

IMPACT OF PIPE COVER ON DRINKING WATER TEMPERATURE

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Impact of Pipe Cover on Drinking Water Temperature

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The research of drinking water temperature is just getting started in recent years. It covers knowledge in drinking water quality, and related to drinking water pipe systems, urban planning, relative policy development and management. Understanding the impact of drinking water temperature and apply practical interventions to control water temperature is challenging. Therefore, I am very honoured to have the opportunity to participate in the research on drinking water temperature and collaborate with top researchers at KWR Water Research Institute. Furthermore, I am thankful to those contributors and supporters, which make the thesis work possible.

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Preface

I grew up in Taiyuan, a city in the central part of China and never live abroad before studying at TU Delft. People in China and some Asian countries have the tradition to drink boiled water. Therefore, I never think about the impact of drinking water temperature on water quality and human health before I got in touch with this thesis project. After being familiar with European habits, it is prevalent for most western Europeans to drink tap water. Hence, the drinking water temperature will be one of the intuitive indicators to evaluate drinking water taste, which can influence tap water quality furtherly. At the same time, I also really want to participate in the challenging topic to transcend myself. This is one of the motivations I started this thesis research.

During the thesis research, my academic version had been broadened. I intensively feel the serious research attitude at TU Delft and KWR Water Research Institute. The experience taught me to think questions from multiple perspectives. Several aspects should be considered to eliminate the influence of high drinking water temperature in daily life. They include academic theoretical research, engineering practice, publicity and education, and policy enactment. This thesis is just a start for me to dedicate myself to ensuring the safety of drinking water. With the development of technology and the improvement of people's requirements for drinking water quality, society and public will pay more attention to ensure the drinking water quality and safety. The scientific research on water quality will also become more and more detailed and refined.

Drinking water temperature is just a microcosm of future research in ensuring drinking water quality. In the process of social progress and development, governors, practitioners, and the public's mentality should be constantly adjusted in order to meet the requirements of world development. As a result, more and more new research fields will be opened up, and more experience will be accumulated from nation to nation. Moreover, to harmonize scientific research and engineering practice, much more need to be tested and discussed.

Water management is an advanced scientific research field in the Netherlands. I feel the meticulous research spirit and serious research attitude at TU Delft and KWR Water Research Institute. I believe the experience of studying and intern in the Netherlands will be a solid foundation and a good start for my career in water management. Regarding the deficiencies and problems in this thesis, you are welcome to correct me and discuss them with me.

Siyuan Wang
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Boy drinks from a tap at a NEWAH WASH water project in Puware Shikhar, Udayapur District, Nepal. Photo by Jim Holmes for AusAID. (13/2529)
Source: https://www.flickr.com/photos/dfataustralianaid/10677903803/

Abstract

Drinking water temperature is an essential parameter for water quality related to the physical, chemical and biological processes in water. However, in many countries, the drinking water temperature has not been taken seriously and was excluded from water quality standards. For example, in the Netherlands, the temperature of drinking water should not exceed 25℃ at customers' taps, which is an advanced guide for ensuring water safety. Moreover, with the tendency of global warming, the drinking water temperature in the distribution system will become higher and higher without sufficient attention and practical solutions. Therefore, understanding the mechanism and cause of water temperature fluctuation is instrumental in finding appropriate measures to cope with it and improve the drinking water quality.

This thesis provides relatively comprehensive and overall ideas to research drinking water temperature. The objective of this thesis consists of three parts: i) Determining impact factors on water temperature; ii) Simulating water temperature in the distribution system; iii) Choosing measures to control water temperature. Firstly, data measurement and analytical methods were applied to determine impact factors on water temperature, and the influence level of each impact factor had been identified. Subsequently, implementing these impact factors to calibrate the water temperature simulation model to verify the model's feasibility. Finally, the performance on reducing water temperature of three measures, porous asphalt, pervious interlocking concrete pavement, and grass cover, were compared to determine the most effective measure from the standpoint of pipe cover. The results show as following: i) Four impact factors are summarized as surface cover material, district heating pipe, shade effect and groundwater level based on the collected data; ii) It is feasible to simulate the water temperature in the water distribution system. For the model of city Almere, around 88% of simulation values had a difference smaller than 1℃ compared with measurement data; iii) Grass cover has a better performance than the porous asphalt and pervious interlocking cement pavement. Additionally, this thesis discusses limitations during the measurement and simulation process and more relative interventions to reduce water temperature.

In summary, this thesis further summarizes the various impact factors that affect the drinking water temperature and the measure to control drinking water temperature has launched from the point of pipe cover compared with previous references. These results provide guiding advice on the engineering projects of constructing and renovating drinking water distribution systems considering water temperature.

Keywords: Water quality, Drinking water temperature, Soil temperature, Drinking water distribution system, Pipe cover, Heat transfer, Simulation model, Measures, Interventions

Nomenclature	
WoS	Web of Science
KWR	KWR water research institute
DWDS	Drinking Water Distribution System
DWT	Drinking Water Temperature
RQ	Research Question
PA	Porous Asphalt
PICP	Pervious Interlocking Concrete Pavement
LID	Low Impact Development

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Chapter 1 Introduction

Water temperature plays an integral part in water taste. In harmony with the "Guidelines for Drinking-water Quality (2017)" which is written by the World Health Organization (WHO) (WHO, 2017):

Cool water is generally more palatable than warm water, and temperature will have an impact on the acceptability of a number of other inorganic constituents and chemical contaminants that may affect taste.

Furthermore, the water temperature can also affect water quality which may act on to do with man state of being healthy directly. Temperature affects not only physical and chemical processes, such as absorption of chemicals and chlorine decay (Powell et al., 2000), but also affects biological processes, like microbial growth (Prest et al., 2016). In addition, it also affects the taste and odor, which is the most intuitive point of view of daily living.

1.1 Background introduction

Drinking water distribution system (DWDS), which consists of water pipelines, storage construction, and connection parts (e.g., flange, tee, valve), is an essential part of the water supply system. The drinking water distribution network should effectively keep and distribute water from drinking water treatment plants to customers' taps which can satisfy the residential, industrial, commercial, and firefighting requirements. One of the most critical purposes of DWDS is to control the microbial content in drinking water to keep a safe public state of being healthy (Agudelo-Vera et al., 2020). The microbial composition of DWDS can be affected by water chemistry (source water, chemical stability, treatment process, and temperature) and infrastructure characteristics (pipe material, pipe age, physical integrity of the system, and number and types of storage facilities in the system) (Ingerson-Mahar and Reid, 2013).

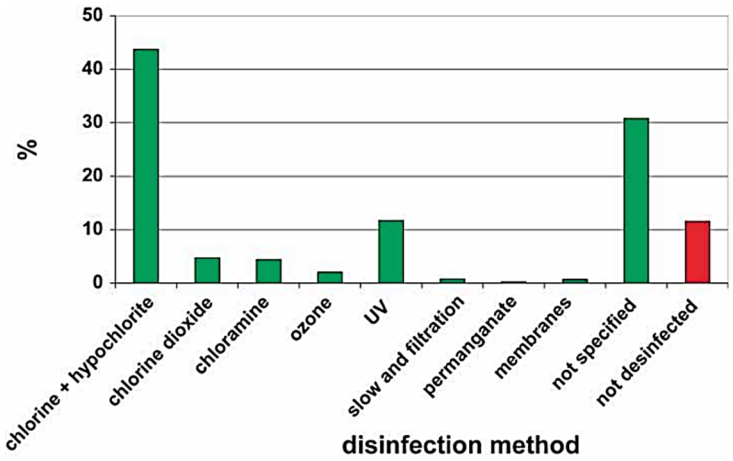


Figure 1 (van der Hoek et al., 2014) Disinfection methods used in drinking water production in Europe (related to total drinking water production).

In order to control the microbial content and composition in the water and give support to good water quality, many countries make requests for chlorine as disinfection allows to maintain the residual chlorine within the treated water in DWDS pipes. However, some European countries, like the Netherlands (Smeets et al., 2009), parts of Germany (Uhl and Schaule, 2004), Austria (Rosario-Ortiz, 2016), do not implement chlorination as a disinfection method. Indeed, there is no residual chlorine in DWDS in these countries. van der Hoek et al. (2014) have counted the disinfection applied for drinking water treatment in European countries and shown in figure 1. It shows that about 45% of European drinking water treatment plants use 'chlorine + hypochlorite' as the disinfection method. The residual chlorine after chlorination disinfection can be effective for hindering bacterial growth. Also, the residual chlorine will disappear caused by drinking water temperature (DWT) increasing. In comparison, the ratio of non-disinfection and UV methods applied in Europe are still more than 20%. Drinking water treatment plant with UV and the non-disinfection process has a potential risk of water quality deterioration caused by DWT fluctuation because of no residual disinfectant in the effluent of drinking water treatment plant. DWT in DWDS is easy to fluctuate during the transition and distribution process from drinking water treatment plant to customers' tap. The fluctuation of water temperature in DWDS could be affected by natural and artificial factors, like meteorological conditions, soil properties, pipe installation depth, groundwater levels, pipe materials, anthropogenic heat source (Blokker et al., 2013b; Agudelo-Vera et al., 2017; Mihalakakou, 2002; Herb et al., 2008). As for building water supply systems, the hot water installations can also affect the drinking water temperature and further affect water quality (Zlatanovic et al., 2017).

Moreover, many other treatment processes (e.g., clariflocculation, filtration, ozonation) are also influenced by DWT (Agudelo-Vera et al., 2020). As for the impact of DWT, the dynamics of microorganisms in the DWDS would be influenced by temperature, which could promote the role of biofilms as a reservoir of opportunistic pathogens and they would as release into the bulk drinking water to be a dynamic pollution source. (Ingerson-Mahar et al., 2013). In summary, DWT is a crucial factor that should be considered to prevent the potential risk of water quality caused by high DWT in some European countries that implement UV disinfection.

The Netherlands is one of the several countries with specific regulations of tap water temperature provided in the Drinking Water Directive (2018). It states that tap water temperature should not exceed 25℃, which is also a threshold of the highest water temperature. Nevertheless, the determination of this value still needs to be more investigated. In the Netherlands, 0.1% of water samples which exceeded 25℃ were reported in the relatively warm year of 2006 within the regular sampling program of the Dutch utilities (Agudelo-Vera et al., 2020). However, with the process of global warming, industrialization, and urbanization, DWT exceeding 25℃ will happen more and more frequently.

The research on the temperature of water sources such as groundwater and surface water has been extensively studied and discussed (Riedel, 2019; Hemmerle et al., 2019; Carraro et al., 2019; Benz et al., 2017a; Benz et al., 2017b; Benz et al., 2016; Benz, 2016; Benz et al., 2015; Martincova et al., 2011; Benyahya et al., 2007; St-Hilaire et al., 2000). However, research on DWT in the distribution process is still in an early stage globally, and little research concentrates on the temperature of tap water which directly influences customers. Applied models of water quality and hydraulic condition of DWDS, which are widely researched and discussed in the literature, usually consider the DWT as constant.

Blokker and Pieterse-Quirijns., 2013 had developed the model for simulating the temperature dynamics in DWDS and predicting DWT in DWDS furtherly which has also been verified many times (Agudelo-Vera et al., 2014; Agudelo-Vera et al., 2015a; Agudelo-Vera et al., 2015b; Zlatanovic et al., 2017). It has shown that the DWT is strongly affected by the surrounding soil temperature of DWDS pipes, and the tap water temperature will finally approach the surrounding soil temperature. Therefore, DWT can easily approach 25℃ and even exceed 25℃ during a warmer period than general summer weather, especially in urban areas. In addition, the anthropogenic heat sources, which are widely distributed in urban areas, such as high voltage cables, district heating networks, can also influence the DWT, and DWT can be higher than 25℃ locally or temporally (Agudelo-Vera et al., 2017). Section 1.2 will provide more detailed content, which summarizes the current research on DWT.

This article presents a relatively complete idea from determining the impact factors, verifying the simulation model for the water temperature in DWDS, and proposing some measures and ideas to cope with high water temperature. The content of each part will follow the research questions (RQ) formulated in section 1.3.

1.2 Literature review

The online databases SCOPUS and Web of Science (WoS) was used. The search was conducted in September 2020, and no time limit was set in the search. The document type and subject area did not limit yet in order to expand the select range of related documents to find more information more or less. Subsequently, performing the screening by language, English and Chinese are chosen. There are four searches conducted in the process. First, (“pipe cover”) AND (“drinking water temperature”) were chosen. There were no relevant documents in both SCOPUS and WoS databases, which indicated that the initial keywords defined are too narrow to search. A second search using a broader scope of keywords (“pipe cover” OR “soil temperature” OR “soil heat”) AND (“drinking water temperature”), The search results of WoS and SCOPUS are the same. Both of these two databases show two same papers, and the results are too little to use as a source of literature review. Subsequently, we prefer to use (“pipe cover” OR “soil temperature” or “soil heat”) AND (“drinking water temperature” OR “drinking water quality”) as keywords to broaden the choice of search result. The search results are predictable to some extent. There are only five papers of Scopus and four papers of WoS. Finally, we choose the keywords of (“pipe cover” OR “soil temperature” OR “soil heat”) AND (“water temperature” OR “water quality”). This choice can expand the scope of drinking water temperature to a broader concept of water quality which is more available to select valuable articles related to the thesis topic. Three hundred seventy-one articles were found in SCOPUS, and 185 articles were found in WoS. After the first screening of these articles, there are only 18 relevant references for the literature review. After this, the snowball method was followed by using these critical documents as a starting point to find other more relevant articles on the subject matter. In total, there are 39 articles used in the thesis project.

There is not much work reported recently in this field, which concentrate on DWT in urban water system. Table 1 summarizes the literature on DWT with their research goals and results, showing the current research phase on DWT.

