of 130 °C. Still, the exact state of the network is unknown. Some parts are newer than others, because of network expansions. And in some cases the insulation layer may be more robust than in others. The state of the network directly affects the heat dissipated to the soil.

In this study, the soil temperatures around city heating mains at three locations were measured. Two locations with primary mains, having inner diameters of 700mm and 500mm; and one location with secondary mains, and an inner diameter of 150mm. When it comes to maximum measured elevated temperature, the two primary mains show comparable results. Both have a measured maximum temperature elevation of approximately 5°C, in comparison to 3°C at the

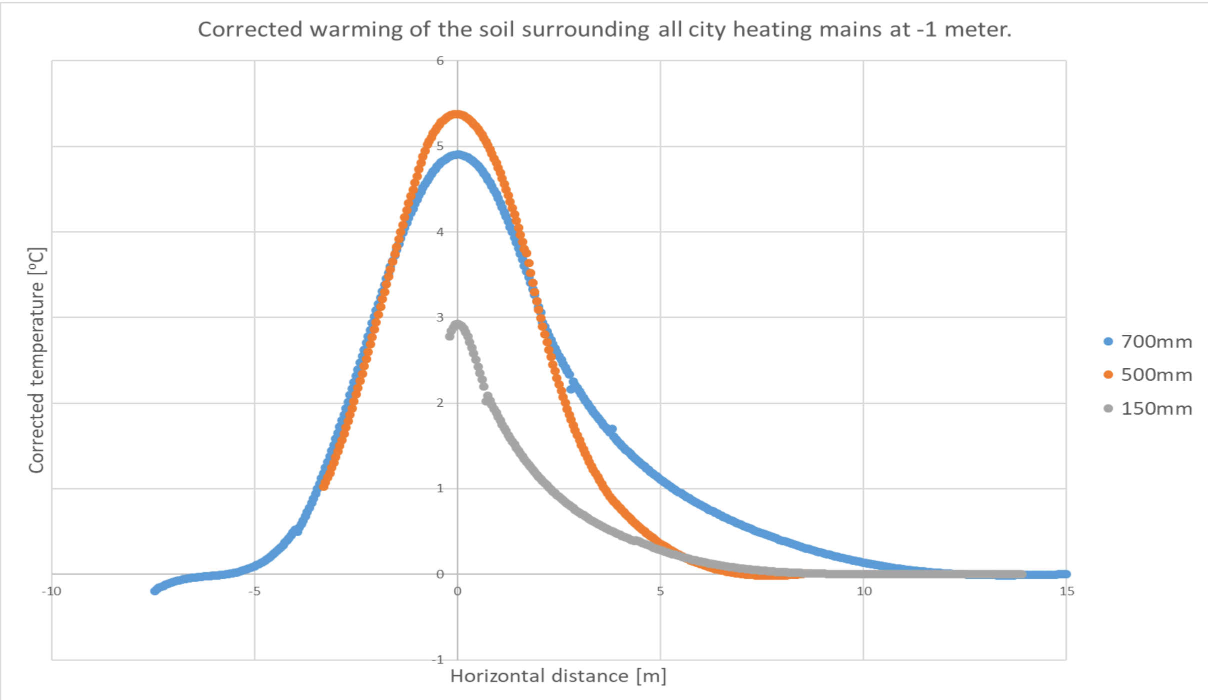


Figure 18: Relative temperature elevations at the three measuring locations containing city heating mains.

secondary main. The remaining difference of 0.4°C between the two temperature maxima around the primary mains can have various causes. It can tell something about the depth or temperature of the mains, but it can also be caused by soil properties, air temperature, or other environmental factors.

Aside from the maximum measured temperature, the heat pattern throughout the soil also differs. The two primary mains show different patterns. The curvature of the 700mm graph looks more like the graph of the 150mm main. These profiles are explained by environmental factors at the measuring site, and not by the AHS themselves. The next paragraph elaborates on the possible causes of the differences. In figure 18, the three relative temperature curves are plotted over the distance from the hottest point above the AHS.

Influencing factors explaining the results

There are some parameters that were assumed to be very important for the soil temperature profile prior to the measurements. As there were: AHS diameter, AHS depth, AHS temperature, state of insulation, thermal properties of the soil, soil coverage, sunshine hours, ambient soil temperature, air temperature, etc. Some have been controlled in the measurements (soil coverage, sunshine hours), others have been documented (certain soil properties, air temperature, AHS dimensions), but some information was impossible to get informed about (some continuous soil properties, heterogeneity of the soil, state of insulation). During the evaluation of the measurements, some factors proved to be more important than others.

The results show that the effect of air temperature has a very big influence on the heat dissipation through the soil. It is expected that this temperature (combined with the resulting uninfluenced ambient soil temperature) is the main reason for the different curvatures of all the graphs in Figure 18. The elevated temperature is documented as the temperature relative to the uninfluenced soil temperature, but in the measuring months the air temperature has been decreasing faster than the soil temperature. The air temperature serves as a boundary condition at the soil surface, and thus affects the whole heat profile of the soil at a depth of 1 m.

Models used to demonstrate if thermal influences are conform NEN guidelines do not only use the soil surface as a boundary condition. Often they also use a neutral zone. While it is wrong to think that the neutral zone, directly under an AHS, lies at the same depth, or has the same temperature as the surroundings (Henning, & Limberg, 2012). This faulty assumption of temperature gradients between soil layers, results in wrongly shaped heat profiles. Thus a similar heat flux from an AHS may warm the soil different than shown in such models. The temperature gradients in and around the soil also explain why two seemingly comparable measuring sites, can show different heat profiles.

For these measurements, the soil properties are not likely to be the dominating cause of the different temperature curves at 1 m bgl. All locations had similar sandy soil textures, and despite the fact that the soil moisture content was different at the Prinsenlaan, this had no visible effects for the heat dissipation. At the Prinsenlaan the groundwater level was measured to be between >1 – 0.7 m bgl over 5 days. This was accompanied by a more moist soil around the sensors. Interestingly enough, the temperature profile shows the exact opposite of what was expected with a wet soil. More water results in a higher thermal conductivity of the soil (i.e. a lower thermal resistivity) (Electricalunits, n.d.). With thermal conductivity being the most important heat transferring process in soils, the expectation was that an increased temperature would have been measured further away from the AHS (Farouki, 1981). For this reason the temperature difference between the air and the soil remains the dominating process for heat dissipation through the soil. Warm air temperatures prevent energy transfers from the soil to the air, having alarming consequences for hot summers.

Aside from the heat dissipation at 1 m bgl, the maximum measured temperatures differ as well. First of all, the 150mm main at the Hofdijk warms the soil directly above the AHS about 3°C. Even though this secondary main operates on a temperature of only 70°C. More interesting is the difference between the two primary mains. Several explanations exist for this higher maximum at the main having the smaller diameter. The simplest explanation can be a depth difference. Directly above the AHS, the temperature changes quickly over depth, which can easily be seen from Figures 14-17. Measurements only 0.5 meter shallower turn out to be considerably colder, depending on the air temperature during the day preceding the measurements. If the 700mm main lies just a bit deeper than the 500mm main, the distance between the sensor and the AHS increases, easily explaining a smaller temperature rise of 0.4°C. The data provided by the municipality of Rotterdam, used for the depth of these mains, points in another direction. However, as mentioned before, nobody is entirely certain of the precise depths of the subsurface infrastructures.

Other explanations for the temperature differences can be derived from Equation 1. This equation calculates the heat flux q (in W/m^2), through a material with thermal conductivity k (in W/m·K) and thickness L (in m), forced by the temperature difference $T_2 - T_1$ (in K or °C). Remarkable is the fact that the insulation layer the 500mm main is thicker than around the 700mm main. The 500mm main the 700mm main and the 150mm main have insulation layers of 94mm, 86mm and 52mm thick, respectively (Logstor, 2019). Thus in these measurements, the temperature is not explained by the differences between the insulation layers. However, a damaged layer could cause considerable problems.

Still, this part of the equation could be a cause for the maximum temperature difference. If the temperature difference between the AHS and the surrounding soil is included. This believe holds for two reasons. First of all, the receiving temperature (T_2) at the measuring location was about 5°C lower at the Prinsenlaan. And secondly, heat loss of water within district heating distribution networks is a well-known phenomenon, especially at high temperatures. Studies have shown heat losses between 10% and 16% (Çomaklı, Yüksel, & Çomaklı, 2004; NVE, 2011).

$$q = -k \cdot \frac{T_2 - T_1}{L}$$

Equation 1: Heat flux q [W/m2], thermal conductivity k [W/m·K], length L [m], and temperature difference T2 – T1 [K or °C].

More energy measured in the soil indicates a higher heat flux from the AHS to the soil. However, more energy to the soil does not necessarily mean a higher maximum temperature. The energy can reach further (and deeper), as is the case at the Hogenbanweg. The total energy released at the measurement sites is unknown, as temperatures are only known up to depths of 1 meter.

Using calculations to explain the different measured temperatures is complicated. The primary mains are both operated at approximately 120°C. If the *k, L,* and T_2 values are inserted in the equation, a higher heat flux is calculated at the Hogenbanweg (Appendix 17). However, a higher heat flux also indicates a faster temperature decrease of the AHS. For the actual decrease of inside temperature, more data is needed on flow velocities, and pressures within the heating system. The table of Appendix 17 presents calculation results and parameters used for the energy fluxes in W/m^2 and W/m, from the mains for inside temperatures from 120°C - 80ºC. These calculations are based on a constant soil temperature around the mains, on constant insulation layers as described above, and the surface size of the mains.

A plausible temperature reduction inside the mains will not be enough to explain the magnitude of the relation between the maximum temperatures. According to the results in Appendix 17, the temperature at the Hogenbanweg would then have be reduced by 36ºC (4.9°C : 5.3°C = 52.66W/m : 56.91W/m). As explained in this chapter, the temperature profile shapes are very important. If these shapes were similar for the two sites, this temperature reduction would have to hold, but that is not the case. In the end, the cause of the lower maximum temperature at the Hogenbanweg is likely a combination of some of the above explanations.

Mitigating, preventing or coping with warm water temperatures

The practical part of this study has given an insight in the warming effects of AHS. After the analysis of TST and the evaluation of old measurements, four different AHS remained suspected of heating up drinking water in the DWDS. Of those four, three were included in measurements. HVPC showed some heating of soil temperatures around them, but the main threat for drinking water are the mains of the city heating system. Temperature increases of more than 5°C and 3°C were measured above primary and secondary district heating mains respectively. It is expected that especially during hot summers, in combination with unfavorable environmental factors, soil temperatures can easily raise above 25°C near AHS. Drinking water mains within several meters of these AHS are at serious risk of becoming hotspots. Especially, if the two run parallel for long stretches, or if residence times within those parts of the DWDS are long.

Future perspective

Despite the fact that AHS are not the only threat for warming of drinking water, these measurements certainly show the seriousness of AHS as part of the problem. Climate has already been proven to be the other part of the problem. Agudelo-Vera et al. (2015) used the KWR STM to confirm that climate alone will not likely cause temperatures to rise above 25°C at the customers tap, at least until 2050 (Figure 19). This prediction is based on the worst case KNMI climate scenario (W+) combined with the peri- urban neighborhoods STM. This climate scenario implies an increase of average temperatures of more than 2°C, longer droughts, and more extreme rain events (KNMI, 2007). If other STM that include AHS are used, the number of exceedances grows up to 83 days a year for 2050. The used models are validated for the area of Rotterdam, making them exceptionally useful for this study. By utilizing the worst case climate scenario of KNMI in this comparison, the number of hotspot days in the future may be a bit overestimated. Still, hotspots are already present, and even the most optimistic climate scenarios show an increase in temperatures in the future. The numbers in Figure 19 show that the risk of water temperatures exceeding 25°C can be controlled, by controlling the effect of the AHS.

	Number of days per year with drinking water temperature >25˚		
	2012	2030 (W+)	2050 (W+)
Peri- urban neighbourhoods	0	0	0
Average city	0	0	7
Hot- spots	9	55	83

Figure 19: Number of days per year with drinking water temperatures >25°C (yellow) and with at least 7 of those days consecutive (orange), (Agudelo-Vera et al., 2015)

Summer clearly is the most risky season for drinking water temperature, because of the combined climate and anthropogenic threats. Despite correcting the data for seasonal fluctuations, the TST analysis earlier in this study is susceptible for climatic extremes. Therefore, Figure 12 and Appendix 6 give a distorted image of the whereabouts of AHS in summer. Even though the measured results of this study specifically map the temperatures around AHS in autumn, there are reasons to believe that the problematic AHS in other seasons are similar. Electricity demands can be bigger than in autumn during hot summers, potentially making them more important AHS; and district heating systems using residual heat operate at constant temperatures throughout the year. Making them more risky AHS in summer.