Table 1 Current research on drinking water temperature

Reference	Targets	Main points
Blokker and Pieterse-Quirijns., 2013	Describe a model that predicts the water temperature in a real DWDS under realistic soil types, ground cover, and weather data.	①It is available to predict the soil temperature at different depths as a function of weather and environmental conditions by micrometeorological model; ② Soil temperature model can predict the DWT in DWDS; ③The model of soil temperature can predict the water temperature experienced at the tap by assuming that soil temperature is constant during 24 hours.
Blokker et al., 2013	Verify the feasibility of extracting thermal energy from drinking water to use for household heating.	①The thermal energy of 1.16℃, which is extracted from drinking water, can provide heating for 900 homes and costs equivalent to heating fewer than 85 homes; ②It is a sustainable way of energy production to extract thermal energy from drinking water and using the soil heat to regenerate the thermal energy of the drinking water.
Agudelo-Vera et al., 2014	Evaluate the feasibility of using weather forecast data to predict soil temperature and DWT in DWDS pipes using the meteorological model developed by Blokker and Pieterse-Quirijns (2013).	①It is feasible to use weather forecast data of two days in advance as an 'early warning system' to predict DWT in DWDS; ②The impact and consequence of climate change on DWT can be assessed by using the micrometeorological model combined with weather forecast data; ③Modelling can provide the possibility to research soil temperature under different soil and land cover types; ④Modelling can also support the decision-making to prevent DWT exceeding the threshold of 25℃.
Agudelo-Vera et al., 2015a	Evaluate the feasibility of using the micrometeorological model developed by Blokker and Pieterse-Quirijns (2013) to predict the maximum daily water temperature in the DWDS two days in advance.	①It is possible to use data of weather forecast as an early warning system to predict DWT in DWDS; ②Using a prediction based on records provides a better estimation to use as an early warning system; ③Modelling soil temperature can support and give valuable information about where and when to take samples on different measurement sites and to better monitor the DWT in DWDS.
Agudelo-Vera et al., 2015b	①How often will the DWT exceed 25℃ in urban areas in the future? ②What is the effect of DWT on water quality? ③ Which measures are feasible to reduce the risk of exceeding the DWT threshold (25℃)?	①It is possible to use weather information to predict soil temperature and DWT in DWDS in peri-urban and urban areas furtherly; ②DWT at the customers' tap is in the summer higher in urban areas compared with the DWT in the peri-urban area; ③Analysis of the DWT in future urban areas showed that peri-urban areas do not have a risk to exceed the threshold of 25℃ now or in the future; ④Different measures (such as green roofs, deeper depth of pipe installation) have limited contribution to reducing soil temperature, which means that different measures should be taken simultaneously to have a noticeable reduction on soil temperature and controlling anthropogenic sources would be the most efficient intervention.
Agudelo-Vera et al., 2017	Find a method to identify heat sources and urban characteristics that locally influence the soil temperature	①The subsurface heat island can be modeled by using a soil temperature model with the input of meteorological data and anthropogenic heat values; ②The proposed method, which combines the mapping of anthropogenic heat sources, modeling of soil temperature, analysis of tap water temperature, and extensive soil temperature measurement, is calibrated to be useful for determining and validating the range of temperature of urban shallow soil during summer; ③It is verified that the underground heat stress in the urban area is caused by a combination of solar radiation, anthropogenic heat sources, and the top layer of soil.

Reference	Targets	Main points
Zlatanovic et al., 2017	Development and validation of a drinking water temperature model in domestic drinking water supply systems	①The model can predict the water temperature in drinking water supply system accurately; ②Inlet water temperature, air temperature, and thermal conductivity of air are considered as the most sensitive parameters in this model; ③Convective process between water and air through the pipe wall is the most dominant transfer process; ④It is believed that the model can be used for multiple pipe materials used in the drinking water supply system.
Agudelo-Vera et al., 2020	A literature review of the current research and knowledge about DWT from source to tap also compares different policies in several countries.	①The data of water temperature is collected in some countries with different and varied standards which is not systematically; ②Although it is acknowledged that lower temperature can improve water quality, the internal relations are not well understood; ③DWT is strongly affected by soil temperature around pipes and groundwater level, but the model which could predict DWT effectively is still unvaried now; ④Future changes of the surrounding environment (such as climate change, the urbanization process, rainwater reuse) are likely to influence DWT more or less.

Based on the above reference, although the simulation model of the DWT has been implemented in the drinking water supply system, drinking water distribution system and domestic drinking water system, the implementation of DWT simulation model in DWDS is not systematic from the stand point of analyzing impact factors with the enough measurement point. Also, the measures for controlling DWT are rarely mentioned. Hence, the research question of this thesis has been proposed in section 1.3 to fill the research gap.

1.3 Research question

In order to cope with the shortcomings of the current simulation model framework mentioned in section 1.1, the main question can be summarized as 'how to prevent high DWT?' in this thesis. In order to answer the key question, three key questions are addressed in this thesis to split the key question:

(1) What are the impact factors on DWT in DWDS?

In order to obtain effective measures to prevent high DWT, it is necessary to understand the DWT change in DWDS. Therefore, on-site measurement activities are available to classify and summarize the impact factors on DWT. The influence level of each impact factor is also estimated in this process, which helps understand the mechanism of DWT change. Hence, a set of relevant sub-key questions are listed below:

1-1 What is the impact of different depths and covers on DWT in DWDS?
1-2 What is the impact of other related infrastructure on DWT in DWDS?
1-3 How to quantify the influence level of each impact factor?

(2) How to simulate DWT in a model?

After understanding the DWT change in DWDS and their impact factors, it is necessary to build a model framework to simulate the DWT in DWDS with considering the different impact factors summarized from the first key question. Therefore, deepening the understanding of water temperature simulation and answering key question 2 would contribute to verifying the feasibility of the model framework. This also provide a practical foundation of water temperature simulation systems. Hence, relevant sub-key questions are shown as below:

2-1 Is it possible to model DWT in DWDS?
2-2 Are there any models available for modeling DWT? If yes, what are the basic principles for how these models work?
2-3 What is the accuracy and reliability of these model prediction results?

(3) Are there any improvements and measures to prevent the occurrence of high DWT?

Controlling DWT in DWDS is a complex process which includes arranging different municipal infrastructures. Additionally, many municipal departments and related stakeholders will be involved in the planning and design process. Therefore, considering

several measures from the point of pipe cover and evaluating the performance of each measure is necessary to discussed. Hence, this thesis will answer the following sub-key questions:

3-1 What interventions or measures from the pipe cover points of view can be used to improve water temperature in the DWDS?
3-2 What is the impact of different interventions on water temperature at different locations in the research system?
3-3 How feasible are these interventions in reality?

1.4 Thesis structure

In order to answer the research question mentioned in section 1.2, Chapter 2 describes the research approach used in this thesis. The relation between research questions and the thesis content is formulated as well. However, to avoid too much content in chapter 2 to make it hard to read and break the coherence understanding of each phase, a detailed explanation of methodologies used in different research phases is provided in each corresponding chapter. Chapter 3 describes the data collection practice at 2 locations of Weesperkarpel and Boszoom. The impact factors and their influence level were analyzed and determined after the continuous data was obtained from sample points. After determining the impact factors on drinking water temperature in DWDS, they will be applied in the model calibration process. Therefore, chapter 4 presents the mechanism of the water temperature simulation model firstly. After that, the calibration process of Almere, a Dutch city, and simulation result analysis were presented. In addition, the limitation and discussion of the simulation results were also discussed in this chapter. After finishing the model calibration process, chapter 5 depicts the different measures to prevent high DWT and provide more choice which can be applied in factual circumstances and still need further research. Subsequently, chapter 6 discusses the deficiency of this thesis. Ultimately, Chapter 7 provides the conclusion and future work.

Chapter 2 Research approach

Chapter 2 describes the research approach. This chapter introduces the research methods into two parts: i)overall framework of research approach; ii)Relation between approaches and research questions. Thus, the overall introduction of research methods is a holistic introduction of the research framework, and the correlation between them will appear in each chapter of Part 2.

2.1 Overall framework of research approach

Figure 2 shows an overview of the research approach used in this thesis. In order to answer the three main questions provided in section 1.3, the thesis follows a research sequence and steps of 'information collection' – 'data collection' – 'data analysis' – 'model calibration' – 'improvement'. Firstly, information about drinking water temperature and related areas, like the impact of different covers on soil temperature around drinking water pipe or soil thermal conduction and groundwater temperature variation, will be collected by literature study. The soil temperature around drinking water pipe is a vital impact factor on DWT, which will be described in section 3.1. Due to the insufficient information and current research progress about DWT in DWDS, some discussion with colleagues in KWR is helpful to get more supplementary information, especially for the current circumstance in the Netherlands. Secondly, to figure out the influence level of different pipe cover on DWT, some data of soil temperature at different depths and DWT in DWDS in the Netherlands should be collected for further analysis. Thirdly, the collected data of soil temperature and DWT will be analyzed and generalized the influence level of different cover of DWDS pipelines.

Additionally, some other related factors found in data collection, which are irrelevant to pipe cover materials and species, will also be considered and analyzed. Then, the influence level of different factors that affect DWT will be introduced to the model framework which KWR designs. Next, the simulation model of DWT for Almere will be calibrated by these new-introduced factors and compared with measurement data collected at some measurements points in Almere to verify the feasibility of this model. Finally, interventions and measures to prevent high DWT will be imagined. After calibrating the simulation model, it will introduce different interventions and measures to test their effectiveness.

2.2 Relationships between research approach and key questions

This section provides a more detailed exposition for the research method, including the contents of each step and the correlation with main questions and key questions provided in section 1.3. It should be notified that some key questions can be answered by yes or no directly. However, others need an explanation from multiple contents to provide a further depiction of the questions with answers of yes or no.

First of all, to be familiar with the impact of pipe cover on DWT, understand the impact factors and how many impact factors on DWT are necessary. Before the data collection step, understanding the impact of soil on water temperature, which will run through the entire text, is needed to know and will be provided in section 3.1. Hence, raw data of DWT and soil temperature collected in two locations of Weesperkarspel and Boszoom with detailed information like, measurement points position, measuring equipment, will be presented in section 3.2. Moreover, some additional limitations that may influence the measuring accuracy will be presented in section 3.3 to show the potential risk of systematic errors. With the background of this thesis project, determining the impact factors from the point of pipe cover is indispensable, which will be presented in sub-section 3.4.1 (**RQ 1-1**). At the same time, the impact of pipe cover on DWT is not single. Other impact factors of municipal infrastructures, underground constructions will also affect DWT. For these impact factors, sub-section 3.4.1, 3.4.2, and 3.4.3 will provide a detailed elaboration (**RQ 1-2**). These impact factors are some common parts in general urban patterns, and other unique factors of different cities should be considered separately. The influence level of each impact factor will be analyzed and estimated by data processing in each sub-section of different factors, respectively (**RQ 1-3**). The step of data processing and identification of impact factors provides a solid foundation for further study on the simulation model.

In the second place, simulating DWT in a model should be considered sequentially to verify the feasibility of combining DWT prediction with the programming method. Section 4.1 will provide a brief introduction of thermal conduction in drinking water will be presented to indicate the possibility of a DWT model simulation (**RQ 2-1**). Section 4.2 will present the DWT simulation model built by KWR with its principle, program operating system (**RQ 2-2**). After that, a brief exposition of the contribution of this simulation model to predicting DWT will be elaborated in section 4.3 to elaborate its practicality in actual circumstances. Based on the understanding of the simulation model from KWR, calibrating a model for a specified city tests the reliability and accuracy stated in section 4.4 and 4.5 by using mathematical metrics, such as RMSE. (**RQ 2-3**). Additional analysis of unfit the part between simulation results and measurement data will be dictated in section 4.6 with discussing limitation of the simulation model from KWR.

Consequently, solutions should be raised after summarizing the impact factors of different points and testing the simulation model for DWT prediction. The overall design thinking of different measures based on thermal conduction in drinking water will be

presented in section 5.1, especially from the viewpoint of pipe cover (**RQ 3-1**). Also, the influence level of each intervention and measure to prevent high water temperature will be determined. Then, introduce these different interventions and measures into the simulation model, which has already been calibrated in the last step. Simulating the model with interventions under an assumed high soil temperature circumstance will be provided in section 5.2 to detect the impact of different interventions on DWT at different locations with high DWT initially (**RQ 3-2**). Finally, the feasibility of different interventions should be considered to evaluate its feasibility in reality, including cost estimation (**RQ 3-3**). In Chapter 7, the conclusion of this thesis will be provided.

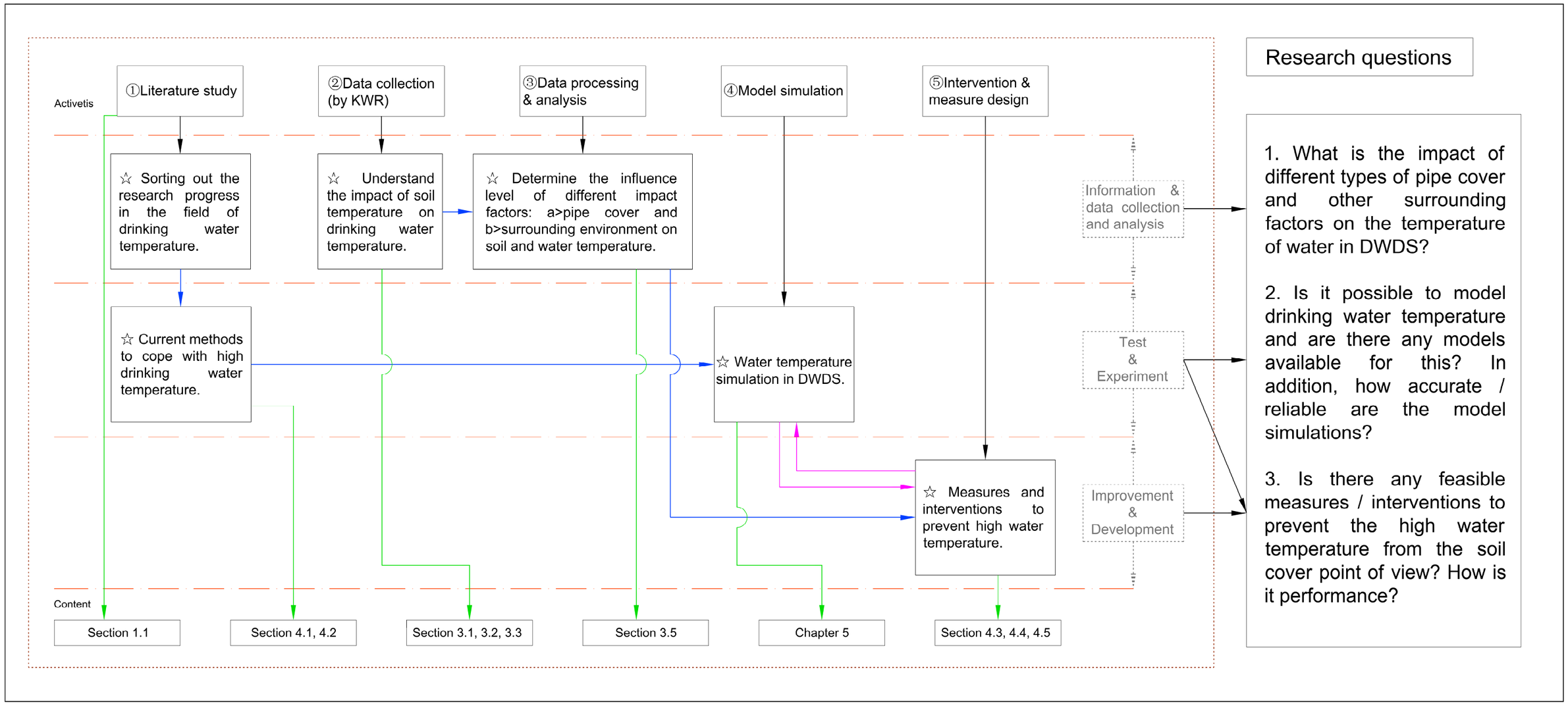


Figure 2 Overall Framework of research approach

Chapter 3 Analyzing the impact factors on drinking water temperature

Soil temperature is a direct factor influencing DWT in DWDS. Therefore, considering that the impact factors on soil temperature can be seen as the impact factors on DWT. Hence, understanding the impact of soil on water temperature is essential to determine the impact factors on water temperature. Therefore, this chapter will introduce soil and water temperature data measured in two locations, and analyze of the different impact factors and their influence level based on the data collected in these two locations. Hence, Chapter 3 is divided into five parts. 3.1 Understanding the impact of soil on water temperature leads readers to know the correlation between soil temperature and drinking water temperature. 3.2 Data collection practice introduces two groups' data measurement in Weesperkarspel and Boszoom, respectively. 3.3 Limitation of measurement condition shows the limiting factors of these two measurements. 3.4 Analysis of the impact factors on drinking water temperature has been stated the impact and influencing level of different impact factors on soil temperature and drinking water temperature. Finally, section 3.5 summarizes the chapter summary and sub-conclusion of the first key question.