Most modifications to the DWDS take time. To make sure that drinking water companies are not overwhelmed by too high drinking water temperatures in the future, it is important to start thinking about ways to mitigate and prevent this from happening. Perhaps drinking water companies could already start interfering locally. When it comes to public health, it is better to be safe than sorry.

In 2018 Agudelo-Vera evaluated multiple measures to reduce the number of hotspots in the DWDS. In November 2019, an extension of this study was published (Van Vossen, Stofberg, & Agudelo-Vera, 2019). Literature orders ways of acting in: general measures, applicable to the whole net; and more targeted measures, which could provide solutions locally during heat waves. In this study a further distinction is made for the targeted measures:

1. Those that limit the energy flux to the soil. Both climatic and anthropogenic heat fluxes can be minimized.
2. Those that limit the heat dissipation through the soil. By influencing the soil thermal properties.
3. Those that limit the heat flux from the soil to the drinking water.

In this section, the most promising general measures will first be discussed. Followed by targeted local measures, ordered per category.

Effective general measures

Based on recent knowledge, several techniques are considered to be the most effective general measures when it comes to mitigating the problem of warm drinking water in urban areas. Two of which actually tackle the physical warming of water, by moving the DWDS to cooler areas. By deepening the distribution system, or avoiding heat sources, the DWDS can be laid in soils reaching less extreme temperatures. Another is to improve communication towards the customer. By informing the customer, the warming is not reduced, but attention is given to the risky consequences of warm water.

Solutions may require collaboration with other companies or governmental agencies. Occasionally, these third parties have conflicting interests. In a time that is all about climate change and energy transitions, water companies often fall to the background in comparison to some other subsurface network operators. To turn this around, the importance of good water quality, and the effect of temperature on that quality, must be brought to the attention of society. The initiation of any large-scale change starts with good lobbying.

Deepening the drinking water distribution network

The idea behind deepening the DWDS is correlated to the principle explained in the "Weather and climate" paragraph in the theoretical framework. Shallow soil layers are more sensitive for short-term temperature fluctuations. The delaying effect of soil on temperature filters out both extreme hot and cold air temperatures. In conventional designs, mains have a varying soil coverage of 0.8 to 1.2 meter. Unfortunately connection mains, in which water can stay stagnant for many hours, usually lie the shallowest.

Van Vossen et al. (2019) determined that deepening the DWDS to 1.5 m bgl, will lead to a maximum temperature decrease of 2.5°C in summer. Exact temperature reduction depends on environmental factors like soil type, sun hours, soil coverage, the presence of AHS, etc. Crossing the groundwater table will moderate the temperature extremes even more. A saturated soil has a higher specific heat capacity, resulting in slower and therefore more limited soil heating due to climatic factors.

Deepening the DWDS will not always be an effective measure to mitigate warming of the drinking water. When related to AHS it may even be counterproductive. Both HVPC and residential heating systems generally lay deeper in the soil than drinking water mains. By deepening the DWDS, you move closer to the AHS. Measurements in summer have to show the net results for deepening near AHS. However, it is expected that deepening the mains may not be as effective as determined by Van Vossen et al. (2019) near AHS. A 3 dimensional STM, including AHS whereabouts, could be a useful tool to accurately display the effects on soil temperature.

Another disadvantage of deepening the DWDS lies in the costs. Compared to current standards, placing the network at a depth of 1.5 m would cost about 70% more (Blokker, Horst, Moerman, Mol, & Wennekes, 2014). Aside from higher installment costs, operational costs would also increase. Blokker et al. (2014) estimated an increase in operational costs of 36%. These costs include the extra risks of damages during excavations.

Altogether, deepening the mains will be effective when it comes to decreasing the average drinking water temperature in summer. However, it involves high costs and the effectiveness close to AHS is questionable. Despite the fact that deepening the DWDS is one of the most discussed measures in scientific literature, one should remain critical of the local efficiency around AHS.

Keeping heat sources at a distance

Another promising general measure, which partly lies within the scope of drinking water companies, is to keep heat sources at a distance. This means not only keeping space between the DWDS and AHS, but also avoiding the sun and hot soil surfaces. Costs of this measure are minimal (Van Vossen et al., 2019). These only contain potentially longer mains. However, good urban planning is required, especially with the increasing number of networks in the subsoil. The municipality of Rotterdam tries to adhere standards that have been laid down in the vision document on subsurface infrastructure (Kovacs, 2016). In an attachment to that document, layouts of the subsurface in different types of streets is schematically represented. Figure 20 shows an example of the subsurface layout below a residential street. In this standard, city heating and drinking water mains are just 2.25 meters apart. A distance deemed not enough, based on the findings of this study.

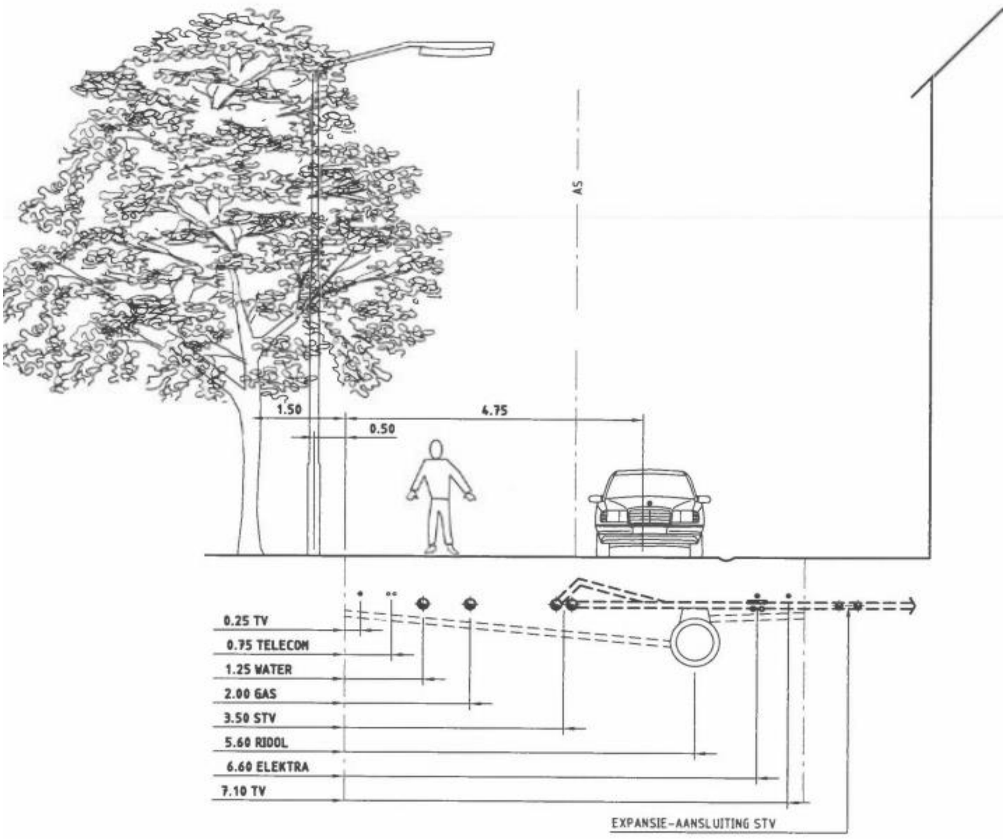


Figure 20: Subsurface layout of underground infrastructure in a residential street in Rotterdam (Kovacs, 2016)

In Rotterdam, and any city on the northern hemisphere for that matter, most shade will be encountered just north of buildings. Shade could decrease soil temperatures at 1 m bgl by 2.5°C in summer, making it the best location for the DWDS (Agudelo-Vera, & Fujita, 2017). On the contrary, the most threatening AHS, can best be placed in the sun on the south side of buildings. If district heating systems are placed in warm soils, less heat will be lost to that soil, making the systems more efficient. So, both network operators benefit from routes on opposite sides of the street, keeping a fair distance between them. To realize this situation, a single sided net would be ideal (Agudelo-Vera et al., 2018). Unfortunately, some sites are more complex and may be unfit for a single sided net. In addition to the ideal situation, it may be better to place mains below green areas. Agudelo-Vera and Fujita (2017) also found that grass as soil coverage could reduce soil temperatures by 2°C, compared to a paved surface.

The perfect subsurface urban planning differs per street. Even with the best intentions from all stakeholders, creating an ideal subsurface layout can prove to be difficult. Results of this study showed that temperature elevations of 1°C were measurable at distances of 2.3 m and 3.8 m – 5.25 m from secondary and primary city heating mains, respectively. In summer, and at unfavorable conditions, these distances are even expected to be larger. Combined with the absence of shade and green, subsurface urban planning can become a site specific logistic challenge.

Documenting standards in directives is advised to reach a stronger position in the subsurface urban planning debate. Good examples of these standards are NEN's. Two examples of NEN's relevant for thermal influences are NEN7171 (Underground utility networks planning) and NEN3654 (Mutual influence of pipelines and high-voltage circuits) (NEN, 2008; NEN, 2014). If a NEN is created specifically for the mutual influences between mains transporting residual industrial heat and drinking water mains, a series of requirements must be met before new city heating mains can be installed.

In conclusion, keeping a distance between the DWDS and heat sources of all kind, is potentially a very promising measure to keep drinking water temperatures low. The costs are low, and several involved stakeholders benefit from the same subsurface layout. To strengthen this measure, design criteria can be documented into standards and norms. A downside lies in the logistic difficulties that come with this measure. Creating enough distance between heat sources and the DWDS may sometimes not even be achievable. Still, every step towards the perfect layout, results in a benefit to drinking water companies.

Informing and advising the customer

This last intervention is hardly ever discussed in literature, because it has no effect on the actual drinking water temperatures in the DWDS. However, informing and advising the customer can provide useful. By involving the customer into the discussion, you could create societal awareness. This awareness can help trigger a change for the drinking water lobby in the future.

The effect of informing the customer must not be underestimated. An example of a campaign that Evides held in the summer of 2019, was on awareness of *Legionella Pneumophila.* The message was to flush the piping system after having been on holiday. The same flushing could help to prevent some risks involved in high drinking water temperatures. Connection mains can be very vulnerable to heating, as relation between residence time and heating time can be very unfavorable in these mains. By advising about flushing, risks for the customer can be reduced, and this may reassure them. Another aspect that customers can be informed about, is extra costs which potentially are necessary to protect the DWDS from climate change and urbanization. It can be explained that a price increase is essential to prevent water quality risks (Agudelo-Vera et al., 2018).

Downsides of this measure is that the effects are hard to quantify. The only way that results may be seen, is in a reduction of complaints on drinking water temperature. Furthermore, any campaign concerning risks in drinking water quality must always be set up thoughtfully. Informing the customer about risks could induce a shock reaction, if it is communicated incorrectly. A worst case scenario would be the possibility of reputational damage.

Hence, an informing campaign can help to create awareness and understanding with the customers, as it did for the flushing campaign this summer. Ideally it could raise a societal debate, strengthening the drinking water lobby in the future. However, effects are difficult to quantify and worst case scenario, informing the customer could work adversely.

Effective targeted measures

Aside from the general measures, there are several techniques that could locally serve as a way to prevent hotspots. Small-scale interventions are useful if whereabouts of hotspots are known. At this point the classification of measures in three categories provides a nice framework. This paragraph will be written in the following order. First, ways to limit the transfer of heat to the soil are discussed. Second, measures to reduce the heat dissipating properties of the soil are addressed. And last, ways to limit the heat flux from the soil to the water are described. In this last category the measures fall entirely in the domain of the drinking water companies.

Limiting the heat transfer to the soil

As mentioned before, heat fluxes to the soil can either be weather related, caused by anthropogenic influences or via a combination of the two. The first energy forms that come to mind when thinking of weather influencing soil temperature are radiant heat and latent heat. Thus solar radiation and evaporation potentials. DWDS could be steered towards more favorable conditions like shade and green areas, as already explained in the previous section. However, there are other ways to avoid negative weather influences, without the need of major interventions.

Instead of steering the mains towards shade and evaporation, this process could also be turned around. Areas could be locally shaded. As an emergency measure, structures could be placed at the surface above drinking water mains. Structures like big plant pots, or awnings over the streets (Van Vossen et al., 2019). Effectively shading can cool soil temperatures with 2.5°C. It being a temporary measure, makes it well applicable during heat waves. Actually implementing shading during heat waves should be done in collaboration with municipalities.