3.1 Understanding the impact of soil on water temperature

Blokker and Pieterse-Quirijns (2013) had divided the environment surrounding the drinking water pipelines into four layers of i) the atmosphere; ii) the roughness layer; iii) the soil surface; iv) the soil, which is helpful to understand the mechanism of the heat transfer process from the atmosphere to the soil. The roughness layer represents the layer between the atmosphere and the surface of the soil. The thickness of the roughness layer strongly depends on the vegetation and buildings' spatial distribution and height, especially in urban areas. The property of air could be changed during the airflow through the roughness layer, which is affected by vegetation and building constructions. Therefore, the heat transfer process can be divided into two sub-processes outside the soil and inside the soil. The sub-process of the outside of soil can be summarized as heat and energy transfer between atmosphere and soil surface, atmosphere and roughness layer, and roughness layer and soil surface. For the inside of soil, the heat transfer process can be recapitulated in four sub-processes: the thermal conduction: i) from the soil surface to the soil; ii) from soil to the outside pipe wall of DWDS; iii) from outside to the inside of pipe wall; iv) from inside pipe wall to the water inside. Also, the thermal conduction through the water should be considered, like the heat transferred from upstream to downstream in DWDS pipelines.

Based on the comprehension of the heat and energy transformation pattern described above, it can be concluded that the soil is in direct contact with the pipe wall of drinking water pipelines in most cases and will also influence DWT in DWDS directly. In addition, the soil temperature can also be influenced by DWT. This is because the heat transfers from the water inside the pipe to the soil through the pipe wall. However, because the mass of soil is much larger than the volume of water inside the DWDS pipe, the heat transfer from water to soil only happens in a small range of the soil around the DWDS pipe. Hence, the soil temperature around the DWDS pipelines can be assumed as a boundary condition for this process. In summary, it is indispensable to collect data of both soil temperature and DWT, which are helpful to analyze the correlation between them, and both can reflect the impact of different pipe covers on DWT. Additionally, soil temperature, an essential parameter of the simulation model, will be introduced in section 4.2.

After understanding the impact of soil on DWT, soil temperature and DWT data, which work as raw data, were collected in two different locations by KWR. In this section, the introduction of different measurement locations with each period of measuring, the surrounding environment of measuring and other related information will be shown in the following contents.

3.2 Data collection practice – Measurement in Weesperkarspel

3.2.1 Overview of measurement points

The measurement point is on the roadside and near the Weesperkarspel wastewater treatment plant and park of Gaasperplas East, as shown in figure 3. It clearly shows the location of measurement points and also shows the relationship with the surrounding environment. The detailed information of Weesperkarspel will be presented in appendix 1.



Figure 3 The measurement point at Weesperkarspel*

*The figure of the measurement points at Weesperkarspel is retrieved from Google Earth.

The measuring period of Weesperkarpel is about a month and a half from 2020/05/21 to 2020/07/01.

3.2.2 Sensors layout

Figure 4 is a technical drawing that depicts the layout of temperature sensors under two different covers. The temperature sensors can be divided into four columns: column G, column GT, column TG, column T.

For the spatial distribution vertically, sensors under the grass cover are named G5, G55, G105, and G155. ‘G’ means under grass cover, ‘5’ means the sensor is at a depth of 5cm, compared with the soil’s surface and shown as the ‘depth related to ground level’ in figure 4. Hence, the column G includes the sensors complete under the grass cover names as ‘G + depth value’. ‘G’ means complete under grass. The same can be obtained, and the column GT includes the sensors under grass near tile names as ‘GT + depth value’. ‘GT’ means under grass near the tile. The column TG includes sensors under tile near grass names as ‘TG + depth value’. ‘TG’ means under tile near the grass. Finally, the column T includes sensors complete under tile names as ‘T + depth value’. ‘T’ represents complete under tile cover. Sensors of the column G and GT connect with one data logger, and the column TG and T connect with another data logger.

For the spatial distribution horizontally, the distance between column G, GT, TG, T and the boundary of the grass cover and tile cover is 238cm, 48cm, 67cm, and 257cm, respectively.

In addition, a power cable between sensor G55 and sensor GT55 is a low voltage cable that can be assumed without any heat emission. There is a data cable next to the drinking water pipe installed between the depth of 105cm and 155cm. The effect of the data cable can also be neglected because of almost no heat emission.

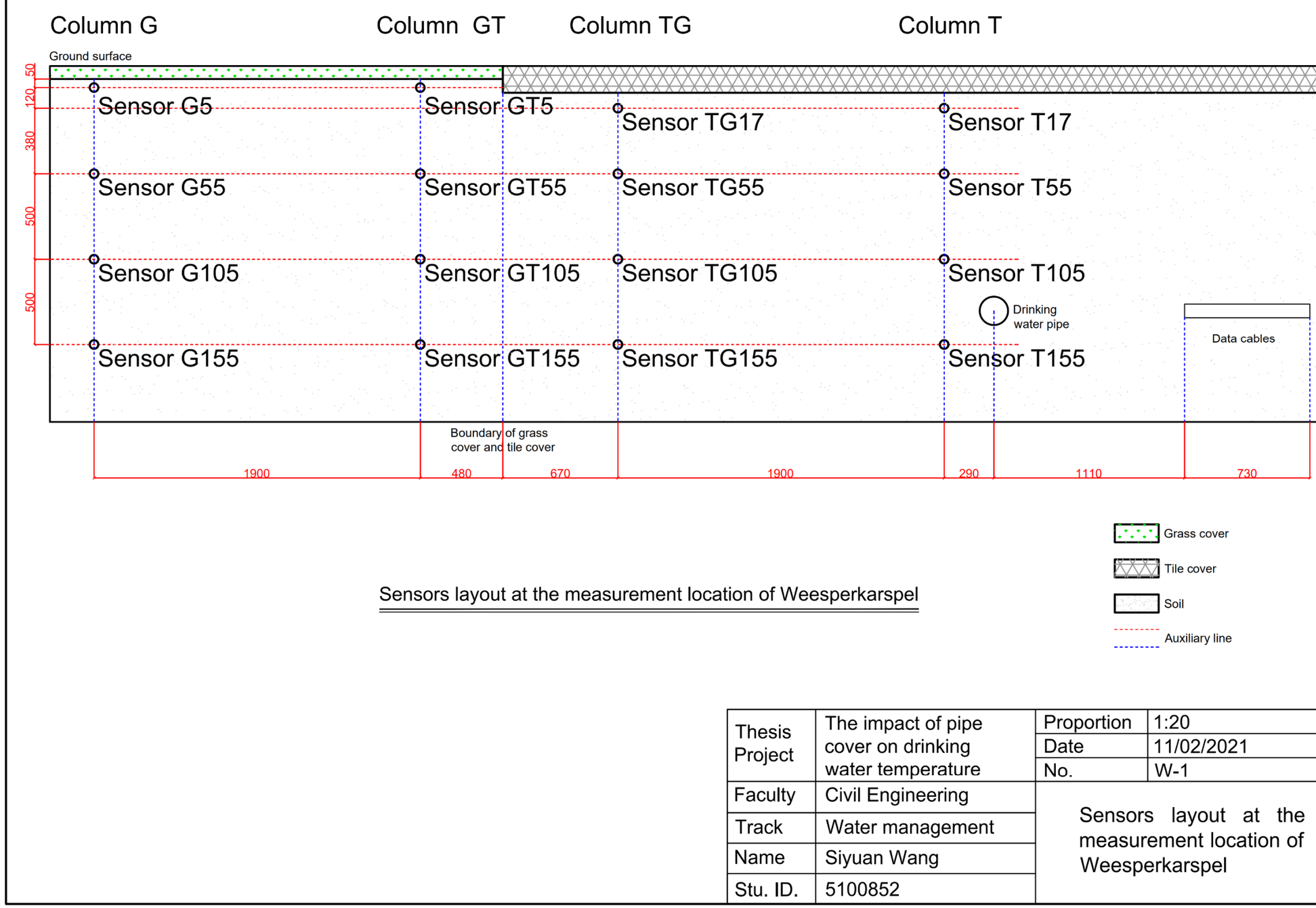


Figure 4 Technical drawing of sensors layout at Weesperkarspel

3.2.3 Type of collected data

Sensors installed in Weesperkarspel collected a set of data every ten minutes from 21/05/2020 to 01/07/2020 (including the start and end dates). The dataset includes the maximum temperature, minimum temperature and average temperature during the ten minutes. The average temperature data of each measurement point with 10min interval is chosen in this thesis which will be analyzed and shown in section 3.4.

3.3 Data collection practice – Measurement in Boszoom

3.3.1 Overview of measurement points

Boszoom is a street in Rotterdam. There are three different measurement points at Boszoom. Figure 5 depicts the location and environment of each measurement point.



Figure 5 Layout of measurement points in Boszoom*

* The figure of measurement points layout in Boszoom is retrieved from Google Earth. The distance between L1 and L2, T2 and L3 are estimated by the tool of measuring distance provided in Google Earth.

The flow direction was from L1 to L3 through L2. The distance between L1 and L2 is estimated as 415m, and the distance between L2 and L3 is about 499m. In addition, the type of measurement data of L1, L2 and L3 has a slight difference. At location L1, Evides Water Company (Evides) measured the inflow velocity, the temperature of ingoing drinking water and soil temperature surrounding the drinking water pipe. The soil temperature surrounding the pipe was measured at location L2 without measuring DWT. As for location L3, Evides measured the temperature of outgoing drinking water and soil temperature surrounding the drinking water pipe.

The measuring period of Boszoom is about three weeks from 2020/05/12 to 2020/06/02.

3.3.2 Sensors layout

The circumstances of sensors layout in Boszoom will be introduced in L1, L2 and L3 separately.

The first measurement location is Kralingsweg, which is shown in figure 6.

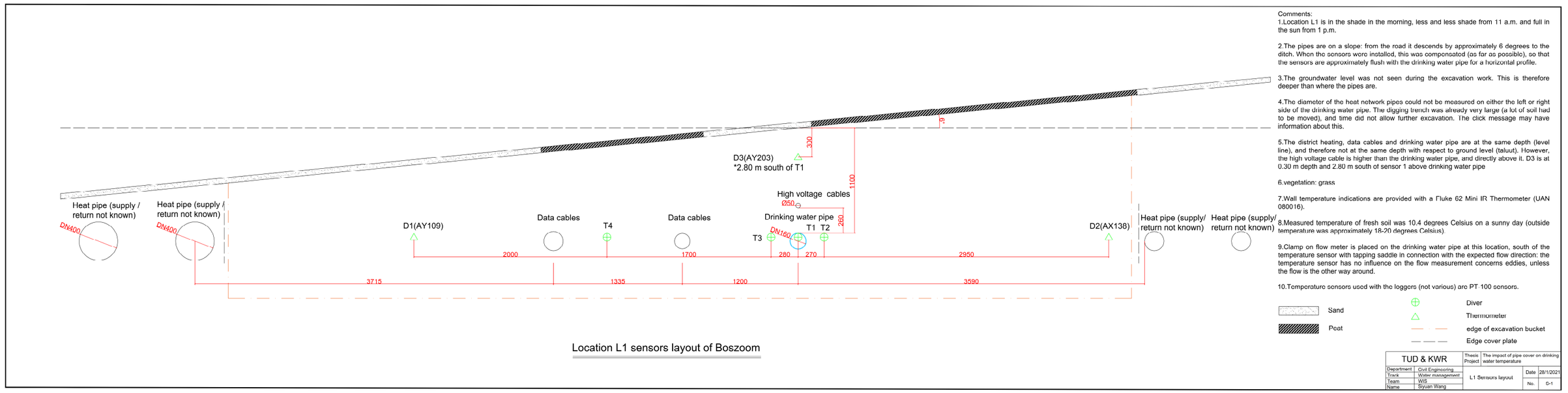


Figure 6 Technical drawing of sensors layout at and underground constructions at location L1 at Boszoom

* Figure 6 is the technical drawing of sensors layout that can show each underground element's position relationship and the actual distance between each element proportionally. More detailed information of location L1 are attached to appendix 2.
* Labels of different kinds of sensors ‘T’ and ‘D’ are presented as thermometer and diver, respectively, which provide the same function as data logging at location L1. However, data collected by thermometers are accurate to one decimal place, and divers are accurate to 2 decimal places.
* Sensor D3 is not installed below the drinking water pipe. However, it is installed at a depth of 0.3m above the drinking water pipe and is about 2.80m north of sensor T1 horizontally.
* The flow meter, which is installed near location L1, is not shown in this figure.

The second measurement location is Vuylstekeweg, which is shown in figure 7.