Bringing more evaporation towards warm pavements is also possible. Aside from creating more open water, which is a challenge in urban areas, water could be sprinkled on the surface over drinking water mains. This Japanese tradition is called 'uchimizu' and dates from the 17th century. Their intention was to cool air temperatures, by distributing one or two millimeters of water over the pavement (Solcerova, van Emmerik, Hilgersom, van de Ven, & van de Giesen, 2018). However, it also effectively cools the surface temperature, with its consequences for deeper soil layers. A decrease of 8°C was measured in Delft just above the paved surface, after spraying 2 mm of water. Making uchimizu a cheap and good measure, that can locally be applied during heatwaves. Problem is that spreading water over the pavement during hot summers may send the wrong image. In these times there is a lot of focus on saving water. By applying uchimizu, about 1 $l/m^2/hr$ should be used during the hot hours of the day to achieve cooling effects.

When the energy flux from AHS to the soil needs to be limited, the parameters of Equation 1 should be influenced. I.e. either the insulation layer around the AHS needs to be improved, or the temperature gradient between the AHS and the soil must be limited. Currently, PUR is the most used insulation material. It has a thermal conductivity of 0.033 W/m·K (Kręcielewska, & Menard, 2015). A thicker layer around an AHS could certainly reduce soil warming. In the case of city heating mains a thicker insulation layer would even serve a double purpose. Not only does the soil stay cooler, the water in the city heating mains stays hotter, and thus less energy is lost. Doubling the thickness of the insulation layer results in half the energy flux from the AHS. Currently, the thickness of the layer is mainly determined based on a comparison between the costs of the insulation layer and the costs of the energy losses. If drinking water companies enter the debate, thicker insulation layers may be considered in the future by more city heating network operators.

Decreasing the water temperatures in city heating mains would also serve as an option to limit warming of the soil. However, this would ask for the use of entirely different techniques. From a drinking water point of view, other types of district heating are preferred, like ATES.

Limiting the heat transfer through the soil

When inspecting heat transferring processes in soils, the thermal conductivity and the specific heat capacity are the two most important properties. Both vary for different soil types (Farouki, 1981). Conduction is the dominant process in heat dissipation through soils, thus a high thermal conductivity leads to further reaching temperature elevations. In contrast, a high specific heat capacity implies that more energy is needed to warm up soil. When there is a constant supply of energy, this does not necessarily mean that the soil does not heat up as much. As long as there is a temperature gradient, the steady state temperature will be the same. However, the a higher specific heat capacity slows down the process. Therefore, a soil with a high specific heat capacity will not warm as much as a soil with a low specific heat capacity, during short periods of high surrounding temperatures.

There are two ways to use these soil properties as a method to mitigate high soil temperatures. Either the texture of the soil can be changed, thus using clay instead of a sandy soils around drinking water mains; or the moisture content of the soil can be changed. On average clay has a higher specific heat capacity than sand. However, there are different types of clay. Thus one value for specific heat capacity is not representative for all clay types. The same holds for different types of sand. Very roughly the values lie around 1500 J/(kg × K) for clay, and around 1000 J/(kg × K) for sand, but there is even some overlap between the range of values of these soiltypes (Engineering ToolBox, 2003; Kodešová et al., 2013; Abu-Hamdeh, 2003; Hamdhan, & Clarke, 2010).

Moisture increases the specific heat capacity of soils, but it also increases the thermal conductivity. Initially, moistening the soil was seen as a good measure to mitigate warming of the soil. This idea has not yet been abandoned, but in the latest KWR report, a more systematic analysis is deemed necessary (Van Vossen et al., 2019). A combination of a high heat capacity and a low conductivity would be ideal soil material. Perhaps a combination of different soil layers could serve as a good multifunctional urban soil.

The soil thermal properties are obviously not the only important factors in urban planning. Sand is a sturdy material to build on. Chances of subsiding are slim, which make it a good foundation for roads and buildings. Furthermore, sand is also a good material to drain the streets after heavy rain showers (Greinert, 2015). The conflicting purposes of soil complicate the usage of different soil types as a measure to mitigate heat transferring processes in the subsoil.

Limiting the heat transfer to the drinking water

In this section, the importance of the relation between the heating time and the residence time shows. Either an increase in heating time or a decrease in residence time must be achieved. If pipe diameters are changed, the relation between those two parameters stays the same (Blokker, & Pieterse-Quirijns, 2010). So other ways to influence these variables must be used.

Blokker et al. (2014) performed a scenario study in which they increased the water consumption at the tap, locally decreasing the residence time inside of the DWDS. They concluded that by increasing the water demand, no temperature reduction at the tap was found. Still, at hotspots it is expected that the temperature might drop temporarily, which affects the biological water quality either way. Increasing water demands is no realistic option, nor is it desired by drinking water companies in summer.

Another way to reduce the residence time in the network is to set valves in such a way, that the DWDS becomes more branched. This also leads to a self-cleaning network Blokker et al. (2014). The counterargument is that a branched system comes at the expense of the supply security. Correct network configuration must be found to make a hybrid DWDS, combining a branched and a looped parts of the system. In this way, both residence times can be reduced and the supply security can remain high.

Also a measure in the scope of drinking water companies is applying an insulation layer. The temperature gradient between the soil and the drinking water is a lot less than between city heating mains and the soil. This also makes the need for isolation a lot less. Still, the heat flux will effectively be reduced. Tap temperatures are not likely going to decrease a lot with isolation, but locally this measure could prove to be useful (Blokker et al., 2014). It shows more potential than reducing the residence time, because with insulation the biofilm temperature can be kept low. If locally a few meters of biofilm would be warmer, bacteria growing in those meters could suddenly come in motion, because of a shock (water hammer pulses, velocity changes, etc.). Insulation also prevents the pipe wall to warm up, resulting in a less active biofilm.

Aqua thermal energy from drinking water

Not all heating of water has negative effects. Warm water holds more energy. Energy that does not need to be added when using warm water in the house for instance. This energy could be used for district heating systems. Extracting heat from water could reduce the carbon footprint of water companies substantially (Ramachandra, 2017). When used for district heating, research has shown that ATES using drinking water, could contribute for 1.5% of the heating needs of urban areas. Not much in comparison to surface water and wastewater, 40% and 15% respectively (KWR, 2019). Still, the process of extracting energy will also cool the drinking water itself. This combination of effects makes it an interesting technique for drinking water companies.

In the Netherlands, ATES store heat and cold in aquifers. In summer the cold water is used and therefore heats up, and in winter this process is reversed. After a few years of operation, the subsurface cold well reaches temperatures between 6°C and 9°C, and the warm well reaches temperatures between 14°C and 17°C (Mol, Kornman, Kerpershoek, & Van Der Helm, 2011). Dutch drinking water company Waternet (2010) estimated that their CO_2 emissions could potentially be reduced by 100 – 1,000 kton/yr, only by recovering heat from drinking and industrial water distribution systems. However, at the start a reduction of only 45 kton/yr is expected, because the wells need to reach their ideal temperatures (Waternet, 2010).

Based on the information from the literature, using ATES in combination with DWDS could indeed help drinking water companies to reduce their carbon footprint and cool their water. However, the water only temporarily stays cool. Van Vossen et al., (2019) analyzed a case study in which they analyzed different scenarios. They concluded that ATES could potentially make water temperatures at the tap 2°C cooler, but it strongly depends on the location and the demand pattern downstream. If continuous flow can be assured in the DWDS, installing an ATES just prior to a hotspot, could prevent very high temperatures at that location.

What stops the mass installation of ATES are the costs. Blokker et al. (2014) concluded that installing a system would cost about €350,000.-, and on top of that come €12.000 of annual operating costs. These costs are so high that Van Vossen et al. (2019), conclude that ATES are no structural solution for residential areas.

Conclusions

It turns out that AHS can have a significant effect on drinking water temperatures. Just as direct sunlight and soil coverage, AHS can result in increased soil temperatures of several degrees. Because soil temperature and drinking water temperature are closely related, the combination of these three factors could form a threat for the drinking water of Rotterdam. So far, the legal limit of 25°C at the tap, is rarely exceeded. However, ongoing climate change and urbanization could change this, potentially resulting in lower drinking water quality. This study supplements the current knowledge on causes of drinking water warming, by providing an insight into the temperature effects of AHS. Furthermore, measures to prevent drinking water from warming are discussed in relation to the measurement results of the practical part of this study.

Both TST and raw results of a soil temperature study provided to be useful in the identification process of potential AHS. Numerous areas in Rotterdam turned out to have statistically warm drinking water. Though, a lot of warm areas differ per season, there are also some striking similarities. Both the city center and the north of Prins Alexander show up as warm areas on the map for the entire the year. By correlating the relatively warm areas of Rotterdam in autumn, to the whereabouts of proposed potential AHS, the most important AHS are identified.

The analysis provides suspicions for four types of potential AHS. City heating mains, HVPC, metro lines, and ATES. Of these, the city heating mains are expected to cause most heating. Whereabouts of these mains correlate extraordinary well to the map of warm areas. The relation between warm drinking water and HVPC and metro lines is less evident, but supported by earlier soil temperature measurements. ATES are not included in the practical part of the study, because of the lack of detailed knowledge on the installments.

Measurement locations are selected for constant environmental factors, and for have an AHS relatively isolated. In total, four locations in Rotterdam are used to measure the effect AHS have on soil temperature. By placing temperature sensors, mostly at 1 m bgl, over a transect perpendicular to the orientation of the AHS, the effect on DWDS can be analyzed best.

The measurements show varying results. As expected, the greatest threat for warming of the drinking water, lies in the city heating system of Rotterdam. Temperature elevations of 5.3°C and 4.9°C are encountered directly above primary mains, and of 3°C above secondary mains. Elevations of 1°C can reach as far as 5.25m from the warmest point above the primary mains, and 2.3m from the secondary mains. Around HVPC a maximum temperature elevation of 0.6°C was encountered. Which is more limited, but should not be underestimated in combination with future climate change and urbanization. Soil temperatures above metro lines, but also around LVPC and sewer mains (which were taken out of ease and need, respectively), show no measurable elevated temperature whatsoever.

The measured results are an indication of what to expect around AHS. These do not only hold for Rotterdam, but also for other urban areas containing these AHS. Still, exact temperature profiles are largely determined by many other aspects. Depth, size, and condition of the AHS are of importance, but environmental factors also have big effects on temperature profiles. One of the most influential parameter turned out to be the temperature difference between the air and the soil. Suggesting that in summer, effects will be worse.

Several strategies to mitigate the warming of drinking water in the distribution system are applicable. In a general sense, it is most sensible to create a distance between any heat source and the distribution system. By placing drinking water mains in the shade, below grass and away from anthropogenic heat sources, warming of the drinking water can be prevented in a relatively inexpensive manner. Logistically, this is much more difficult, and it is advised to document guidelines in norms and standards.

Measures can also be targeted local and temporal hotspots. Small parts of the DWDS, which are only risky during heatwaves, can be addressed a lot quicker. Often through less drastic measures. These measures can focus on restraining the heat flux from the heat source to the soil, the heat flux through the soil, and the heat flux from the soil to the drinking water.

A last way to cope with higher drinking water temperatures, is to extract energy from drinking water by installing ATES. The combination of shortly cooling the water and decreasing their carbon footprint, make it an interesting technique for drinking water companies. ATES could help provide for part of the heat requirements of urban areas, but the high installation and operation costs of the systems make them no structural solutions for high temperatures in residential areas.

Recommendations for further research

Further research should expand the knowledge in a few directions. First of all, as a supplement to this study, the amount of measurements needs to be expanded. Measurements were limited to a time period of just over one month. Enough to form a sound image of the effects of AHS in autumn. However, more measurement locations spread out over all seasons are necessary to complete the information on how AHS affect soil and drinking water temperatures all year round. Especially for the summer months more measurements are required. The combination of a warm soil and surface temperature, may result into differently shaped heat profiles around AHS. Let alone the expected higher absolute temperatures. City heating mains operate at the same temperatures in summer. So, the temperature gradient between AHS and the surrounding soil remains high.

Another section that needs more attention is the heating within drinking water mains. KWR and Evides have already started planning a study to measure this process along a kilometer long distribution main. One of the goals of KWR is to add another dimension to the soil temperature model, but the results will also help in the risk assessment of hotspots.

A last, and ever ongoing branch of research, focusses more on water quality. Effects of temperature on physical, chemical, and biological processes are roughly know. Still, especially concerning biological processes, more knowledge can be gained. As mentioned, the legal limit for drinking water temperatures at the tap is 25 °C. However, this is established somewhat arbitrary. Is it possible to adjust this temperature limit upwards?