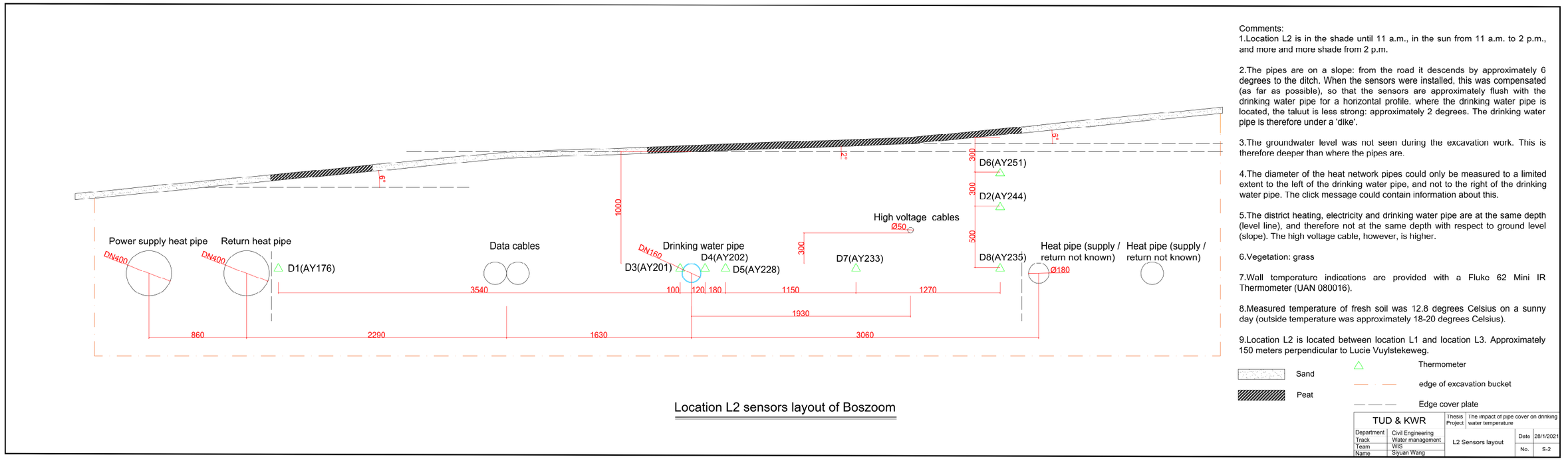


Figure 7 Technical drawing of sensors layout at and underground constructions at location L2 at Boszoom

* Figure 7 is the technical drawing of sensors layout that can show each underground element's position relationship and the actual distance between each element proportionally. More detailed information of location L2 are attached to appendix 3.
* Labels of sensor ‘D’ are presented as a diver, which can record temperature data at location L2.
* Sensors D1 to D6 are installed simultaneously, which is the same as the pipe installation depth. Sensors D6 to D8 are installed vertically at the same straight line at a depth of 110cm, 60cm and 30cm.

The third measurement location is Prinsenlaan which is shown in figure 8.

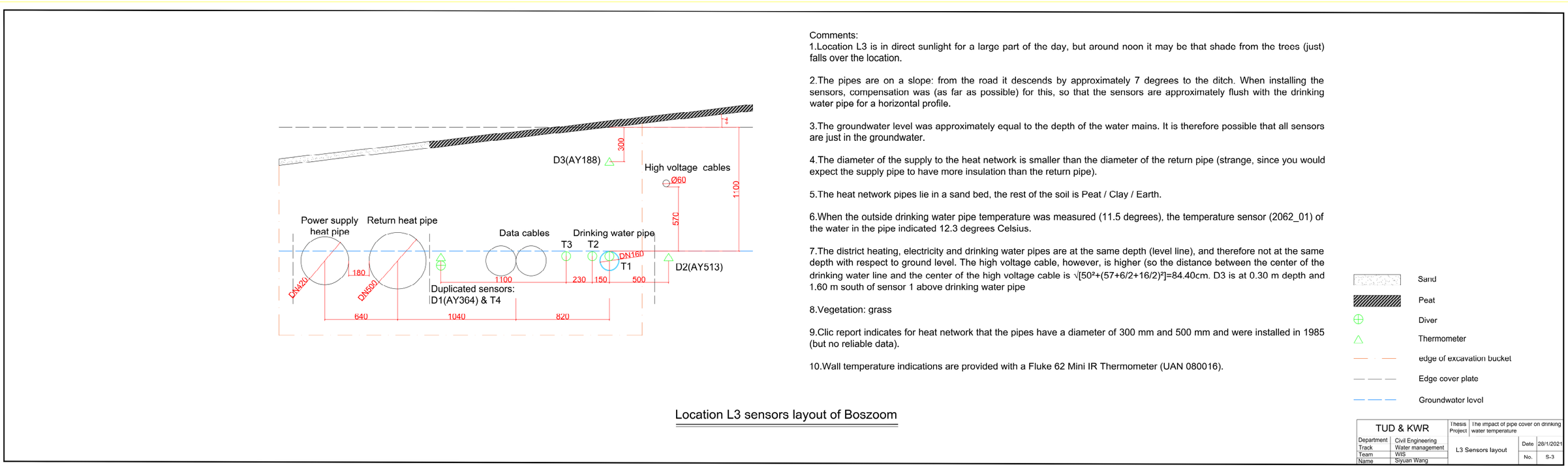


Figure 8 Technical drawing of sensors layout at and underground constructions at location L3 at Boszoom

* Figure 8 is the technical drawing of sensors layout that can show each underground element's position relationship and the actual distance between each element proportionally. More detailed information of location L3 are attached to appendix 4.
* Labels of different kinds of sensors ‘T’ and ‘D’ are presented as thermometer and diver, respectively, providing the same function as data logging at location L3.
* Sensors D1 and T4 are installed duplicated to measure the soil temperature at the same position with two types of sensors.
* Sensor D3 is not installed below the drinking water pipe. However, it is installed at a depth of 0.3m above the drinking water pipe and is about 1.80m north of sensor T1 horizontally.

3.3.3 Type of collected data

There are two kinds of sensors installed in Boszomm, shown as followings: i) For sensor ‘diver’, diver D7, D8 in location L2 and diver D2 in location L3 started collecting data from 12/05/2020, diver D3 in location L1 and diver D3 in location L3 started collecting data from 14/05/2020. Other divers started collecting from 29/04/2020. All divers stop collecting data on 03/06/2020. Diver collected data every 15 min with the accuracy of two decimal places; ii) For sensor thermometer, thermometers collected data from 12/05/2020 to 03/06/2020. However, data collected during 19/05/2020 2:00 to 19/05/2020 14:15 is lost in location L3 because of battery drain. Thermometers collected data every 15 min with the accuracy of one decimal place.

3.4 Limitation of the measurement condition

Based on the description of two measurement points shown in previous paragraphs, there are many limitations during the measurement process, which may be caused by environmental restrictions, human factors, equipment accuracy, etc. Therefore, this section provides a summarization of limitations during the measurement period.

3.4.1 In Weesperkarspel

1. There is a variable shade area at the measurement location in Weesperkarspel, as shown in appendix 1. However, it is hard to determine the impact of shade from surrounding sparse woods. Therefore, it is neglected after considering the actual condition around the measurement location.

2. During the measurement period in Weesperkarspel, the original grass cover on the measurement area had been destroyed and did not grow again. Indeed, the sensors installed under grass were actually under bare land with surrounding vegetation (grass, bush and trees). Also, the temperature under bare land may be higher than the temperature under grass cover with an insulation barrier to weaken the radiation intensity, which the soil can absorb.

3. The variation of soil moisture was not considered accurately, affecting the thermal conductivity directly. Instead, the rainfall volume is an essential factor of soil temperature, increasing soil moisture.

4. Due to the environmental restriction, the drinking water pipe installed under the tile cover is inconvenient to measure the drinking water temperature.

3.4.2 In Boszoom

1. The sensors installed at locations L1, L2 and L3 are all under a slope with different buried depths in different positions. Therefore, different thicknesses of soil cover on the sensor may lead to different absorption of solar radiation, leading to different temperature records.

2. There are two types of temperature sensors applied at location L1 and location L3 of diver (Fluke 62 Mini IR Thermometer (UAN 080016)) and thermometer with different brands, different models and different accuracy. The precision of the thermometer is one decimal place and two decimal places for the diver. Although diver and thermometer are regarded as the same sensor for temperature measurement, they would cause deviation because of their different mechanisms.

3. The measurement periods of divers and thermometers are not the same. Therefore, the overlapping period is preferable to analyze.

4. Data recorded by four thermometers at location L3 had been missed due to battery drain during 2020/05/19 2:00 to 2020/05/19 14:15. Section 3.4 provides the incoherent data.

In summary, both Weesperkarspel and Boszoom measurements would destroy the original soil structure, which may also cause deviation.

3.5 Impact factors on drinking water temperature

In this section, different kinds of impact factors will be discussed, and the influence level of each factor will be summarized

and quantified by comparing temperature data collected by sensors in different positions, which can also prepare for model simulation in the next chapter.

3.5.1 The variation of soil temperature in different depth

Before explaining different impact factors on DWT and soil temperature, variation of the soil temperature along the depth will be discussed as the start. Then, in order to summarize the pattern of temperature difference at different covers, sensors of 1st column are chosen to visualize the data and shown in figure 9.

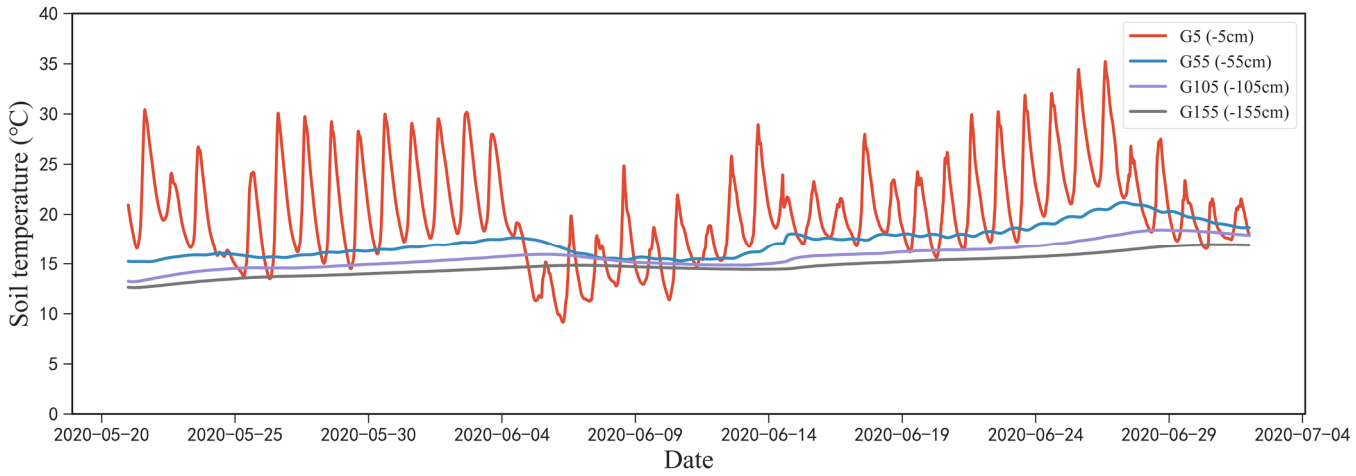


Figure 9 Comparison of soil temperature recorded by sensor G5, G55, G105, G155

It can be observed by comparing the soil temperature at different depths (red polyline). For deeper soil temperature, the trend lines of Sensor G55, G105 and G155 become more and more stable as depth increases. Variation of deeper soil temperature with air temperature is not evident compared with soil temperature at a depth of 5cm.

Table 2 Variance and average of soil temperature recorded by sensor G5, G55, G105, G155 at Weesperkarspel

Location	G5	G55	G105	G155
Average (°C)	20.1	17.3	15.8	14.8
Variance (°C)	21.4	2.5	1.6	1.1

* The value of variance and average is calculated with the soil temperature data measured during the period of 21/05/2020 ~01/07/2020

Table 2 shows the variance and average value of soil temperature recorded by sensor G5, G55, G105, and G155 during measurement period of 21/05/2020 ~01/07/2020 (at a depth of 5cm, 55cm, 105cm and 155cm). It can be determined that the average temperature during the measurement period becomes smaller and smaller with the depth increasing, which means that the soil temperature decreases with depth increasing in the range of 0-155cm. Similarly, variance becomes smaller and smaller with depth increasing, which means that the soil temperature becomes more and more stable with deeper depth and less and less sensitive to variation of air temperature above the soil surface. As a result, the annual amplitude of soil temperature decreases with the depth increasing. In high latitude areas, the annual amplitude disappears at a depth of 20-25 m, disappearance occurs in mid-latitude areas at a depth of 15-20 m, and low latitude areas are 5-10 m. Below these depths, the temperature change is too small to detect, so it is called a constant layer of soil temperature. Similarly, in the annual variation of soil temperature, the time of occurrence of the highest and lowest temperature lags with the depth increasing. As the depth increases by 1 m, the lag time increases by about 20 to 30 days (Zheng, 1989).

3.5.2 Different cover types

Based on the environment of two measurement areas in Weesperkarspel and Boszoom, it can be found that the measurement area in Boszoom has complicated underground constructions with sand and peats cover, which is difficult to rule out the interference of other factors and only analyze for different types of cover materials. In comparison, measurement data from Weesperkarspel is more suitable for analyzing the influence level of different impact factors from the point of different pipe covers.

Data classification should be done before the data processing. As in Weesperkarpel, there are 16 sensors installed in 4

columns, and each column represents a cover type as shown in table 3, which corresponds to figure 4.

Table 3 Classification of different cover types at Weesperkarspel

	cover type	Distance from boundary*
Column G	Complete under grass	238cm
Column GT	Under grass near tile	48cm
Column TG	Under tile near grass	67cm
Column T	Complete under tile	257cm

* Distance from boundary means that the horizontal distance between sensor to the boundary of grass and tile cover.

Figure 4 shows that the drinking water pipe installed next to the data cable at a depth between 105cm and 155cm. Indeed, the analysis will concentrate on the soil temperature data at a depth of 105cm and 155cm. In addition, based on the data from KWR, the range of pipe installation depth is generally between 1.00m and 1.10m in the Netherlands. Hence, it is preferable to focus on the soil temperature data at a depth of 105cm which is closer to the general pipe installation depth in the Netherlands.

The cover type of 'complete under tile', which is most common in urban areas as paved streets, is chosen as the reference and standard cover type. The temperature difference between cover types of 'complete under tile (Column T)' and 'complete under grass (Column G)', 'under grass near tile (Column GT)', 'under tile near grass (Column TG)' will be calculated separately to determine the influence level of different cover types.

Table 4 Temperature difference between column G and T at the depth of 105cm and 155cm in whole measurement period at Weesperkarspel

Period	Type	D_T105 - G105 (℃)	D_T155 - G155 (℃)
	Depth	105cm	155cm
21/05 ~ 01/07	min	3.0	2.5
	max	5.2	3.6
	average	4.1	3.0

* 'D' means 'difference'; 'D_T105 - G105' means the difference between sensor T105 and sensor G105.
* The min, max and average value are calculated from the data recorded by sensor T105, G105, T155, G155 at Weesperkarspel during the period of 21/05/2020~01/07/2020.

After combining the temperature difference between the first column and fourth column at depths of 105cm and 155cm in the whole measurement period, as shown in table 4, it can be concluded that the soil temperature with the cover of 'complete under tile' is about 4.1℃ higher than with the cover of 'complete under grass' at a depth of 105cm and about 3.0℃ higher at a depth of 155cm. In addition, the distance between the measurement of 'complete under tile' and 'complete under grass' is 495cm.

The temperature difference between the cover type of 'complete under tile' and 'under grass near tile', 'under tile near grass' can be calculated in the same way. The result is shown in table 5 and 6, respectively.