References

Abu-Hamdeh, N. H. (2003). Thermal properties of soils as affected by density and water content. *Biosystems engineering*, *86*(1), 97-102.

Agudelo-Vera, C., Castro-Gama, M., Blokker, E.J.M., van der Zwan, S., & Nugroho, D. (2019). Results temperature measurements in Krimpen aan den Ijssel 2018 and validation 2D-Soil temperature model. Concept Memo, KWR. 23 July 2019.

Agudelo-Vera, C.M. (2018). *Aanpak om de hotspots in het leidingnet terug te dringen*. Nieuwegein. KWR. BTO 2018.024.

Agudelo-Vera, C.M., Blokker, E.J.M., Kater, H.D., & Lafort, R. (2017). Identifying (subsurface) anthropogenic heat sources that influence temperature in the drinking water distribution system. *Drinking Water Engineering and Science, 10*(2), 83-91.

Agudelo-Vera, C.M., Blokker, E.J.M., van der Wielen, P.W.J.J., & Raterman, B.W. (2015). *Drinking water temperature in future urban areas*. KWR. BTO 2015.012.

Agudelo-Vera, C.M., & Fujita, Y. (2017). *Hotspots in het leidingnet.* Nieuwegein. KWR. BTO 2017.023.

Albers, R. A. W., Bosch, P. R., Blocken, B., Van Den Dobbelsteen, A. A. J. F., Van Hove, L. W. A., Spit, T. J. M., van de Ven, F., van Hoof, T., & Rovers, V. (2015). Overview of challenges and achievements in the climate adaptation of cities and in the Climate Proof Cities program. *Elsevier, 83,* 1-10.

Arya, P. S. (2001). *Introduction to micrometeorology* (Vol. 79). Elsevier.

Beuken, R. H. S., Lavooij, C. S. W., Bosch, A., & Schaap, P. G. (2008). Low leakage in the Netherlands confirmed. *Water Distribution Systems Analysis Symposium 2006* (pp. 1-8).

Blokker, E.J.M., & Albert, M.F.M.A. (2017). *Overzicht toepassing van sensoren en ICT in de watermeter*. KWR. 2017.101.

Blokker, E.J.M., Horst, P., Moerman, A., Mol, S., & Wennekes, R. (2014). *Haalbaarheid van maatregelen tegen ongewenste opwarming van drinkwater in het leidingnet.* Nieuwegein. KWR. 2014.057.

Blokker, E.J.M., & Pieterse-Quirijns, I. (2010). Model voor de berekening van de watertemperatuur in het leidingnet. *H_2O*, *43*(23), 46.

Blokker, E.J.M., & Pieterse-Quirijns, I. (2013). Modeling temperature in the drinking water distribution system. *Journal-American Water Works Association, 105*(1), E19-E28.

Blokker, E. J. M., Vreeburg, J. H. G., Beverloo, H., Klein Arfman, M., & Van Dijk, J. C. (2010). A bottom-up approach of stochastic demand allocation in water quality modelling. *Drinking Water Engineering and Science*, *3*(1), 43-51.

Centraal Bureau voor de Statistiek (2019). Regionale kerncijfers Nederland. Retrieved on 26-11-2019, from: https://opendata.cbs.nl/statline/#/CBS/nl/dataset/70072NED/table?fromstatweb

Çomaklı, K., Yüksel, B., & Çomaklı, Ö. (2004). Evaluation of energy and exergy losses in district heating network. *Applied thermal engineering*, *24*(7), 1009-1017.

De Cian, E., Lanzi, E., & Roson, R. (2013). Seasonal temperature variations and energy demand. *Climatic Change*, *116*(3-4), 805-825.

De Cian, E., Lanzi, E., & Roson, R. (2007). The impact of temperature change on energy demand: a dynamic panel analysis.

Dijkstra, S. (2013) Concept Warmteafdracht. Rotterdam: Eneco.

Electrical units (n.d.) What is soil thermal resistivity? Retrieved on 10-12-2019, from: http://www.electricalunits.com/soil-thermal-resistivity/

Encyclopaedia Britannica (2005) Student's t-test. Retrieved on 30-12-2019, from: https://www.britannica.com/science/Students-t-test

Engineering ToolBox (2003). Thermal Conductivity of common Materials and Gases. Retrieved on 8-7-2019, from: https://www.engineeringtoolbox.com/thermal-conductivity-d_429.html.

Engineering ToolBox (2003). Specific heat of common substances. Retrieved on 13-12-2019, from: https://www.engineeringtoolbox.com/specific-heat-capacity-d_391.html.

Evides Waterbedrijf (2019). Evides Waterbedrijf: Jaarverslag 2018. Retrieved on 2-7-2019, from: https://www.evides.nl/over-evides/de-organisatie/jaarverslagen.

Farouki, O. T. (1981). *Thermal properties of soils* (No. CRREL-MONO-81-1). COLD REGIONS RESEARCH AND ENGINEERING LAB HANOVER NH.

Greinert, A. (2015). The heterogeneity of urban soils in the light of their properties. *Journal of Soils and Sediments*, *15*(8), 1725-1737.

Hamdhan, I. N., & Clarke, B. G. (2010). Determination of thermal conductivity of coarse and fine sand soils. In *Proceedings of World Geothermal Congress* (pp. 1-7).

Henning, A., & Limberg, A. (2012). Veränderung des oberflächennahen Temperaturfeldes von Berlin durch Klimawandel und Urbanisierung. *Brandenburgische Geowiss. Beitr*, *19*(1), 81-92.

Intergovernmental Panel on Climate Change (2014). *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp

Jacobs, A. F., Heusinkveld, B. G., & Holtslag, A. A. (2011). Long-term record and analysis of soil temperatures and soil heat fluxes in a grassland area, The Netherlands. *Agricultural and Forest Meteorology, 151*(7), 774-780.

Klok, L., Zwart, S., Verhagen, H., & Mauri, E. (2012). The surface heat island of Rotterdam and its relationship with urban surface characteristics. *Resources, Conservation and Recycling, 64*, 23-29.

KNMI (2007) KNMI Klimaatscenario's. KNMI'06: Samenvatting. Retrieved on 09-01-2020, from: klimaatscenarios.nl/knmi06/samenvatting/

Kodešová, R., Vlasakova, M., Fer, M., Tepla, D., Jakšík, O., Neuberger, P., & Adamovský, R. (2013). Thermal properties of representative soils of the Czech Republic. *Soil and Water Research*, *8*(4), 141-150.

Kovac, W. (2016). Visiedocument Ondergrondse Infrastructuur. Retrieved on 12-12-2019, from: https://www.rotterdam.nl/wonen-leven/leidingenbureau/Visisedocument-ondergrondse-infrastructuur.pdf

Kręcielewska, E., & Menard, D. (2015). Thermal Conductivity Coefficient of PUR Insulation Material from Pre-Insulated Pipes After Real Operation in District Heating Networks and After Artificial Ageing Process in Heat Chamber. *Ciepłownictwo, Ogrzewnictwo, Wentylacja*, *46*(2), 46-52.

KWR (2019). Heating homes with energy from water has promising future. Retrieved on 13-12-2019, from: https://www.kwrwater.nl/en/actueel/heating-homes-with-energy-from-water-has-promising-future/

Lehtola, M. J., Juhna, T., Miettinen, I. T., Vartiainen, T., & Martikainen, P. J. (2004). Formation of biofilms in drinking water distribution networks, a case study in two cities in Finland and Latvia. *Journal of Industrial Microbiology and Biotechnology, 31*(11), 489-494.

Li, X., & Zhao, H. (2006). Development of a Model for Predicting Trihalomethanes Propagation in Water Distribution Systems. *Chemosphere, 62*(6) 1028.

Logstor (2019) *Product Catalogue. District Energy.*

Meerkerk, M.A., & Beuken, R.H.S. (2017). *Richtlijn drinkwaterleidingen buiten gebouwen.* Nieuwegein. KWR. PCD 3:2017.

Menberg, K., Blum, P., Schaffitel, A., & Bayer P. (2013). Long-term evolution of anthropogenic heat fluxes into a subsurface urban heat island. *Environmental Science en Technology, 47*(17), 9747-9755.

Ministerie van VROM (2011). Drinkwaterwet. Wet productie en distributie van drinkwater en de organisatie van de openbare drinkwatervoorziening. Den Haag.

Moerman, A., Blokker, M., Vreeburg, J., & Van der Hoek, J. P. (2014). Drinking water temperature modelling in domestic systems. *Procedia Engineering, 89*, 143-150.

Mol, S. S. M., Kornman, J. M., Kerpershoek, A. J., & Van Der Helm, A. W. C. (2011). Opportunities for public water utilities in the market of energy from water. *Water science and technology*, *63*(12), 2909-2915.

NASA (2019). The Effects of Climate Change. Retrieved on 2-7-2019, from: https://climate.nasa.gov/effects/

NEderlandse Norm (2014). Wederzijdse beïnvloeding van buisleidingen en hoogspanningssystemen. Delft.

NEderlandse Norm (2008). Ordening van ondergrondse netten - Deel 1. Delft.

Norwegian Water Recources and Energy Directorate (2009) Energi Norge Folder. Retrieved on 10-12-2019, from: https://www.nve.no/global/energi/analyser.

OverMorgen (2017) Warmtenetten rond Rotterdam. ArcGIS online.

OverMorgen (2018) WKO vergunningen. ArcGIS online.

Peterson, H., Pratt, R., Neapetung, R., & Sortehaug, O. (2006). Integrated biological filtration and reverse osmosis treatment of cold poor quality groundwater on the North American prairies. *Recent Progress in Slow Sand and Alternative Biofiltration Processes*, 424.

Pochwała, S., & Kotas, P. (2018). Possibility of obtaining wastewater heat from a sewage treatment plant by the means of a heat pump–a case study. In *E3S Web of Conferences* (Vol. 44, p. 00144). EDP Sciences.

Pothof, I. W. M., & Blokker, E. J. M. (2012). Dynamic hydraulic models to study sedimentation in drinking water networks in detail. *Drinking Water Engineering and Science*, *5*(1), 87-92.

Ramachandra, R. (2017). Warmte en koude uit drinkwater. Eindhoven: Technische Universiteit Eindhoven.

RET (n.d.) Infra. Retrieved on 5-12-2019, from: https://corporate.ret.nl/over-ret/infra

Revesz, A., Chaer, I., Thompson, J., Mavroulidou, M., Gunn, M., & Maidment, G. (2016). Ground source heat pumps and their interactions with underground railway tunnels in an urban environment: A review. *Applied Thermal Engineering, 93*, 147-154.

Rosario-Ortiz, F., Rose, J., Speight, V., Von Gunten, U., & Schnoor, J. (2016). How do you like your tap water?. *Science*, *351*(6276), 912-914.

Sadiq, R., & Rodriguez, M.J. (2004). Disinfection By-products (DBPs) in Drinking Water and Predictive Models for Their Occurrence: A Review. *Science of the Total Environment, 321*(1) 21.

Safe Drinking Water Foundation (n.d.). Water Temperature. Retrieved on: 8-7-2019, from: https://www.safewater.org/fact-sheets-1/2018/8/15/water-temperature-fact-sheet.

Serageldin, A., Abdelrahman, A. K., Ali, A. H., & Mohamed S. R. O. (2015). Soil Temperature Profile for Some New Cities in Egypt : Experimental Results and Mathematical Model. *14th International Conference on Sustainable Energy Technologies – SET 2015*, Nottingham, UK: SET 2015, 1–9.

Slee, K.G.L., & Tjan, S.Y.P.Y. (2015). Handboek Leidingen: Rotterdam 2015. Rotterdam: Gemeente Rotterdam.

Smulders, E. (2006). Temperatuurfluctuaties in waterdistributienetten, Tilburgse Waterleiding Maatschappij.

Solcerova, A., van Emmerik, T., Hilgersom, K., van de Ven, F., & van de Giesen, N. (2018). Uchimizu: A Cool (ing) Tradition to Locally Decrease Air Temperature. *Water*, *10*(6), 741.

Sommer, W. (2015) Modelling and monitoring of Aquifer Thermal Energy Storage. [PhD thesis]. Wageningen University, Wageningen.

TenneT (2019) TenneT Asset Hoogspanning. ArcGIS online.

Tsilingiridis, G., & Papakostas, K. (2014). Investigating the relationship between air and ground temperature variations in shallow depths in northern Greece. *Energy*, *73*, 1007-1016.

Van Bel, N. (2017). *Literatuuronderzoek naar de invloed van temperatuur op groei van opportunistische pathogenen in drinkwater.* Nieuwegein. KWR. BTO 2017.024.

Van Daal, K.H.A., & Slaats, P.G.G. (2008). *Klimaatverandering en de gevolgen voor waterdistributie – een inventarisatie van onderzoeksbehoeften.* Nieuwegein. KWR. BTO 2008.007.

Van der Molen, M., Kooi, H., Smulders, E.F.P.A., & Heijman, S.G.J. (2008). *Warmteindringing in de bodem.* Nieuwegein. KWR. BTO 2008.053.

van der Molen, M., Pieterse-Quirijns, I., Donocik, A., & Smulders, E. (2009). Eigenschappen bodem en oppervlak beïnvloeden temperatuurstijging rond drinkwaterleidingen. *H 2 O*, *42*(7), 33.

Van der Wielen, P.W.J.J. (2017). *Waarde KG22 en Aeromonas als wettelijke parameters nagroei.* Nieuwegein. KWR. BTO 2017.028.

Van Haastrecht, R. (2005) Rotterdam heeft de primeur van boren onder de stad. Amsterdam: Trouw.

Van Summeren, J.R.G., Vries, D., Albert, M.F.M.A, & Verbree, J. (2017). *Analyse van 'slimme meter'-data voor het in kaart brengen van hotspots in het distributienet.* Nieuwegein. KWR. KWR 2017.059.

Van Vossen, J., Stofberg, S.F., & Agudelo-Vera, C. (2019). *Effectiviteit maatregelen tegen opwarming drinkwater in leidingen.* Nieuwegein. KWR. BTO 2019.080.

Versteegh, J.F.M., & Dik, H.J.J. (2007). *The quality of drinking water in the Netherlands in 2006.* RIVM Report: 703719022.

Volk, C., Dundore, E., Schiermann, J., & Lechevallier, M. (2000). Practical evaluation of iron corrosion control in a drinking water distribution system. *Water research, 34*(6), 1967-1974.

Wang, Y., Berardi, U., & Akbari, H. (2016). Comparing the effects of urban heat island mitigation strategies for Toronto, Canada. *Energy and Buildings*, 114, 2-19.

Waternet (2010). Waternet klimaatneutraal 2020 (Waternet Climate Neutral 2020). Waternet, Strategic Centre, Amsterdam, The Netherlands.

World Health Organization (2019). Drinking-water: key facts. Retrieved on 2-7-2019, from: https://www.who.int/en/news-room/fact-sheets/detail/drinking-water

World Health Organization (2011). Guidelines for drinking-water quality. *WHO chronicle*, *38*(4), 104-8.

Zlatanović, L., Moerman, A., van der Hoek, J. P., Vreeburg, J., & Blokker, M. (2017). Development and validation of a drinking water temperature model in domestic drinking water supply systems. *Urban Water Journal, 14*(10), 1031-1037.

Zwarts & Jansma Architects (2019) Metrostation, Rotterdam. Retrieved on 5-12-2019, from: https://www.zja.nl/nl/metro-station-Rotterdam

Appendices

Appendix 1: Python script used for the AHS identification phase

```
import numpy as np
import matplotlib.pyplot as plt
import pandas as pd
import math
from scipy import stats
from rijksdriehoek import rijksdriehoek
rd = rijksdriehoek.Rijksdriehoek()
import xlsxwriter

########## Data Reading & Ordening ##############

TT = pd.read_csv("Tapmetingen 2000-Nu met coordinaten gefilterd.csv",delimiter = ";")
Mod = pd.read_csv("Temp_Rott_Average.csv",delimiter = ";")

SimTemp = np.zeros(2804)
for i in range (2804):
    a=24*i
    b=a+24
    SimTemp[i]=Mod[a:b].mean()

Date=pd.date_range(start="1-Jan-2012", end="4-Sep-2019")

TT.Date = pd.to_datetime(TT.Date, dayfirst=True)

Month = []
Day = []
Year = []
X = []
Y = []
Sim = []

for i in range (len(TT)):
    Month.append(TT.Date[i].month)
    Day.append(TT.Date[i].day)
    Year.append(TT.Date[i].year)
    rd.from_wgs(TT.Lat[i], TT.Long[i])
    X.append(rd.rd_x)
    Y.append(rd.rd_y)
    Sim.append(SimTemp[TT.Date[i]==Date])


TT['month'] = Month
TT['year'] = Year
TT['day'] = Day
TT['X'] = X
TT['Y'] = Y
TT['Model'] = Sim
TT['verschil']=(TT.Temp-TT.Model)


######## Corrected model results and differences with tap #####
mov = np.convolve(TT.verschil,v=np.repeat(1.0, 5)/5,mode='valid')

mov10= []
mov10.append(TT.verschil[0])
mov10.append(TT.verschil[1])
mov10.append(TT.verschil[2])
mov10.append(TT.verschil[3])

for i in range(len(mov)):
    mov10.append(mov[i])

CorrMod = []
for i in range (len(TT.Model)):
    CorrMod.append(TT.Model[i]+mov10[i])

CorrDif = []
```

```
CorrDif = []
for i in range (len(CorrMod)):
    CorrDif.append(float(TT.Temp[i])-float(CorrMod[i]))
TT['CorrDif'] = CorrDif

q = TT.CorrDif.quantile(0.90)
p = TT.CorrDif.quantile(0.10)
ran = q-p

TT = TT[(TT.CorrDif<q+1.5*ran) & (TT.CorrDif>p-1.5*ran)]
######### Variables ###########

Summer = (TT.month>5) & (TT.month<9)
Winter = (TT.month>11) | (TT.month<3)
Autumn = (TT.month>8) & (TT.month<12)
Spring = (TT.month>2) & (TT.month<6)
Study = (TT.month==10)# | (TT.month==11)

Xmax = TT.X.max()
Xmin = TT.X.min()
Xlen = Xmax-Xmin
Ymax = TT.Y.max()
Ymin = TT.Y.min()
Ylen = Ymax-Ymin

Sum = TT[Summer]
Win = TT[Winter]
Aut = TT[Autumn]
Spr = TT[Spring]
Stud = TT[Study]

All = TT

######### Function ##############

def Tapdata(Rad, Thresh, Season, Pval=0.05):
    GridX = []
    GridY = []
    XCO = []
    YCO = []
    PVAL = []
    m = Season.CorrDif.mean()
    print('The population mean = ',m)
    a = np.empty((int(math.ceil(Ylen/Rad)),int(Xlen/Rad)))
    a[:] = np.nan
    for j in range (int(math.ceil(Ylen/Rad))):
        CenY = Ymin + Rad * j
        for k in range (int(Xlen/Rad)):
            CenX = Xmin + Rad * k
            c = np.sqrt((Season.Y-CenY)**2 + (Season.X-CenX)**2) < Rad
            if np.sum(c) > Thresh:
                a[j,k] = np.mean(Season.CorrDif[c])
                t , p = stats.ttest_1samp(Season.CorrDif[c],m)
                if (p < (Pval/2)) & (t > 0):
                    print('\nGrid [',k,',',int(math.ceil(Ylen/Rad))-1-j
                    GridX.append(k)
                    GridY.append(int(math.ceil(Ylen/Rad))-1-j)
                    XCO.append(np.round(Xmin + Rad * k))
                    YCO.append(np.round(Ymin + Rad * j))
                    PVAL.append(p)
    Temperature = np.flipud(a)
```

```python
    Temperature = np.flipud(a)
    plt.figure(figsize=(15,12))
    plt.imshow(Temperature, cmap = 'rainbow');
    plt.colorbar()
    plt.title('Tap sample temperature distribution, clustered in circles with a radius of '
    plt.ylabel('Y  ',fontsize = 20, rotation = 'horizontal')
    plt.yticks(fontsize = 15)
    plt.xlabel('X',fontsize = 20)
    plt.xticks(fontsize = 15)
    File = GridX,GridY,XCO,YCO,PVAL

    workbook = xlsxwriter.Workbook('Aut40b.xlsx')
    worksheet = workbook.add_worksheet()
    row = 1
    for col, data in enumerate(File):
        worksheet.write_column(row, col, data)
    workbook.close()

######### Data Analysis "Example" ##############

XGrids = 40
Rad = Xlen / XGrids

Tapdata(Rad,5,Aut)

######### Plotting ###########

plt.figure(figsize=(17,12))
plt.scatter(TT.X,TT.Y,c=TT.CorrDif,cmap='rainbow')
plt.colorbar()

```

Appendix 2: Vertical design guidelines prepared by the municipality of Rotterdam

Legschema leidingen

TE PASSEREN LEIDINGEN:

leiding- dekking t.o.v. bestaand peil	TE LEGGEN LEIDINGEN:	Telecom - PTT interlokaal - CU (oud)	gas leiding gietijzer (distributienet-oud)	CAI incl. huisaansluiting	Telecom huisaansluiting GV / CU	Telecom overige kabels GV / CU	drinkwater huisaansluiting	drinkwater leiding ≤ 250 mm	drinkwater leiding > 250 mm	gas huisaansluiting ≤ 0,1 MPa	gas huisaansluiting > 0,1 MPa	gas leiding ≤ 0,1 Mpa	gas overige leidingen	elektriciteit huisaansluiting + OV + signaal	elektriciteit laagspanning	elektriciteit hoogspanning ≤ 25 kV	elektriciteit hoogspanning > 25kV	elektriciteit gelijkspanning	stadsverwarming huisaansluiting	stadsverwarming distributieleiding	stadsverwarming transportleiding	riool huisaansluiting	riool (PVC) ≤ 400 mm	riool (beton) /singelverb./spuileid./coll.r.	(riool)persleiding, brandblusleiding	overige leidingen
	dekking in m:	0,60	0,65	0,60	0,50	0,60	0,80	0,70	1,00	0,50	0,80	0,80	1,00	0,60	0,60	0,80	1,00	1,00	0,90	0,70	1,00	≥0,95	≥1,10	≥1,10	1,00	1,00
0,60	CAI incl. huisaansluiting	O	O	■	 O	O	O	O	O	 O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
0,50	Telecom huisaansluiting GV / CU	O	O	O	■	O	O	O	O	 O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
0,60	Telecom overige kabels GV / CU	O	O	 O	 O	■	O	O	O	 O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
0,80	drinkwater huisaansluiting	 O	 O	 O	 O	 O	■	O	O	 O	O	O	O	 O	 O	O	O	O	O	 O	O	O	O	O	O	O
0,70	drinkwater leiding ≤ 250 mm	 O	 O	 O	 O	 O	 O	■	O	 O	O	O	O	 O	 O	O	O	O	O	 O	O	O	O	O	O	O
1,00	drinkwater leiding > 250 mm	 O	 O	 O	 O	 O	 O	 O	■	 O	 O	 O	O O	 O	 O	 O	O O	O O	 O	 O	O O	 O	O O	O O	O O	O O
0,50	gas huisaansluiting ≤ 0,1 MPa	O	O	O	O	O	O	O	O	■	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
0,80	gas huisaansluitingen > 0,1 MPa	 O	 O	 O	 O	 O	 O	 O	O	 O	■	O	O	 O	 O	O	O	O	O	 O	O	O	O	O	O	O
0,80	gas leiding ≤ 0,1 Mpa	 O	 O	 O	 O	 O	 O	 O	O	 O	 O	■	O	 O	 O	O	O	O	O	 O	O	O	O	O	O	O
1,00	gas, overige leidingen	 O	 O	 O	 O	 O	 O	 O	O O	 O	 O	 O	■	 O	 O	 O	O O	O O	 O	 O	O O	 O	O O	O O	O O	O O
0,60	elektriciteit huisaansluiting + OV + signaalkabel	O	O	 O	 O	 O	O	O	O	 O	O	O	O	■	O	O	O	O	O	O	O	O	O	O	O	O
0,60	elektriciteit laagspanning	 O	O	 O	 O	 O	O	O	O	 O	O	O	O	 O	■	O	O	O	O	O	O	O	O	O	O	O
0,80	elektriciteit hoogspanning ≤ 25 kV	 O	 O	 O	 O	 O	 O	 O	O	 O	 O	 O	O	 O	 O	■	O	O	O	 O	O	O	O	O	O	O
1,00	elektriciteit hoogspanning > 25kV	 O	 O	 O	 O	 O	 O	 O	O O	 O	 O	 O	O O	 O	 O	 O	■	O O	 O	 O	O O	O O	O O	O O	O O	O O
1,00	elektriciteit gelijkspanning	 O	 O	 O	 O	 O	 O	 O	O O	 O	 O	 O	O O	 O	 O	 O	O O	■	 O	 O	O O	 O	O O	O O	O O	O O
0,90	stadsverwarming huisaansluiting	 O	 O	 O	 O	 O	 O	 O	O	 O	 O	 O	O	 O	 O	 O	O	O	■	 O	O	O	O	O	O	O
0,70	stadsverwarming distributieleiding	 O	 O	 O	 O	 O	O	O	O	 O	O	O	O	 O	 O	O	O	O	O	■	O	O	O	O	O	O
1,00	stadsverwarming transportleiding	 O	 O	 O	 O	 O	 O	 O	O O	 O	 O	 O	O O	 O	 O	 O	O O	O O	 O	 O	■	 O	O O	O O	O O	O O
≥0,95 (peilmaten)	riolering huisaansluiting	 O	 O	 O	 O	 O	 O	 O	O O	 O	 O	 O	O O	 O	 O	 O	O O	O O	 O	 O	O O	■	O O	O O	O O	O O
≥1,10 (peilmaten)	riolering (PVC) ≤ 300 mm	 O	 O	 O	 O	 O	 O	 O	O O	 O	 O	 O	O O	 O	 O	 O	O O	O O	O O	 O	O O	O O	■	O O	O O	O O
≥1,10 (peilmaten)	riolering (beton), singelverbinding, spuileiding en collecteurriool	 O	 O	 O	 O	 O	 O	 O	O O	 O	 O	 O	O O	 O	 O	 O	O O	O O	 O	 O	O O	 O	 O	■	O O	O O
1,00	(riool)persleiding, brandblusleiding	 O	 O	 O	 O	 O	 O	 O	O O	 O	 O	 O	O O	 O	 O	 O	O O	O O	 O	 O	O O	O O	O O	O O	■	O
1,00	overige leidingen	 O	 O	 O	 O	 O	 O	 O	 O	 O	 O	 O	 O	 O	 O	 O	 O	 O	 O	 O	 O	O O	O O	O O	 O	■