Table 5 Temperature difference between column GT and T at the depth of 105cm and 155cm in whole measurement period at Weesperkarsepel

Period	Type	D_T105 - GT105 (℃)	D_T155 - GT155 (℃)
	Depth	105cm	155cm
21/05 ~ 01/07	min	1.0	0.6
	max	2.6	1.6
	average	1.8	1.1

* 'D' means 'difference'; 'D_T105 - GT105' means the difference between sensor T105 and sensor GT105.
* The min, max and average value are calculated from the data recorded by sensor T105, GT105, T155, GT155 at Weesperkarspel during the period of 21/05/2020~01/07/2020.

Soil temperature with the cover of 'complete under tile' is about 1.8℃ higher than 'under grass near tile' at a depth of 105cm. As for the depth of 155cm, the soil temperature of 'complete under tile' is 1.1℃ higher than 'under grass near tile'. The distance between the measurement of 'complete under tile' and 'under grass near tile' is 305cm;

Table 6 Temperature difference between column TG and column T at the depth of 105cm and 155cm in whole measurement period at Weesperkarsepel

Period	Type	D_T105 - TG105 (℃)	D_T155 - TG155 (℃)
	Depth	105cm	155cm
21/05 ~ 01/07	min	-0.2	-0.1
	max	1.1	1.1
	average	0.4	0.4

* 'D' means 'difference'; 'D_T105 - TG105' means the difference between sensor T105 and sensor TG105.
* The min, max and average value are calculated from the data recorded by sensor T105, TG105, T155, TG155 at Weesperkarspel during the period of 21/05/2020~01/07/2020.

Soil temperature with the cover of 'complete under tile' is about 0.4℃ higher than 'under grass near tile' at a depth of 105cm. As for the depth of 155cm, the soil temperature of 'complete under tile' is also 0.4℃ higher than 'under grass near tile'. The distance between the measurement of 'complete under tile' and 'under grass near tile' is 190cm;

It is also necessary to consider the standard of how we can determine which DWDS pipelines are under which kinds of cover. For that, the horizontal distance between each column of sensors and the boundary can be used to estimate the effective range of each cover type. As shown in figure 4, the horizontal distance between the first column and boundary is 238cm, and for the fourth column is 257cm. Therefore, it can be estimated that a DWDS pipeline is determined as 'complete under grass' or 'complete under tile' should reach the requirement that there is grass or tile cover within a radius of at least about 2.0m based on the pipeline shown in appendix 5.

In the same way, the horizontal distance between the second column and boundary is 48cm and between the third column and boundary is 67cm. Hence, it can be estimated that a DWDS pipeline is determined as 'under grass near tile' or 'under tile near grass' should reach the requirement that there is grass or tile cover within a radius in the range of 0.5m to 1.0m based on the pipeline as shown in appendix 6.

Ultimately, considering both the influence level of different cover types in Celsius degree and their effective range, the conclusion of the influence level of different covers can be summarized in table 7.

Table 7 Influence level of different cover type at the depth of 105cm

Classification	Effect on temperature	Sphere of influence
complete under tile	Standard T_soil	R≥2m
complete under grass	-3.0~4.1℃	R≥2m
under grass near tile	-1.1~1.8℃	0.5m≤R≤1m
under tile near grass	-0.4℃	0.5m≤R≤1m

3.5.3 Shade

Due to the limitation of collected data, it is hard to summarize the impact of shade on soil temperature because of the variation of shade area both in Weesperkarspel and Boszoom. Indeed, obtained the information of 'shade from surrounding trees may lead to ca 1-1.5 °C lower temperatures in the soil at about 1 m depth' in the the report of Effectiveness of measures against heating drinking water in pipes (Dutch: Effectiviteit maatregelen tegen opwarming drinkwater in leidingen). Therefore, the influence level of shade compared with the unshaded area is -1~1.5℃ for both grass cover area and tile cover area.

The influence level of shade could be varied because the shaded area caused by surrounding trees and buildings will vary with the direction of solar radiation.

3.5.4 District heating network pipe

The impact of district heating network pipe on DWT and soil temperature can be observed from the data collected at locations L1, L2 and L3 in the measurement area of Boszoom.

The prerequisite is that the installation depth of the district heating network pipe is the same as the installation depth of the

drinking water pipe at a depth of 110cm, which may be different in some actual circumstances.

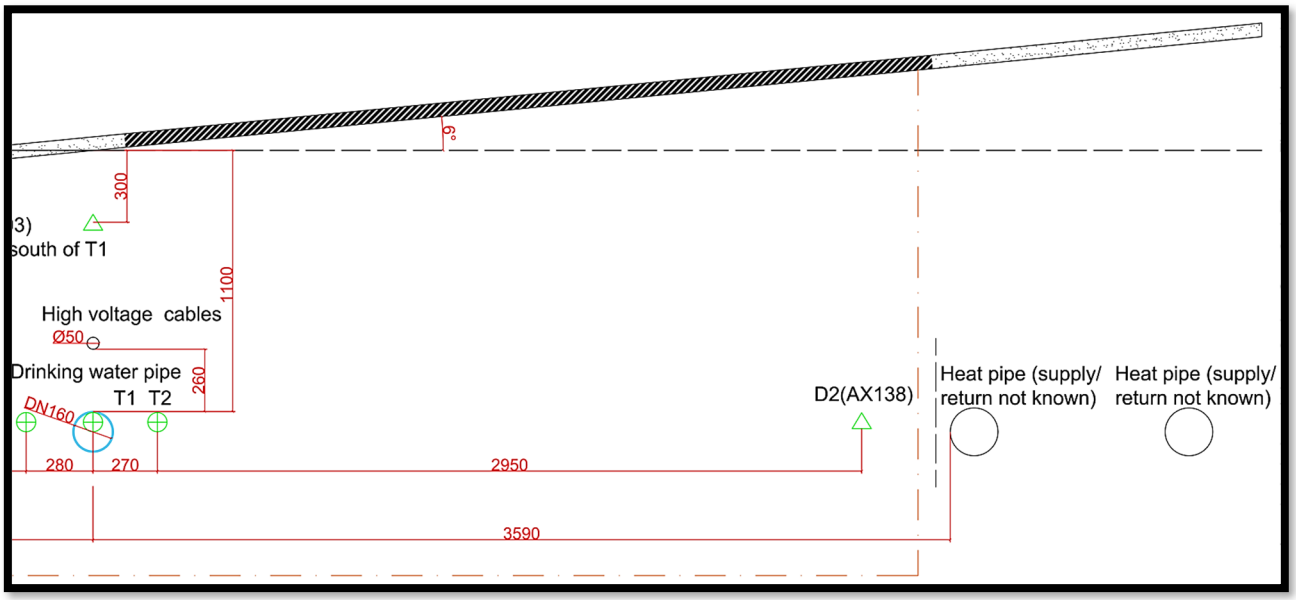


Figure 10 Right part of section view of measurement area at location L1 in Boszzom

Figure 10 shows the section view of the actual position relationship in part of location L1. There are district heating pipes at each side of the DWDS pipeline. However, there is no sensor near the left heat pipe. The distance between the closest sensor (D1) and the wall of the left heat pipe is about 2m which is too far to analyze the impact of heat pipes.

Instead, figure 10 shows the circumstance of the right side at location L1 in Boszoom. The distance between the closest sensor (D2) and the wall of the heat pipes is about 37cm, which is appropriate to analyze the impact of the heat pipe. Furthermore, there are no any obstacles between the heating pipe on the right and drinking water pipe except for sensor T2 and D2. Therefore, sensor T1, T2 and D2 are chosen as the target sensor for data analysis, as shown in figure 10. Sensor T1 represents the DWT, sensor T2 represents the soil temperature around the pipe (the distance between sensor T2 and DWDS pipe wall is only 19cm), D2 means the soil temperature affected by the district heating pipe. It can be obtained from figure 6 that the distances between the heat pipe wall and sensor D2, T2, T1 are 37cm, 332cm, 359cm, respectively. In addition, both the distance between the heat pipe wall and sensor T1, T2 are longer than 3 meters, which can assume that the heat pipe does not affect sensor T1 and T2.

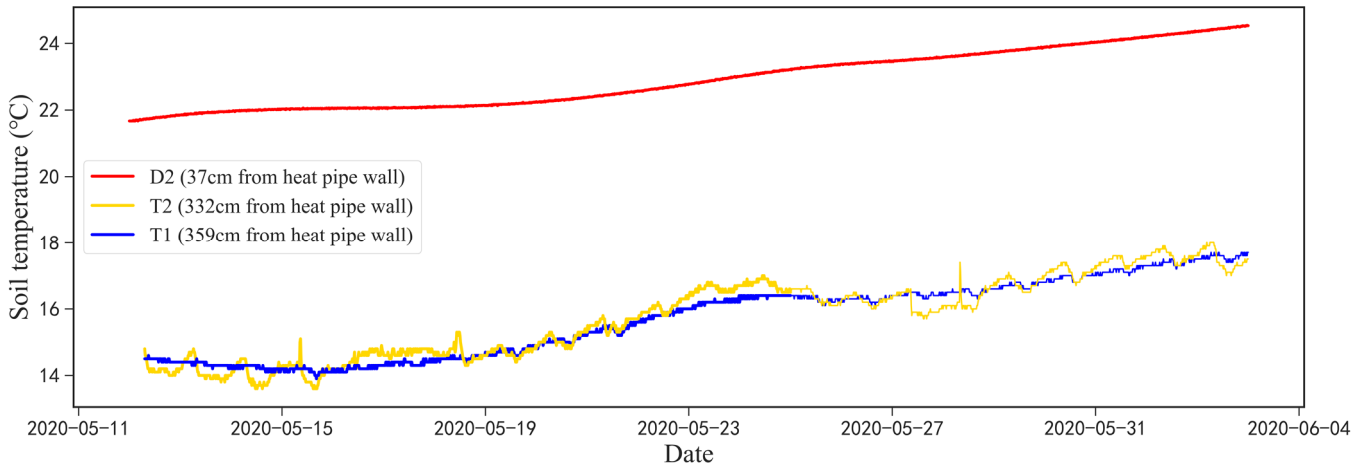


Figure 11 Measurement data of sensor T1, T2 and D2 at location L1 in Boszoom from 2020/05/12 to 2020/0603

Figure 11 shows the temperature change with an upward trend collected by sensor T1, T2 and D2 at location L1 in Boszoom from 2020/05/12 to 2020/06/03. It can be found that the soil temperature around the heat pipe (sensor D2) is much higher than DWT (sensor T1) and soil temperature around the drinking water pipe (sensor T2). The DWT in the drinking water pipe (sensor T1) is almost the same as the soil temperature around the drinking water pipe (sensor T2). The fluctuation of soil temperature around heat pipe (sensor D2) is more evident than DWT (sensor T1), which can be explained that the heat

capacity of soil is smaller than water. Hence, the soil is easier to increase or decrease its temperature with the same volume of heat absorption.

Table 8 Temperature difference between sensor T1, T2 and D2 at location L1 in Boszoom

	D_D2-T1 (℃)	D_D2-T2 (℃)	D_T2-T1 (℃)
distance	322cm	295cm	27cm
Max	8.1	8.5	0.90
Min	6.2	6.1	-0.90
average	7.2	7.2	0.1

* 'D' means 'difference'; 'D_D2-T1' means the difference between sensor D2 and sensor T1.
* The min, max and average value are calculated from the data recorded by sensor D2, T1, T2 at test location L1 in Boszoom during the period of 12/05/2020~03/06/2020.

Table 8 provides the maximum, minimum and average difference between D2 and T1, D2 and T2, T1 and T2 during the period of 12/05/2020~03/06/2020. The average difference between DWT (sensor T1) and soil temperature around drinking water pipe (sensor T2) is only 0.1℃, which can be assumed to be almost the same. Hence, it can be concluded that the influence level of the heat pipe can increase the soil temperature by around 6.1℃~8.5℃ (by taking the limit value) with the distance from the heat pipe wall of about 37cm. Furthermore, the diameter of the two heat pipes and the distance between these two pipes and the function (supply or return) are unknown.

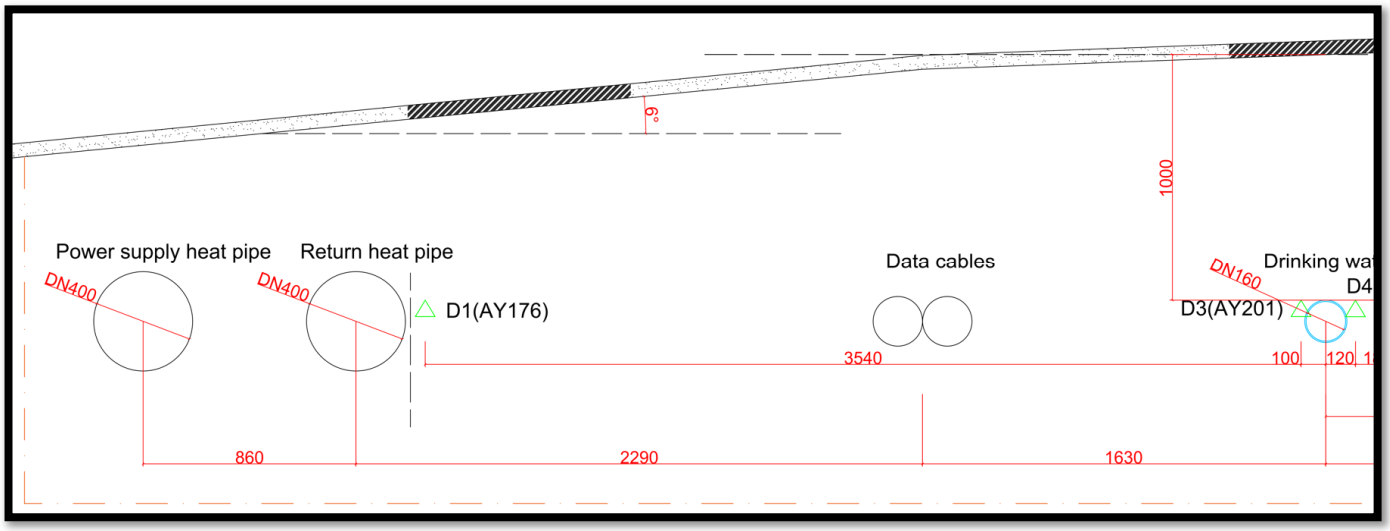


Figure 12 Section view on the left side at location L2 in Boszzom

Moreover, figure 12 shows the section view of the position relationship in part of location L2. There are district heating pipes at each side of the DWDS pipeline. Due to a high voltage cable on the right side of location L2 at Boszoom, the analysis only focuses on the left side. The high voltage cable can affect the sensors on the right side more or less. Indeed, the discussion of the influence of heat pipes on soil temperature will only consider the left side of location L2 at Boszoom.