Uitzonderingen:

0,70	minimale dekking in groenvoorziening	
1,00	in leidingenstroken	kruisende leidingen: dekking ≥ 2,5 m

Opmerkingen:

Vergelijking drukeenheden: 0,1 MPa = 1 bar ≈ 0,1 N/mm²	O	= te leggen over O = te leggen onder
	O O	= in ontwerp a.h.v. proefsleuven te bepalen
Versie: september 2009 - concept		= bestaande leidingen die niet meer nieuw worden gelegd

(Slee, & Tjan, 2015)

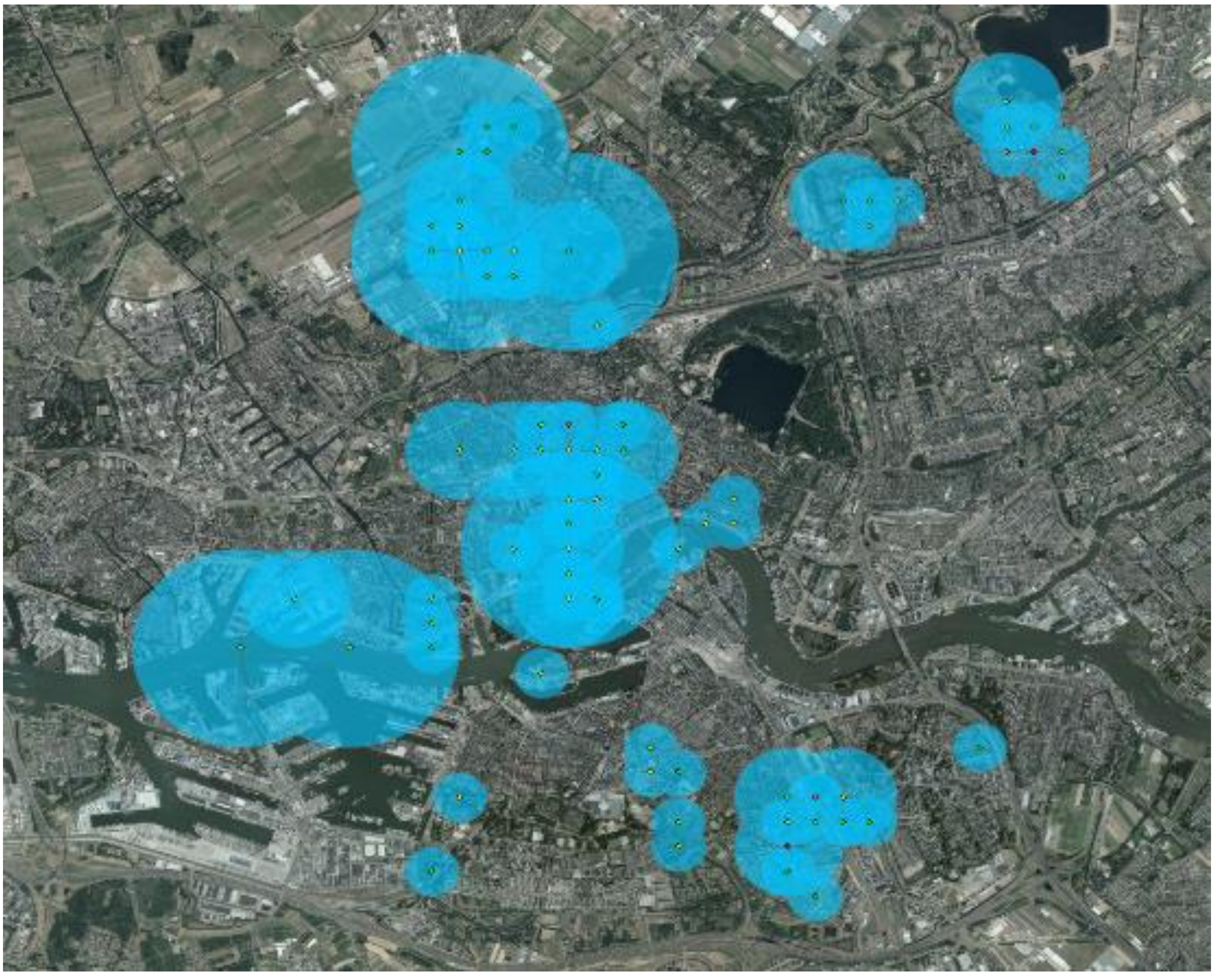
Appendix 3: The sensor installation form

Temperature sensor installation form					
General					
Filled in by					
Installation final at: dd-mm-yyyy / hh:mm					
Removal start at: dd-mm-yyyy / hh:mm					
ID location measuring site					
GPS location measuring site: [lat, long] (Incl. photos of site)					
AHS category: Line – Point – Diffuse					
AHS detail					
Depth below ground level AHS: cm					
Diameter or size of AHS:					
Surroundings					
Soil type: Sand – Clay – Combination [sizes]					
Groundwater level: cm below ground					
Soil coverage					
Sunlight: from – till					
Sensor					
Sensor type					
Sensor ID					
Distance from AHS (X; one side negative)					
Sensor depth (Y)					
Sensor type					
Sensor ID					
Distance from AHS (X; one side negative)					
Sensor depth (Y)					

Appendix 4: Costs involved in this study

Activity	Price per activity	Number of times executed	Costs
KLIC-request	€16,50 per request	6 Requests	€99,-
Mechanic	€80,- per hour	About 15 hours	€1200,-
Sensor preparation	€1600,-	Single action	€1600,-
			Total: €2899,-

Appendix 5: Statistically significant warm grid cells in winter



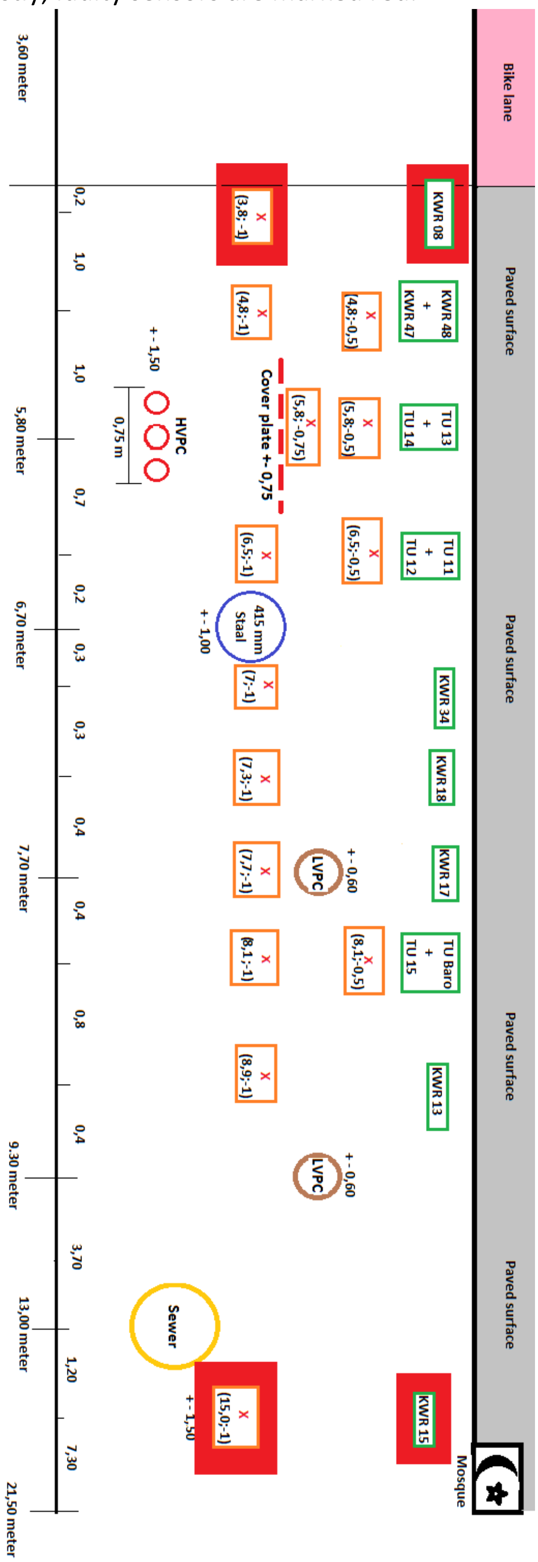
Appendix 6: Statistically significant warm grid cells in spring

Appendix 7: Statistically significant warm grid cells in summer

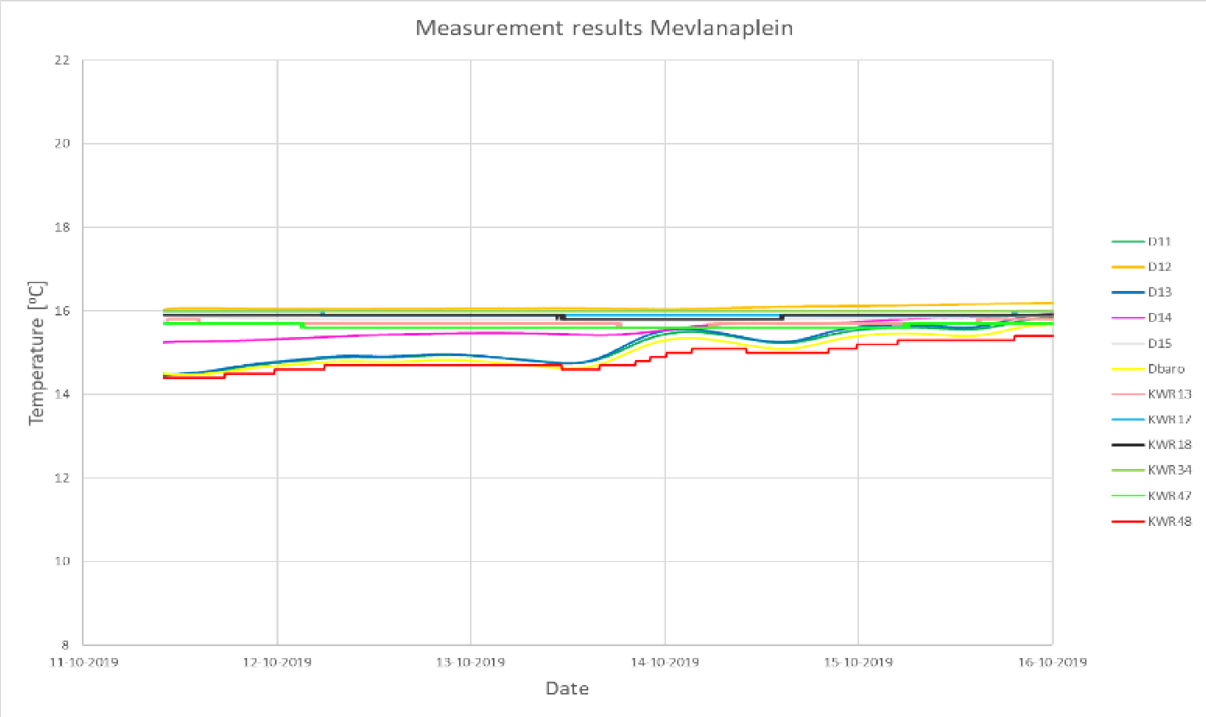
Appendix 8: Statistically significant warm grid cells in autumn

Appendix 9: Measurement setup, Mevlanaplein

This is a schematic image of the soil profile perpendicular to the AHS, corresponding to the measuring site. Many things are processed in the picture. The sensor locations are marked by a red X, accompanied by relative coordinates for horizontal orientation and depth, all surrounded by an orange rectangle. The sensor ID is documented above surrounded by a green rectangle. The whereabouts of subsurface infrastructure is given. City heating mains in purple, HVPC in red, DWDS in blue, LVPC in brown, sewers in yellow. Furthermore, on the bottom horizontal distances between infrastructures and landmarks are given. Lastly, faulty sensors are marked red.