Figure 12 shows the distance between the closest sensor (D1) and the wall of the left heat pipe is about 28cm which is appropriate to analyze the impact of the heat pipe. There are two data cables. It can be assumed that no heat emission from it, between heat pipe on and drinking water pipe except for sensor D1 and D3. Therefore, sensor D1 and D3 are chosen as the target sensor for data analysis as shown in figure 12. Sensor D3, which is only 2cm from the DWDS pipe wall, represents the soil temperature around the pipe. Moreover, sensor D1 represents the soil temperature affected by district heating pipes. It can be obtained from the figure that the distances between the heat pipe wall and D1, D3 are 28cm, 364cm, respectively. In addition, the distance between the heat pipe wall and D3 is longer than 3 meters, which can assume that the heat pipe does not affect sensor D3.

The methods used to analyze the data collected by sensor D1 and D3 will be the same as the method used in section 3.4.4.1. The result of figure 'Measurement data of sensor D1 and D3 at location L2 in Boszoom from 2020/05/12 to 2020/0603' and table 'Temperature difference between sensor D1 and D3 at location L2 in Boszoom' are presented in appendix 7.

In conclusion, the influence level of the heat pipe can increase the soil temperature by around 7.1~7.8℃ with a distance

from the heat pipe wall of about 28cm. Furthermore, the diameter of both two heat pipes on the left is 400mm with a distance of 46cm (wall to wall), and the heat pipe, which is closer to sensor D1, is a return heat pipe. The other one is a supply heat pipe.

As for location L3, it has a compact layout between sensors, different cables and pipes presented in figure 8. Therefore, the influence of heat pipe can be determined by comparing the temperature difference between sensor D1(or T4) and sensor T1(or T2) theoretically. However, some disturbing factors could influence the comparison result. The first reason is that the distance between the wall of the return heat pipe and the wall of the drinking water pipe is only 153cm. Hence, it cannot be determined if the heat pipe does not influence the temperature in or around the drinking water pipe. The second reason is that the groundwater level at location L3 is almost the same as the installation depth of the drinking water pipe, and the sensors were submerged by groundwater. Therefore, the high groundwater level may lead to lower soil temperature than regular soil without the water submerged. Indeed, location L3 will not be used as a target point to analyze the impact of heat pipe on DWT or soil temperature around DWDS pipe.

Conclusively, the influence level of heat pipe on soil temperature can be summarized by combining the three temperature ranges as shown in table 9.

Table 9 The influence level of heat pipe corresponds to different distance

distance from heat pipe (cm)	influence level (℃)	Location
37	6.1~8.5	L1
28	7.1~7.8	L2

3.5.5 Groundwater level

The impact of groundwater level on DWT and soil temperature can be estimated from the data collected at location L3 in the measurement area of Boszoom. However, the groundwater level at a depth of 1.10m only happened in location L3, which cannot compare with other data, so that it can only be estimated roughly.

In order to estimate the influence level of groundwater level at a depth of 1.10m, two sensors are chosen with similar conditions except for the appearance of groundwater to compare their difference: sensor D7 in location L2 and sensor T3 in location L3. Table 10 shows the condition of the relative position of each sensor with surrounding stuff

Table 10 The condition of the relative position of sensor D7 (location L2) and T3 (location L3)

	distance from wall high voltage cable (cm)	distance from heat pipe (cm)
D7 (Location L2)	56.6	152
T3 (Location L3)	86.5	146

* The detailed information of the relative position of sensor D7 (location L2) and sensor T3 (location L3) is presented in figure 7 and 8, respectively

Table 11 Temperature difference between D7 (location L2) and sensor T3 (location L3)

Period	Type	D_D7-T3 (℃)
12/05~03/06	**Max**	2.3
	Min	1.1
	Average	1.7

* 'D' means 'difference'; 'D_D7-T3' means the difference between sensor D7 and sensor T3.
* The data during 2020/05/09 2:00 and 2020/05/09 14:15 is absent because of battery drain of sensor T3 (location L3).
* The min, max and average value are calculated from the data recorded by sensor D7 at test location L2 and T3 at test location L3 in Boszoom during the period of 12/05/2020~03/06/2020.

In summary, it can be estimated that the groundwater level at a depth of 1.10m can decrease the soil temperature by 1.1~2.3℃ at the same depth of soil. However, the estimated range is not accurate enough, with a more significant distance between sensor T3 to voltage cable than sensor D7. Also, the formats of high voltage cable and heat pipe are not the same. Also, groundwater level increases and is higher than the depth of 1.10m which often occurs in the Netherlands. Therefore, the soil moisture will increase, and the thermal conduction will decrease, lowering the soil temperature by more than 1.1~2.3℃.

3.6 Chapter discussion

Classifying the impact factors provides systematic thinking to analyze the cause of DWT variation in this chapter. However, this chapter only states and analyzes different impact factors horizontally. The vertical analysis on each factor is still absent. With further research, vertical analysis of each impact factor on DWT will become more and more detailed.

Based on our findings, it remains drawbacks and challenges during the research process. In data measurement and collection, the measurement of soil temperature and DWT with different impact factors is not continuous and systematic. In this chapter, the influence level of district heat pipe on soil temperature and DWT are only measured in specific distances. Therefore, it cannot be summarized as a linearized correlation between the influence level of pipe water and the distance between district pipe and DWDS pipe. It is also similar to the influence level of groundwater level, which is at a depth of around 1.0~1.1m, which cannot be generalized as the influence level of different groundwater levels. Similarly, it is also available to research on the relation between heat emission and heating pipe diameter. It can provide deeper understanding on the impact of heating pipe on surrounding soil temperature, which can influence the DWT near it. Therefore, the incoherent measurement of DWT with different impact factors may affect the model's accuracy during the calibration process.

3.7 Chapter summary

Chapter 3 mainly presents the detailed information of two parts: i) The measuring condition of Weesperkarpel and Boszoom, including the location, measuring period, pipe cover type, sensor layout, and related impact factors from surrounding infrastructures the measurement area. ii) The analysis of influence level of different impact factors from the data collected in two measurement areas.

There are five kinds of impact factors on DWT, different depth, different pipe cover material, shade, district heating pipe and groundwater level. In the range of about 0-1.5m depth, the deeper the depth, the lower the soil temperature. However, the different depths will not be mainly considered in actual circumstances because the pipe installation depth in the Netherlands is at a depth of 1.00m~1.10m which is a relatively fixed range. Hence, more attention will be paid to different pipe/soil cover types and other related impact factors like underground infrastructure, groundwater level and shade.

- Therefore, compared with the soil temperature under the tile cover, it can be summarized as follows:
  - The soil temperature complete under grass is about 3.0~4.1℃ lower than complete under tile;
  - The soil temperature under grass near tile is 1.1~1.8℃ lower than complete under tile;
  - The soil temperature under tile near grass is 0.4℃ lower than complete under tile.

- The impact of district heating pipe on soil temperature is about 6.1~8.5℃ higher than without impact of heating pipe. In addition, the scope of influence is about 0.3~0.4m around the district heating pipe.

- Shade from surrounding trees may lead to about 1-1.5 °C lower temperatures in the soil at about 1 m depth.

- Groundwater with the same level of pipe installation depth (at a depth of around 1.1m) can lead to a 1.1~2.6℃ lower soil temperature compared without the impact of groundwater.

The value of each influence level of different impact factors will be an essential reference for simulating water temperature in the simulation model. Additionally, the range of each factor is not constant. It should be determined with actual circumstances in different regions.

Chapter 4 Water temperature simulation in drinking water distribution system

In order to cope with the high-water temperature in extreme conditions with global warming progress, it is necessary to construct a framework with water temperature prediction and the early-warning system. As the core of water temperature prediction and early-warning system, the water temperature simulation model should be calibrated with local conditions of different cities, and the accuracy of the model should be verified. Therefore, Chapter 4 will solve the second key question of the feasibility of the water temperature simulation model in six sections. Section 4.1 introduces the framework of the water temperature simulation model developed by the KWR Water Research Institute. Section 4.2 illustrates the contribution of the simulation model to predicting water temperature, which can help readers understand the water temperature simulation system. Section 4.3 states the calibration process for Almere, a city in the Netherlands, with the main idea and process of calibration from the writer's thought and the function of the simulation model. Hence, analysis of simulation should be done after calibration in section 4.4. Section 4,5 will discuss additional explanations of unexplained points (fitting points that do not match well). It will also list some possible reasons for these unexplained points and the suggestion of model development in the future. Finally, the chapter conclusion section 4.6 will present the chapter summary.

4.1 The framework of the simulation model

As an introduction of the impact of soil on water temperature in section 3.1, it is clear that the temperature change of drinking water is determined by the surrounding soil temperature of the drinking water pipe. Hence, the temperature variation process of drinking water can be divided into three different heat transfer processes (Blokker and Pieterse-Quirijns., 2013) as follows.

- Heat conductive process from the outer pipe wall to the inner pipe wall;
- Heat convective process of the flowing water inside the pipe;
- Heat convective process outside the pipe.

In addition, the boundary condition for the heat transfer can be determined as soil temperature around the pipe. Thus, it is from the surrounding soil of the pipe to the water inside, like mentioned in section 3.1.

Therefore, the water temperature of different pipe segments can be calculated theoretically as the sum of original water temperature, which is the temperature of inflow of the pipe segment, and the temperature variation (increase or decrease) caused by the three thermal conduction processes. The heat transfer process also shows that it is feasible to simulate the DWT in a simulation model.

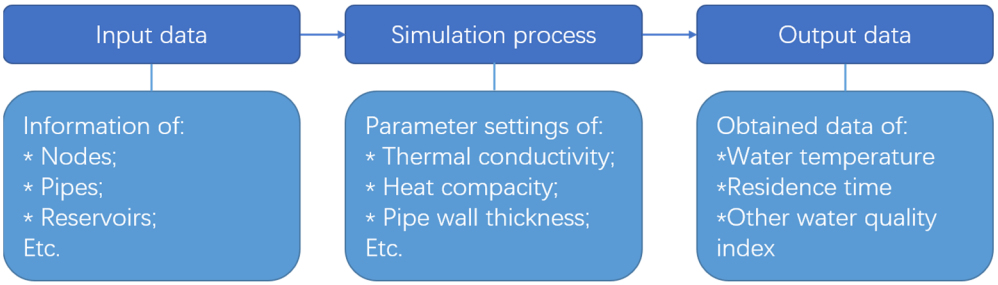


Figure 13 Steps of water temperature simulation

Figure 13 presents the steps of water temperature simulation. First, we import input data with the information of DWDS like the demand of each node, length of each pipe segment. Then, operating the simulation model, which includes calculating DWT in each node and pipe, with the input file. Finally, the output data of DWT and other water quality indexes will be collected for further analysis.

4.1.1 Building equations

The instantaneous change of DWT can be described as the difference between water temperature and the temperature of the surrounding environment. The thermal energy balance equation can be presented as (Zlatanovic et al. 2017):

$$E_{T,t+\Delta t} - E_{T,t} = \Delta E_T \quad (1)$$

Where:

$E_{T,t+\Delta t}$——The amount of thermal energy in the given volume at time t;
$E_{T,t}$—— The amount of thermal energy in the given volume at time t+Δt;
ΔE_T——The change of thermal energy in the given volume over the time interval Δt.

Therefore, the differential equation of temperature change can be built by introducing the parameter of water volume and physical properties of water:

$$\frac{dT_{water}}{dt} = \frac{4h_{total}}{\rho_{water} C_{p,water} d_{pipe}} (T_{outer\ wall} - T_{water}) \quad (2)$$

Where:

T_{water}——the actual temperature of water [K];
$T_{outer\ wall}$——the temperature of the outer wall of drinking water pipe (surrounding environment) [K];
$C_{p,water}$——specific heat capacity of water [J/(kg×K)];
ρ_{water}——density of water [m3/kg];
d_{pipe}——pipe diameter [m];
h_{total}——the overall heat transfer coefficient [W/(m2×K)];

The overall heat transfer coefficient can be calculated by integrating the three different heat transfer processes introduced above: i) conductive process from the outer pipe wall to the inner pipe wall; ii) convective process of the flowing water inside; iii) convective process outside the pipe. The overall heat transfer coefficient, which is closely related to the thermal resistance process, can be determined as (Zlatanovic et al. 2017):

$$h_{total} = \frac{1}{\frac{1}{h_{water}} + \frac{1}{h_{pipe}} + \frac{1}{h_{soil}}} \quad (3)$$

In this equation (Çengel, 2020):

h_{water}—— heat transfer coefficient of water, which represents the inner part of pipe [W/(m2×K)];
h_{pipe}—— heat transfer coefficient of pipe, which represents the wall of pipe [W/(m2×K)];
h_{soil}—— heat transfer coefficient of soil, which represents the surrounding environment of pipe [W/(m2×K)];

The heat transfer coefficient for the water in the pipe can be calculated as:

$$h_{water} = \frac{Nu_{water} \lambda_{water}}{d_{pipe}} \quad (4)$$

Where:

Nu_{water}——Nusselt number for water (Nu; Janssen & Warmoeskerken 1991; Earle, 2013);
λ_{water}——thermal conductivity of water [W/(m×K)].

The value of Nusselt number, shown in table 12, highly depends on the liquid flow conditions (stagnant, laminar or turbulent) (Nu; Janssen & Warmoeskerken 1991; Earle, 2013).

Table 12 Changes of Nusselt number

Flow condition	Reynolds number*	Nusselt number
stagnant	Re≤10	5.8
laminar	10<Re≤2300	3.66
turbulent	Re>2300	0.023Re0.8Pr1/3

* The Reynolds number corresponds to flow condition applies to flow in the pressure pipe;
* Pr is Prandtl number.

The heat transfer coefficient for pipe wall can be calculated as:

$$h_{pipe} = \frac{2\lambda_{pipe}}{d_{pipe} \times \ln\left(\frac{d_{outer\ pipe}}{d_{pipe}}\right)} \quad (5)$$

Where:

$d_{outer\ pipe} = d_{pipe} + pipe\ wall\ ratio \times d_{pipe}$, which is the outer diameter of the drinking water pipe (m);
λ_{pipe}—— thermal conductivity of pipe wall which depends on pipe materials [W/(m×K)].

The heat transfer coefficient for surrounding soil can be calculated as:

$$h_{soil} = \frac{2\lambda_{soil}}{d_{pipe} \times \ln\left(\frac{d_{outer\ pipe\ with\ soil\ layer}}{d_{outer\ pipe}}\right)} \quad (6)$$

Where:

$d_{outer\ pipe\ with\ soil\ layer} = d_{outer\ pipe} + 2 \times thickness\ of\ penetration\ layer$, $thickness\ of\ penetration\ layer$ means that the penetration depth into the soil where DWT influences the soil temperature;
λ_{soil}—— thermal conductivity of soil depends on soil types [W/(m×K)].

Substituting equations (4), (5) and (6) in equation (3), it can end up with equation (7):

$$h_{total} = \frac{1}{d_{pipe} \times \left[\frac{1}{Nu_{water}\lambda_{water}} + \frac{ln\left(\frac{d_{outer\ pipe}}{d_{pipe}}\right)}{2\lambda_{pipe}} + \frac{ln\left(\frac{d_{outer\ pipe\ with\ soil\ layer}}{d_{outer\ pipe}}\right)}{2\lambda_{soil}}\right]} \quad (7)$$

Subsequently, substituting equation (7) in equation (2), the final equation for DWT change can be put in EPANET multispecies extension (EPANET-MSX; Shang et al., 2008) with the boundary conditions of $T_{water}(t = 0) = T_{water,0}$ and $T_{water}(t = \infty) = T_{outer\ wall}$.

4.1.2 Input file

EPANET can export the input file of the DWT simulation model with the '*.inp' file, which includes the detailed information of the DWDS network. This kind of information is indispensable for simulating DWT in the model. Table 13 presents the needed information for the input file.

Table 13 Information of input file

Infrastructure	Parameters
Junctions	ID, Elevation, Demand, Demand pattern
Reservoirs	ID, Head, Demand Pattern
Tanks	Elevation, Initial Level, Minimum Level, Maximum Level, Diameter, Minimum Volume, Minimum Volume, Volume Curve, Overflow
Pipes	ID, Start Node, End Node, Length, Diameter, Roughness, Minor loss, Status (Open/Close)
Pumps	ID, Start Node, End Node, Parameters
Valves	ID, Start Node, End Node, Parameters, Type, Setting, Minorloss
Tags	/
Demands	Junction, Demand, Pattern, Category
Status	ID, Status/Setting
Pattern	ID, Multipliers
Curves	ID, X-value, Y-Value
Controls	/

4.1.3 Operation file of water quality (water temperature)

The operation file of the water simulation is built based on the frame of EPANET-MSX, which is an extension to the original EPANET. EPANET-MSX allows it to model any system of multiple and interacting chemical species, including the index of water temperature, microorganisms and related parameters.

Put equation (2) into the EPANET-MSX by setting the parameters of thermal conductivity coefficient of water, pipe wall and surrounding soil and constants like water density, specific heat capacity. Based on the division of different sections in the EPANET multi-species extension user's manual (Shang et al., 2008), table 14 shows the section keywords of the EPANET-MSX file and the detailed information of parameter setting will be presented in appendix 8.

Table 14 Section keywords of EPANET-MSX file

Type	Description
[TITLE]	Adds a descriptive title to the data set
[OPTIONS]	Sets the values of computational options
[SPECIES]	Names the chemical species being analyzed
[COEFFICIENTS]	Names the parameters and constants used in chemical rate and equilibrium expressions
[TERMS]	Defines intermediate terms used in chemical rate and equilibrium expressions
[PIPES]	Supplies the rate and equilibrium expressions that govern species dynamics in pipes
[QUALITY]	Supplies initial conditions for selected species throughout the network
[PARAMETERS]	Allows parameter values to be assigned on a pipe-by-pipe basis
[REPORT]	Specifies reporting options

4.1.4 Output file

The output file of the DWT simulation model can be exported as '*. rpt' file including the selected species for all (or parts) of links and nodes, enacted in the [REPORT] section introduced in the above part.

4.2 The contribution of the simulation model to applying in the real circumstance

The constructed simulation model framework is valuable to apply in actual circumstance, divided into two parts: i) Engineering field; ii) Research field.

With the global warming trend, the crisis of high DWT, especially in countries with high temperatures all year round, will inevitably happen and more frequently. The appearance of water quality deterioration will be followed by high DWT, explained in section 1.1. In order to cope with the circumstance, it is necessary to predict the occurrence point or area of high DWT first and then decrease DWT. Therefore, the water temperature simulation model can help predict the occurrence area of high DWT combined with the weather forecast data. It will allow enough time for implementing measures to cope with the occasional crisis of high DWT, e.g., increase soil moisture to decrease the temperature of soil contacted with DWDS pipe, notify people by media to boil water instead of drinking tap water directly. For continuing crisis, replacing the pipe cover material can solve it, like changing tile cover to grass or pervious paving material, explained in section 5. The above statement is for avoiding high DWT in existed systems, and as for DWDS construction in the planning and design stage, simulating the DWT temperature with the design parameters of DWDS before the construction phase can help designers and engineers to find the area with the potential crisis of high DWT. After then, make some adjustments on the pipe cover materials in the area with potential risk to control and decrease the water temperature under the standard value. In summary, these are two main applications in the engineering field.

The simulation model is also instrumental in the research field. As for research on the distribution of microorganisms, which is sensitive to temperature variation, in DWDS pipes, the simulation model can be used for preliminary selection of target pipe for water sampling. Select pipes or nodes with high and low temperatures based on the simulation result and sample water in these pipes and nodes for further analysis. It is more convenient and time-saving to find target pipes instead of measuring the water temperature manually. In addition, although some areas have installed the thermometers in DWDS, it is almost impossible to monitor the DWT of all pipes based on consideration of cost and maintenance. Furthermore, it can also introduce some parameters about microorganisms and chemical elements, which can be simulated with DWT simultaneously and helpful for observing the change of water quality with DWT variation.

In summary, the simulation model can be expanded to be a multifunction model which can provide an integrated water quality index to adapt to the further requirement of drinking water quality.

4.3 Calibration methodology

After comprehending the mechanism of the DWT simulation model, the model application test will be provided in this section in order to present the model calibration process under the framework of model temperature.

4.3.1 Calibration approach

The method of 'trial and error' was implemented in the model calibration process, a manual approach and a fundamental problem-solving method (Campbell, 1960). It consists of repeating, varying attempts which are continued until success.

The measurement used for calibration is the DWT, measured at some points in the test area. The calibration parameter is the pipe wall temperature (T_{soil}), assumed that same as the surrounding soil temperature of DWDS pipelines. The simulated DWT can be obtained by modelling with the pipe wall temperature. Finally, it can assess the performance of the DWT simulation model by comparing measured and simulated DWT values at specific points.

4.3.2 Main idea of calibration

The model calibration is mainly for configuring the model to be more closed with actual circumstances. Complete calibration can make the difference between simulation results and measurement results smaller and smaller or even the same.

The model calibration for the teat area will be concentrated into measurement points. For calibration, each pipe should be observed and analyzed with the following four aspects.

- Which kind of pipe cover type does each pipe have?
- Is it affected by shade from surrounding trees or buildings?
- Is it affected by district heating pipes?
- Is it affected by groundwater level?

These four aspects of different impact factors on DWT, which have been analyzed with each influence level in chapter 3, composes the judgment standard for the parameter setting of each pipe.

As for the influence level of each impact factor is summarized as a range, it is available to choose any value in the range for pipe wall temperature setting (T_{soil}) theoretically, and the calibration process will mainly depend on modification of pipe wall temperature setting (T_{soil}). The combination of effects of different factors is calculated by the accumulation method. For instance, soil temperature at a depth of 1.10m to 1.20m is 20℃ under tile cover without any shade, district heating pipe and groundwater effect. A DWDS pipe, which includes a measurement point, is installed under a grass cover with shade effect from surrounding trees. It could be explained that the soil temperature at a depth of 1.10m to 1.20m will decrease with the effect of grass cover and shade. Based on the influence level of grass cover and shade analyzed in section 3.4, the surrounding soil temperature of the pipe decreased from 20℃ to [20 - (3.0~4.1) – (1~1.5)] = 14.4~16.0℃. Among the equations, - 3.0~4.1℃ is the influence level of grass cover compared with tile cover, - 1~1.5℃ is the influence level of shade compared with the unshaded area. After determining the rough range of soil temperature around the DWDS pipe segment under grass cover with shade, the pipe wall temperature (T_{soil}) can be set by choosing the reasonable value in this range. After choosing a specific value of pipe wall temperature (T_{soil}) and simulating under this setting, the simulation result will be obtained. It is necessary to adjust the pipe wall temperature (T_{soil}) setting to make the simulation result closer to the measurement result. If the obtained simulation value is higher than the measurement value when choosing the upper limit value (16.0℃) of pipe wall temperature (T_{soil}), we can change the value set as a lower value to lower the simulation value. After several rounds of simulation with continuous modification of pipe wall temperature (T_{soil}), the model will be well-calibrated with a slight difference between simulation value and measurement value, explained in section 4.4.2.

In addition, it is inappropriate to use the influence level of different impact factors analyzed from Weesperkarspel and Boszoom into another test area. The influence level of different impact factors used in the model calibration of the test area should be analyzed from soil temperature and DWT data collected in the target test area. However, due to the epidemic of COVID-19, it is limited to collect relative data in the test area and also with limitation of municipal management and measurement area selection.

4.3.3 Target test area

The test area is Almere in Flevoland province and belongs to Amsterdam 's city circle, which is one of the newest cities in the Netherlands. Figure 14 shows the DWDS layout of Almere. The map of Almere used in QGIS is built by pdok.nl with the coordinate reference system of EPSG:28992.

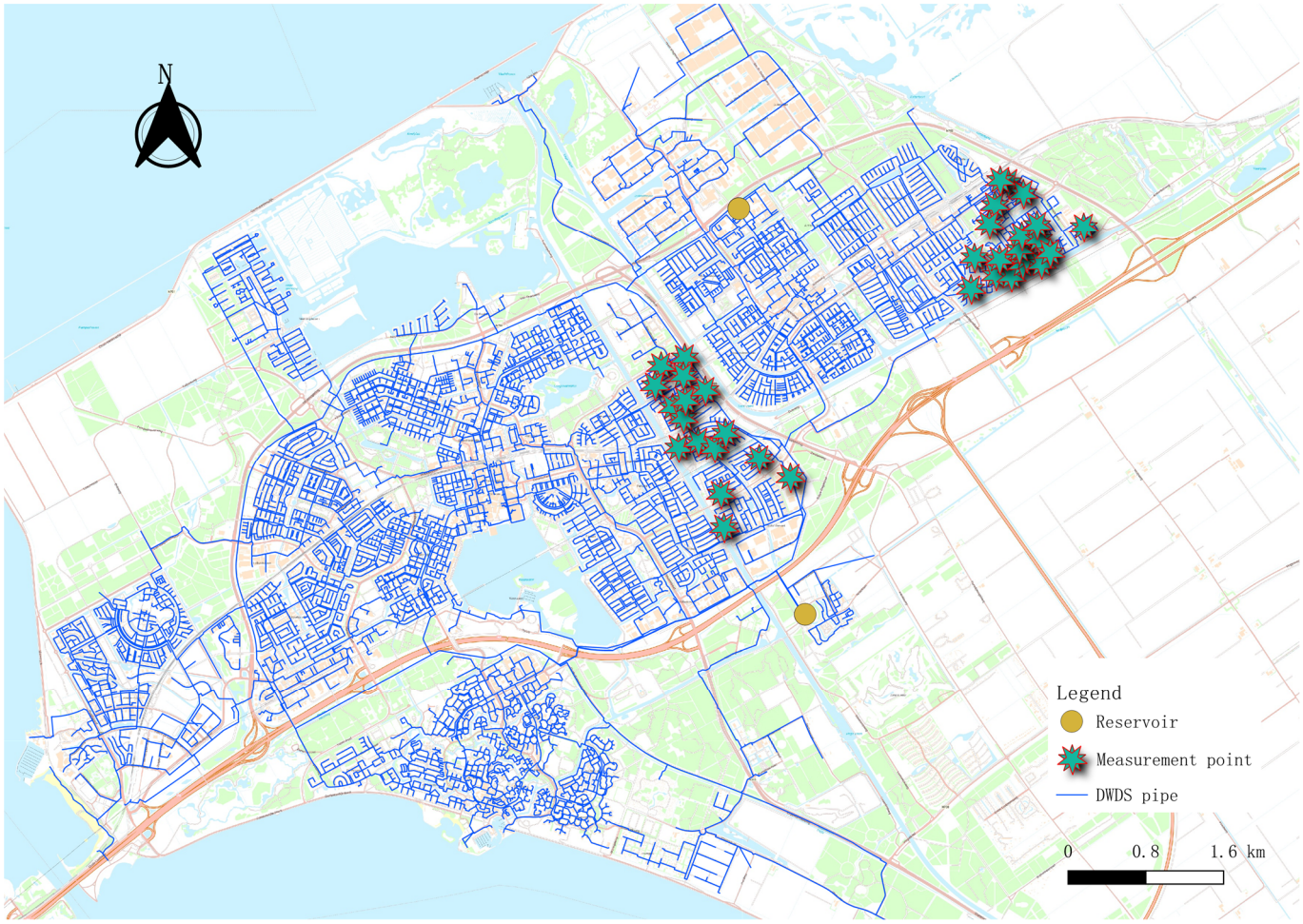


Figure 14 DWDS layout of Almere with measurement points label

There are two water sources in Almere, and each water source has two reservoirs for drinking water supply. It also can be observed that 35 measuring points of DWDS in Almere concentrate in two parts. Sixteen of them are located in districts of Tussen de Vaarten and Tussen de Vaarten Zuid (left part in figure 14). Nineteen of them are located in districts of Stripheldenbuurt and Eilandenbuurt (right part in figure 14). Hence, the model calibration for Almere will be mainly for these two parts.