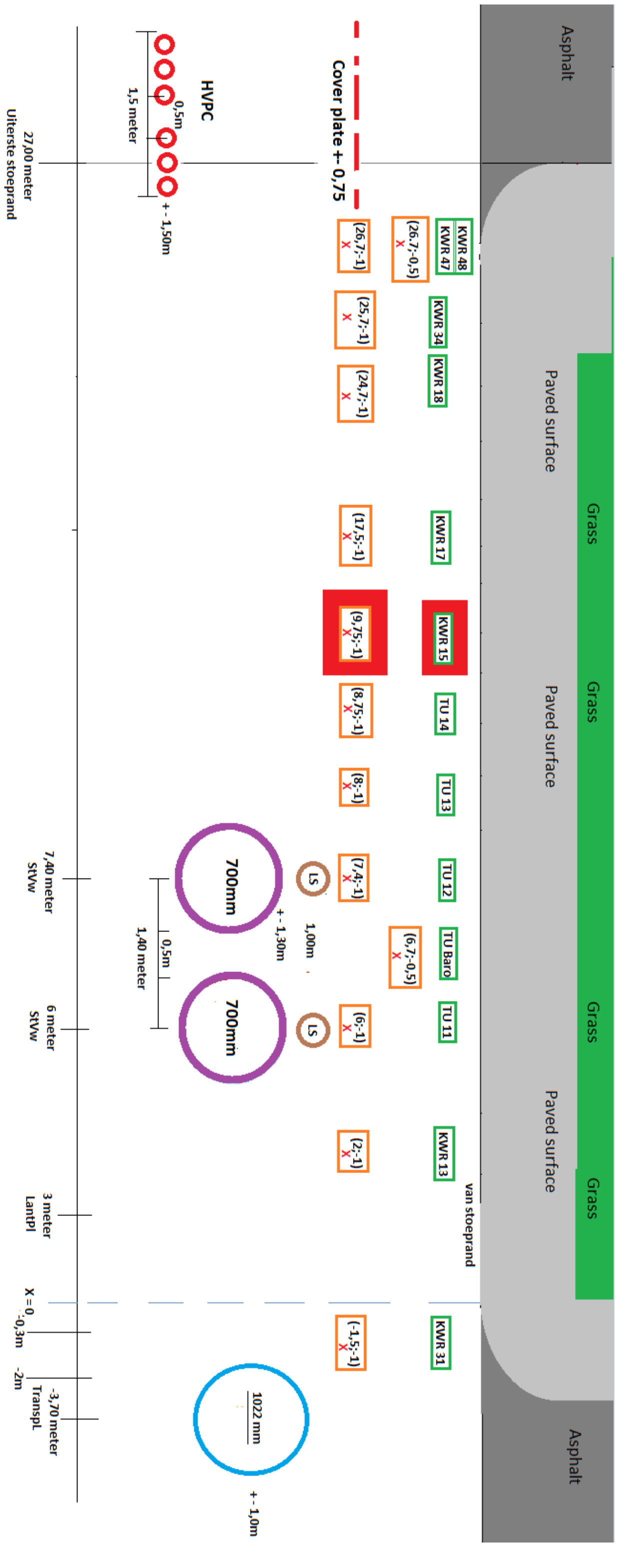


Appendix 10: Measurement results, Mevlanaplein

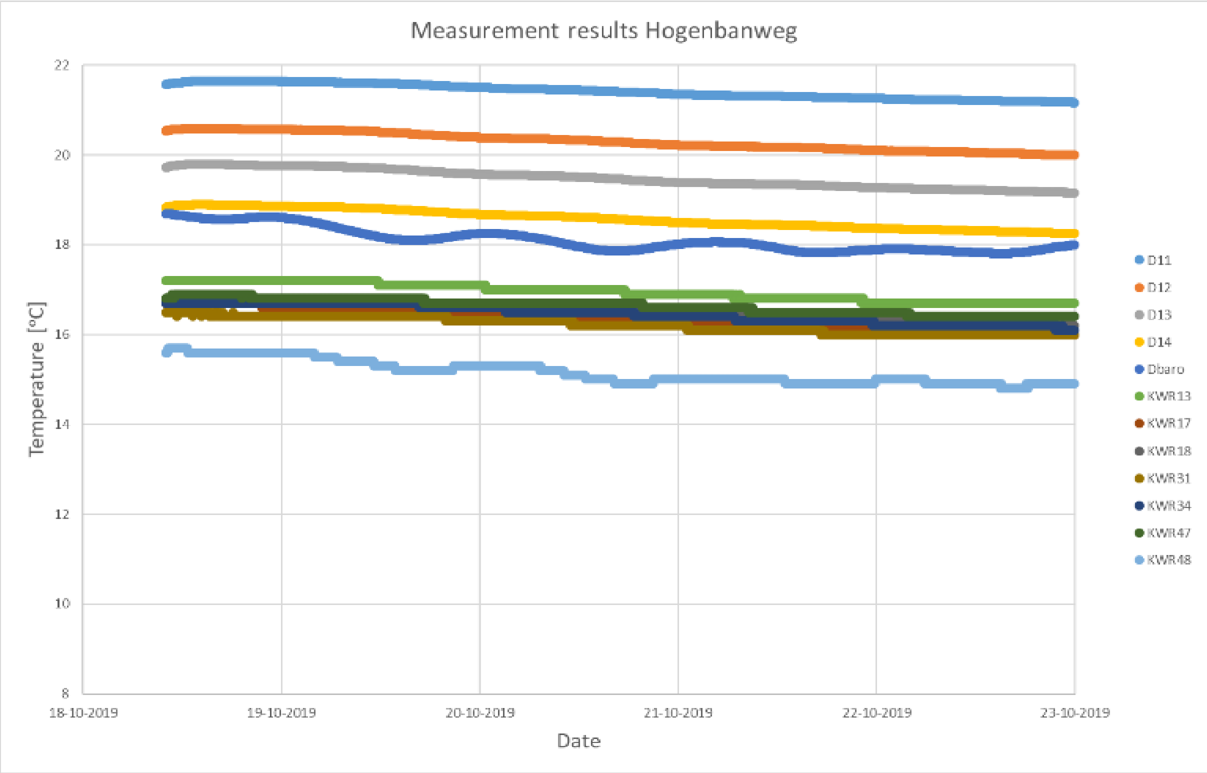


Appendix 11: Measurement setup, Hogenbanweg

This is a schematic image of the soil profile perpendicular to the AHS, corresponding to the measuring site. Many things are processed in the picture. The sensor locations are marked by a red X, accompanied by relative coordinates for horizontal orientation and depth, all surrounded by an orange rectangle. The sensor ID is documented above surrounded by a green rectangle. The whereabouts of subsurface infrastructure is given. City heating mains in purple, HVPC in red, DWDS in blue, LVPC in brown, sewers in yellow. Furthermore, on the bottom horizontal distances between infrastructures and landmarks are given. Lastly, faulty sensors are marked red.

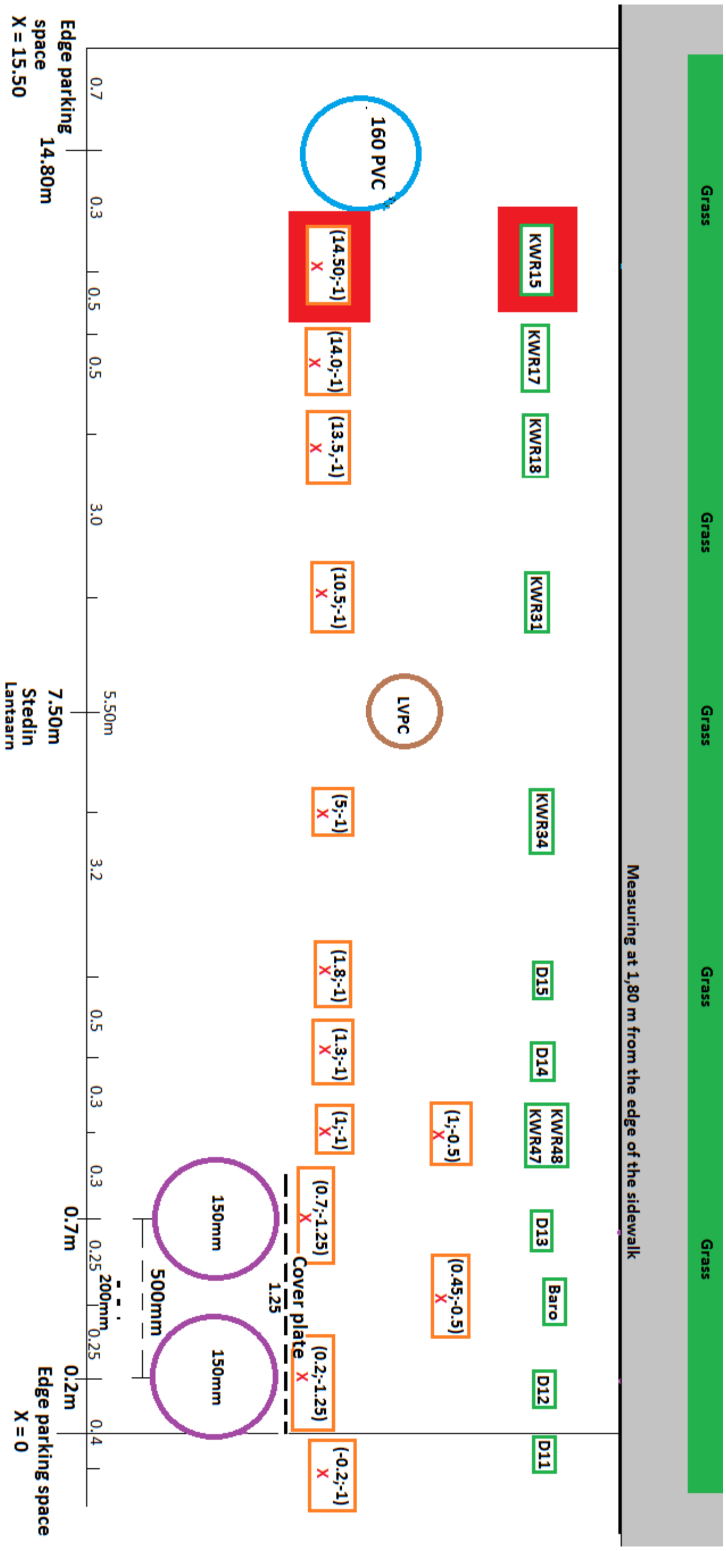


Appendix 12: Measurement results, Hogenbanweg

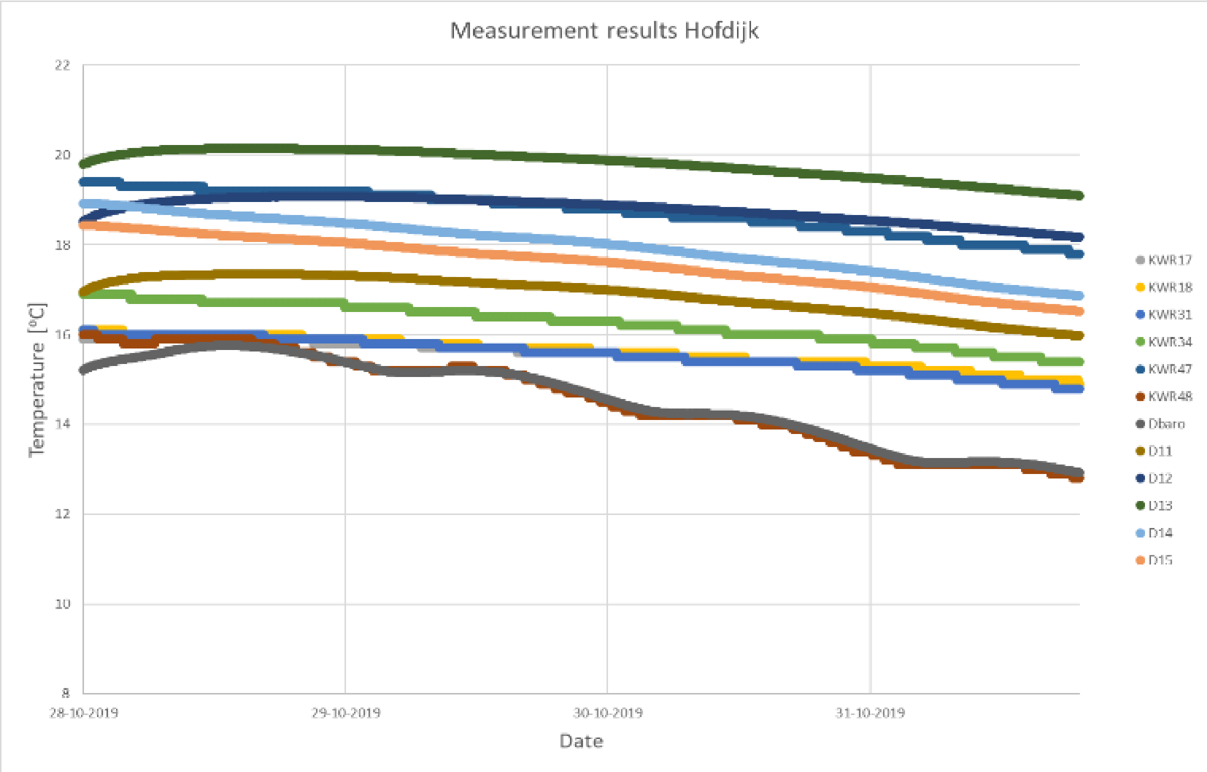


Appendix 13: Measurement setup, Hofdijk

This is a schematic image of the soil profile perpendicular to the AHS, corresponding to the measuring site. Many things are processed in the picture. The sensor locations are marked by a red X, accompanied by relative coordinates for horizontal orientation and depth, all surrounded by an orange rectangle. The sensor ID is documented above surrounded by a green rectangle. The whereabouts of subsurface infrastructure is given. City heating mains in purple, HVPC in red, DWDS in blue, LVPC in brown, sewers in yellow. Furthermore, on the bottom horizontal distances between infrastructures and landmarks are given. Lastly, faulty sensors are marked red.

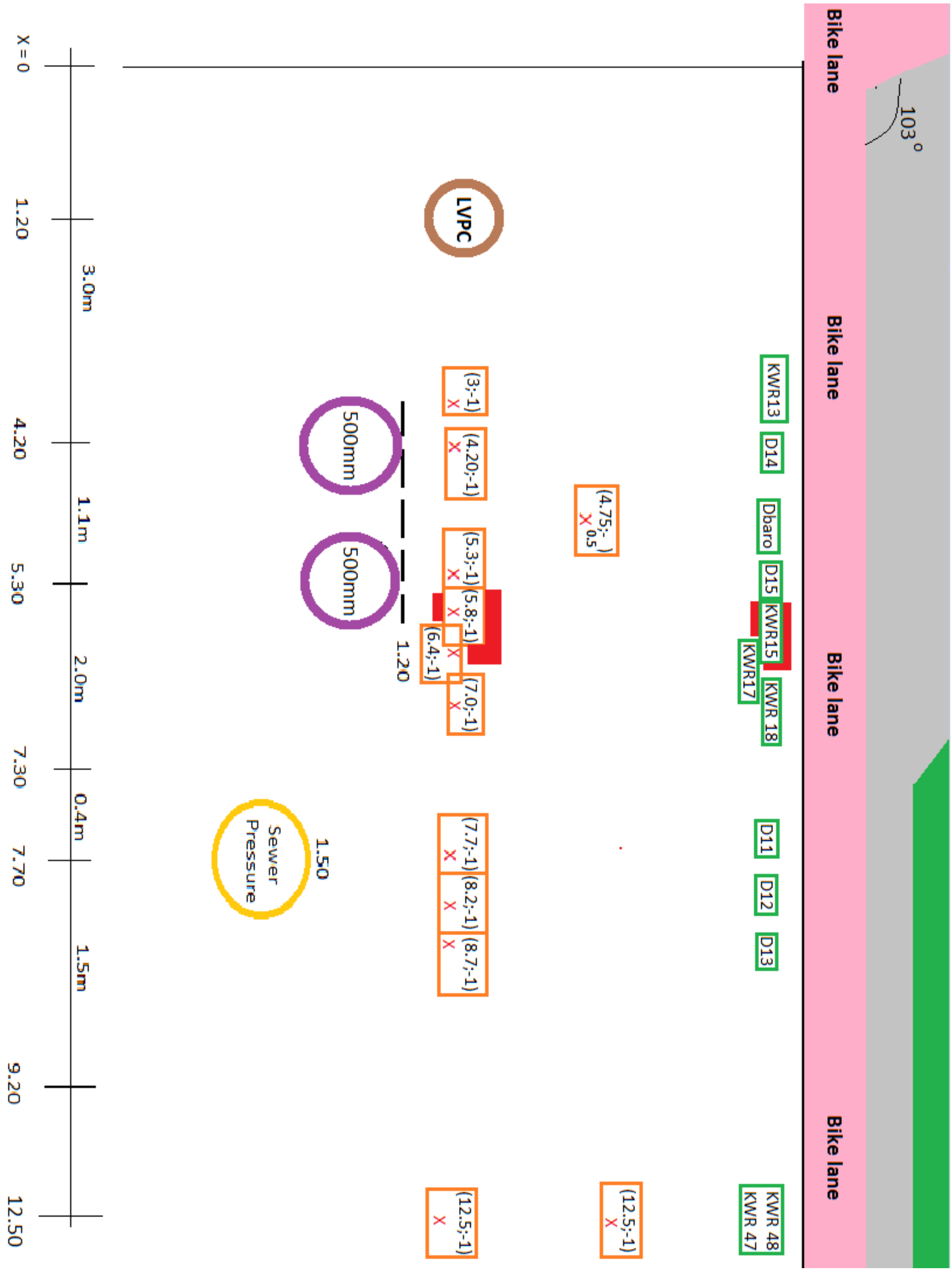


Appendix 14: Measurement results, Hofdijk

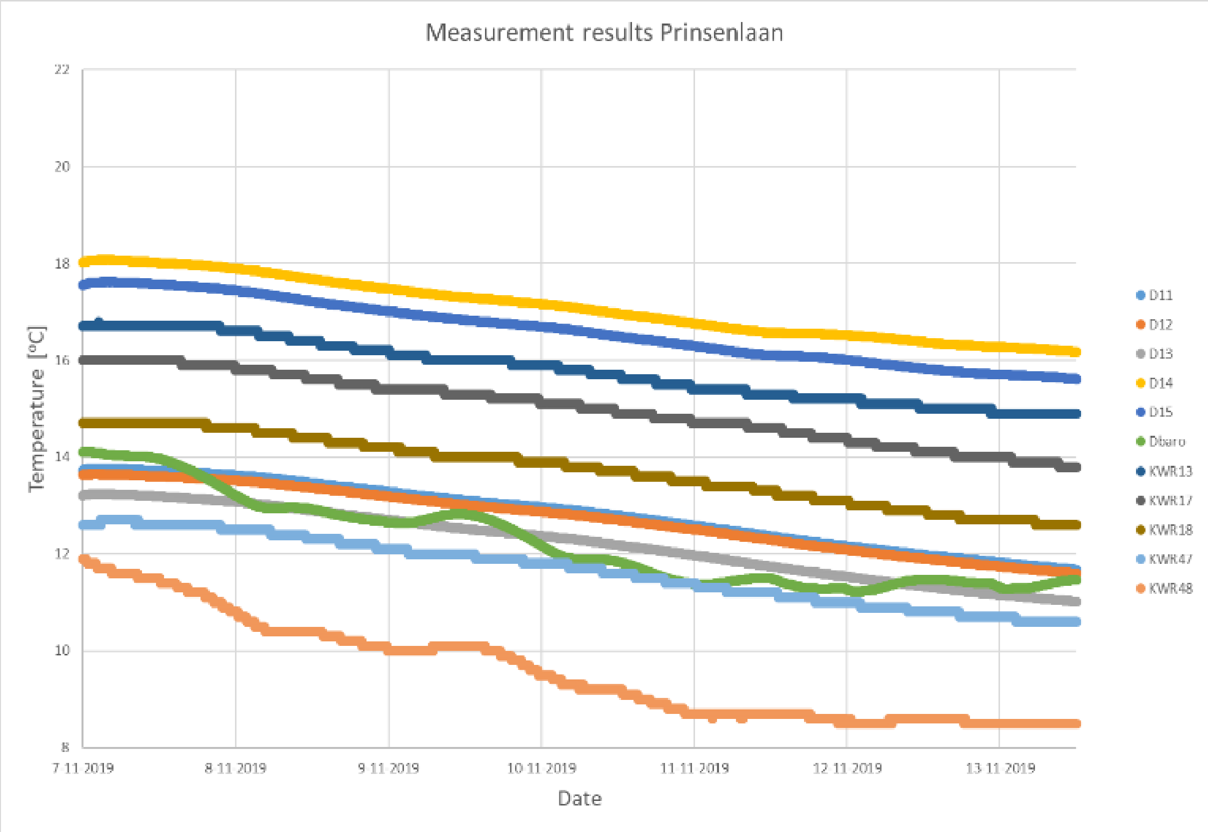


Appendix 15: Measurement setup, Prinsenlaan

This is a schematic image of the soil profile perpendicular to the AHS, corresponding to the measuring site. Many things are processed in the picture. The sensor locations are marked by a red X, accompanied by relative coordinates for horizontal orientation and depth, all surrounded by an orange rectangle. The sensor ID is documented above surrounded by a green rectangle. The whereabouts of subsurface infrastructure is given. City heating mains in purple, HVPC in red, DWDS in blue, LVPC in brown, sewers in yellow. Furthermore, on the bottom horizontal distances between infrastructures and landmarks are given. Lastly, faulty sensors are marked red.



Appendix 16: Measurement results, Prinsenlaan



Appendix 17: Fluxes from primary city heating mains for changing temperatures

	Prinsenlaan	-	Hogenbanweg	
T2 (°C)	16.8		21.6	
k (W/(m*°C))	0.033		0.033	
L (m)	0.094		0.086	
r (m)	0.25		0.35	
T1 (°C)	Energy flux (W/m2)	Total energy flux (W/m)	Energy flux (W/m2)	Total energy flux (W/m)
120	36.23	56.91	37.76	83.03
119	35.88	56.36	37.37	82.19
118	35.53	55.81	36.99	81.35
117	35.18	55.26	36.61	80.50
116	34.83	54.70	36.22	79.66
115	34.47	54.15	35.84	78.82
114	34.12	53.60	35.46	77.97
113	33.77	53.05	35.07	77.13
112	33.42	52.50	34.69	76.28
111	33.07	51.95	34.30	75.44
110	32.72	51.40	33.92	74.60
109	32.37	50.84	33.54	73.75
108	32.02	50.29	33.15	72.91
107	31.67	49.74	32.77	72.06
106	31.31	49.19	32.39	71.22
105	30.96	48.64	32.00	70.38
104	30.61	48.09	31.62	69.53
103	30.26	47.53	31.23	68.69
102	29.91	46.98	30.85	67.85
101	29.56	46.43	30.47	67.00
100	29.21	45.88	30.08	66.16
99	28.86	45.33	29.70	65.31
98	28.51	44.78	29.32	64.47
97	28.16	44.23	28.93	63.63
96	27.80	43.67	28.55	62.78
95	27.45	43.12	28.17	61.94
94	27.10	42.57	27.78	61.09
93	26.75	42.02	27.40	60.25
92	26.40	41.47	27.01	59.41
91	26.05	40.92	26.63	58.56
90	25.70	40.37	26.25	57.72
89	25.35	39.81	25.86	56.88
88	25.00	39.26	25.48	56.03
87	24.64	38.71	25.10	55.19
86	24.29	38.16	24.71	54.34
85	23.94	37.61	24.33	53.50
84	23.59	37.06	23.94	52.66
83	23.24	36.51	23.56	51.81
82	22.89	35.95	23.18	50.97
81	22.54	35.40	22.79	50.12
80	22.19	34.85	22.41	49.28