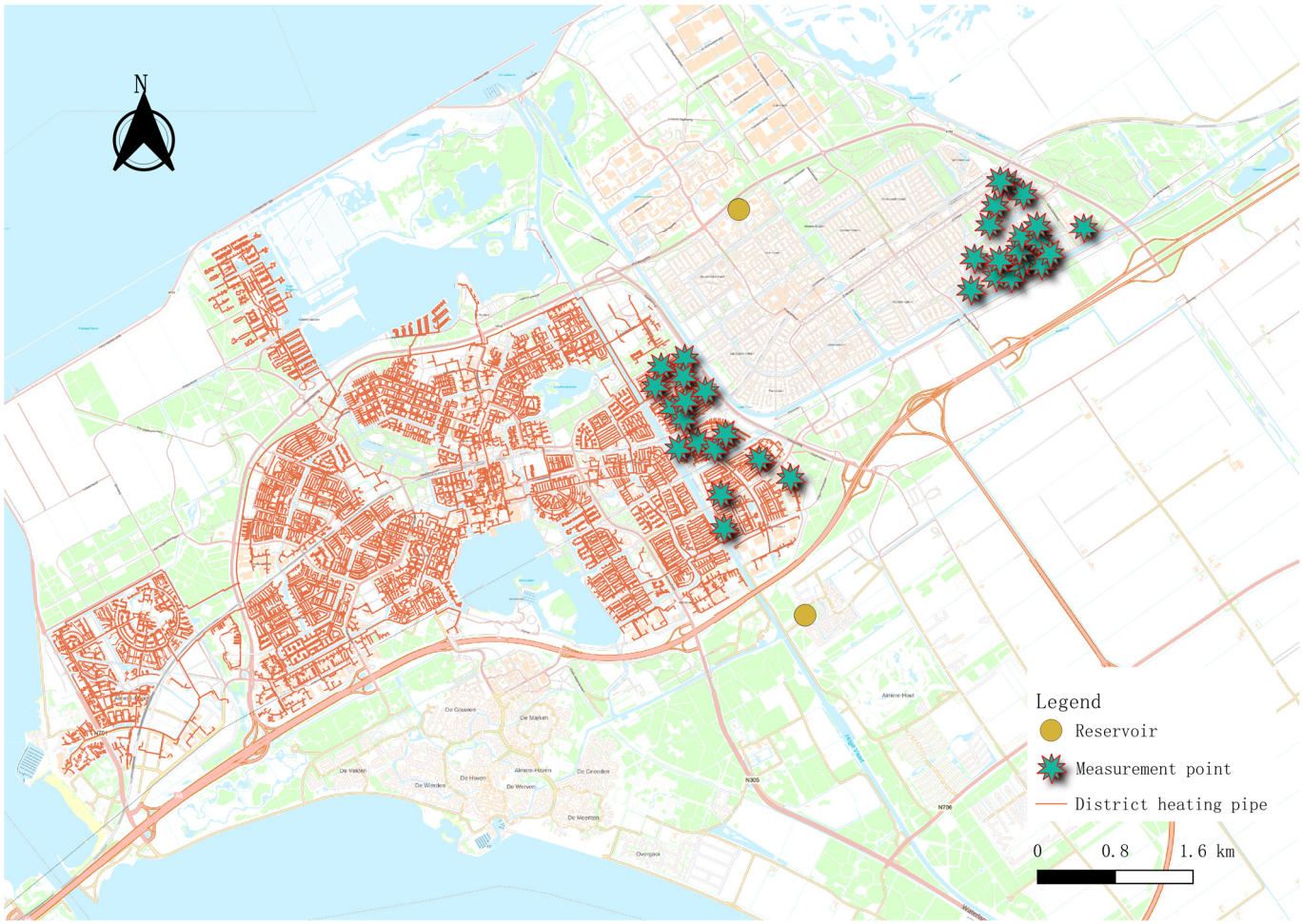


Figure 15 District heating network layout of Almere with measurement points label

Figure 15 presents Almere's district heating pipe network which is only installed in Almere's the middle and west parts. Therefore, sixteen measurement points located in Tussen de Vaarten and Tussen de Vaarten Zuid districts (left part) may be affected by district heating pipes. Furthermore, the installation depth of district heating pipes is about 0.80m, which is 0.3~0.4m above the DWDS pipe. Hence, the DWDS pipe may be affected while crossing with district heating pipe in some areas.

4.3.4 Measurement date and weather

The measurement at Almere took place on 31/08/2020. Unfortunately, there is not any weather data of Almere recorded by the Royal Netherlands Meteorological Institute (Dutch: Koninklijk Nederlands Meteorologisch Instituut) on the date. Therefore, the weather record of Lelystad, a city next to Almere, is chosen for reference.

The air temperature is in the range of 12.3℃~17.9℃, and the average temperature on 31/08/2020 is 15.3℃ in Lelystad. The average value of relative air humidity is 70% without precipitation. In addition, the sunshine duration is about 6.3h with sometimes cloudy.

4.3.5 Parameter setting

KWR had collected the DWT data of 35 measurement nodes in Almere, and each node has two measurement values in the morning and afternoon, respectively, on 2020/08/31. Soil temperature with the type of 'complete under tile cover' has been chosen as the standard pipe wall temperature, which compares with different types of pipe cover because the test area of Almere is an urban area with more tile cover similar to pavement type. The soil temperature at a depth of 1.10~1.20m under in peri-urban area on 2020/08/31 was simulated by the soil temperature model from KWR as 19℃ (as shown in figure 16). Moreover, we also reference the measurement result of some measurement points in Almere, which are under tile cover and not obviously influenced by other factors. Finally, the standard pipe wall temperature (T_{soil}) was set as 19℃ in the default state. Based on the standard pipe wall temperature (T_{soil}), regulating pipe wall temperature of some DWDS pipes with different pipe covers and affected by different impact factors will achieve the target of model calibration.

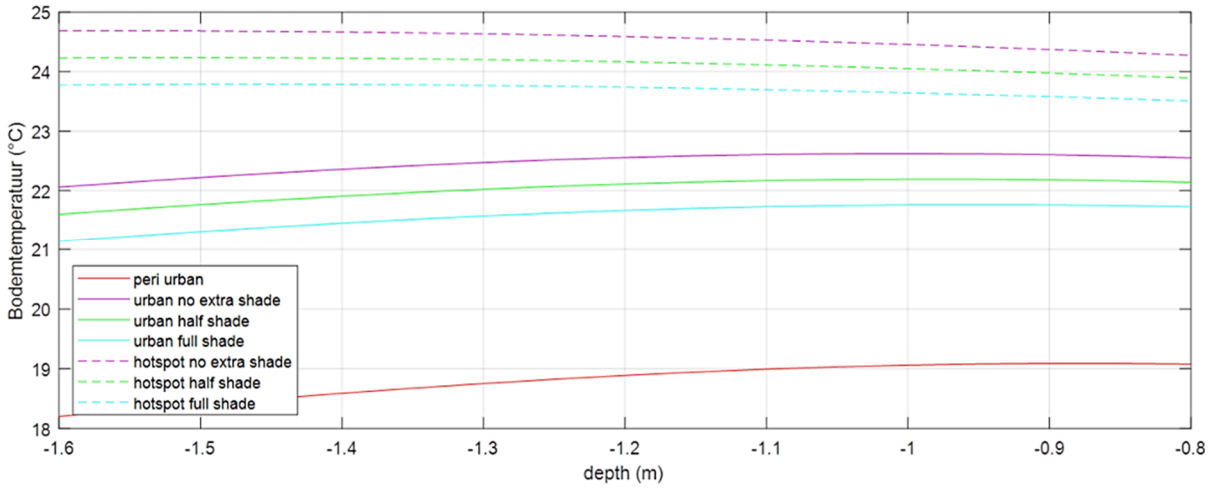


Figure 16 Soil temperature simulation results under different circumstances

* The line of 'peri urban' means that the general soil temperature under the circumstances of peri-urban area without high population density and we can find that the soil temperature is around 19℃ at a depth of 1.10m.

Table 15 states the important parameter setting of DWT simulation in Almere.

Table 15 Important parameter setting in Almere

Classification	Name	Value	Unit	Description
CONSTANT	T_wall	19.0	[C]	Temperature of soil, around the pipe wall
PARAMETER	T_wall	variable value	[C]	Temperature at pipe wall, to use to simulate hot spots
CONSTANT	Pr	7	[-]	Prandtl number, water at 20 C
CONSTANT	rho_water	1e3	[kg/m3]	Density of water
CONSTANT	Cp_water	4.19e3	[J/kg.K]	Specific heat capacity of water
CONSTANT	lambda_water	0.57	[W/m.K]	Thermal conductivity coefficient of water
CONSTANT	lambda_PVC	0.16	[W/m.K]	Thermal conductivity coefficient of PVC (pipe material)
CONSTANT	lambda_soil	1.6	[W/m.K]	Thermal conductivity coefficient of soil
CONSTANT	pipewall_ratio	0.052	[-]	Pipe wall thickness/diameter of pipe for calculate
CONSTANT	ground_pen_depth	0.20	[m]	The penetration depth into the soil where temperature is influenced by water temp
CONSTANT	Re_cutoff_1	10	[-]	Cutoff value for low Reynolds numbers (stagnant)
CONSTANT	Re_cutoff_2	2300	[-]	Cutoff value for high Reynolds numbers (turbulent)
CONSTANT	Nu_stagnant	5.8	[-]	Nusselt value for low Reynolds numbers (stagnant flow)
CONSTANT	Nu_laminar	3.66	[-]	Nusselt value for medium Reynolds numbers (laminar flow)

As shown in table 15, the first line and second line show the same parameter (T_wall) with different classifications. Classification of 'CONSTANT' means that the parameter of 'T_wall' is constant for all pipe segments as 19.0℃ without different pipe settings. 'PARAMETR' means that 'T_wall' is 19.0℃ by default. The 'T_wall' of each pipe can be set as different values in the '[PARAMETERS]' section shown in table 14. It means we can set the specific pipe wall temperature for each pipe segment corresponding to the actual circumstance. Therefore, it is preferred to set the 'T_wall' as 'PARAMETR' in this simulation process.

Another parameter worthy of explaining is the 'ground_pen_depth'. This parameter is linked with the heat convective process outside the pipe, as stated in section 4.1. When the surrounding soil temperature is lower than the water temperature inside the DWDS pipe, the heat will emit from the water inside to the soil outside the pipe. Therefore, the

'ground_pen_depth' represents how big the scope of water temperature inside effect on surrounding soil. In this case, it is assumed that the penetration depth is 0.2m as constant, which means that the heat emitted from the water inside influence the soil of 0.2m around the DWDS pipe. However, this is not accurate enough and cannot be determined as constant in the actual circumstance. Theoretically, the impact scope of the convective heat process outside the pipe is related to the flow volume (also can be seen as pipe diameter), flow velocity, and soil texture. The deeper penetration depth of the surrounding soil, the more heat volume will emit from water inside. Moreover, the correlation between heat penetration depth and flow volume, velocity and soil texture, respectively, is still not clear enough. Therefore, the penetration depth is 0.2m for all pipe segments by KWR in this project. More detailed information of parameter setting is presented in appendix 9.

The DWT in Almere were measured at different hydrants on 31st, August, 2020. The hydrant had relatively low flow volume. Therefore, it can be assumed that there is no effect of connection pipe and related drinking water infrastructure on DWT. In addition, the measurement is performed once in the morning and once in the afternoon. The measurement results measured from the 35 locations show a range of DWT between 13.0℃ to 21.0℃, which is a comprehensive scope for analyze the model accuracy later.

4.3.6 Combination of impact factors

The model calibration of Almere is based on pipe wall temperature setting (T_{soil}). Comparing the DWDS network in QGIS map with Google Earth can find the location of each pipe. This method can help to determine the different kinds of pipe cover. Similarly, this approach can also use for determining if the pipe segments are affected by shade. Comparing the overlapping area of DWDS and district heating network can determine whether DWDS pipe is affected by the district heating pipe. If there are some crossing or short distance between DWDS pipe and district heating pipe, it can be determined that the DWDS pipe is influenced by heating pipe. The influence level of district heating pipe on DWT depends on the distance and relation between DWDS pipe and heating pipe.

The pipe wall temperature setting with the effect of district heating pipe will be modified continuously to make the simulation closer to objective circumstances. In actual circumstances, DWDS pipe paralleled with district heating pipe with a distance of 0.3-0.4m is rare to see in Almere. Instead, crossing the district heating pipe and DWDS pipe often happens in Almere, as shown in figure 17. The inlet heating pipe of each house crosses with DWDS pipe and is located 0.3~0.4m above the DWDS pipe. This distance between DWDS pipe and branch heating pipe, which is paralleled with DWDS pipe, is about 3m. Hence, it is assumed that the DWDS pipe is not affected by branch heating pipe. Therefore, the influence level of the inlet heating pipe on the DWDS pipe will be smaller than +6.1℃, which is summarized in section 3.5.4.

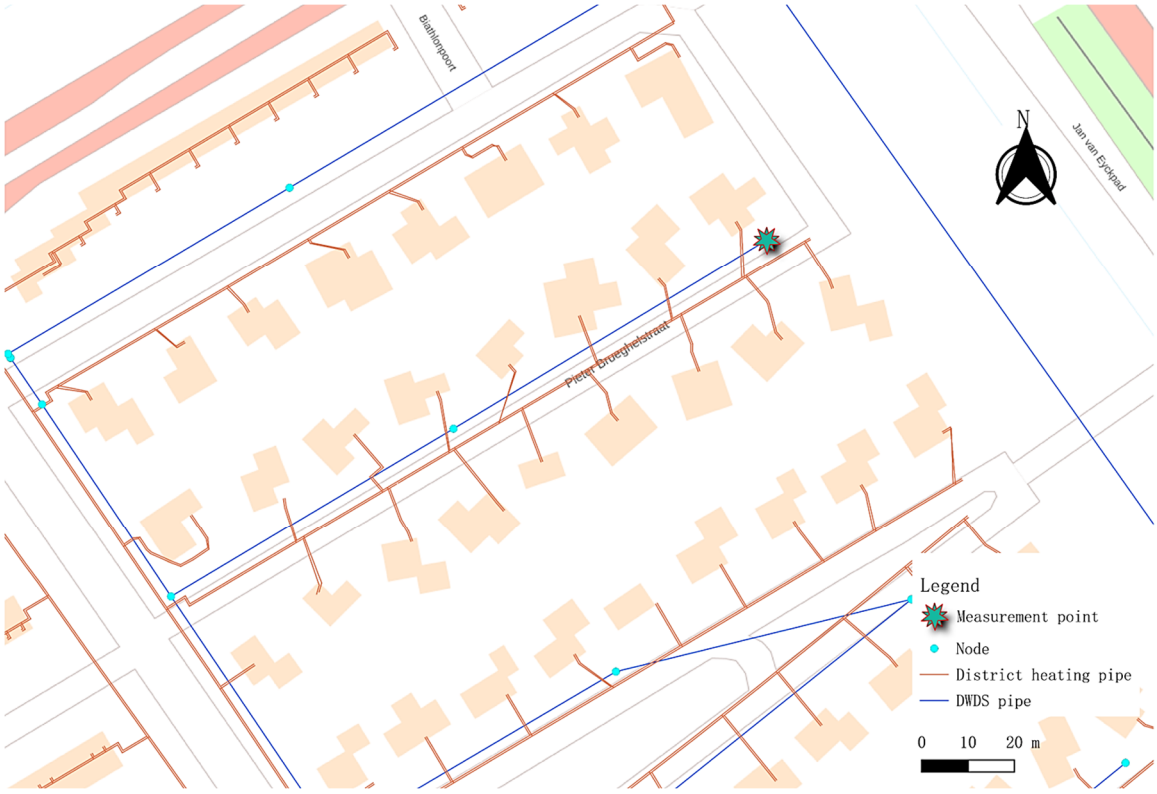


Figure 17 Circumstance of heating network pipe crossing with DWDS pipe

Additionally, groundwater level data was not accessible in this simulation. Also, Koreimann et al. (1997) introduced that more than 90% of groundwater levels in the Netherlands is less than 4 m below the surface level. Referring to the groundwater level monitoring data in Nieuwegein, located to the Southwest of Almere with a distance of 50km, the groundwater level at some monitoring points can even reach the surface level. These points can be seen as 'cold spots' with a low soil temperature because of the high groundwater level. Furthermore, measurement results of some points have a relatively big difference from simulation results. Therefore, after considering the heat stress of Almere achieved from Almere Climate Atlas, it is reasonable to speculate that some measurement points could be affected by high groundwater level. For this circumstance, the impact factor of groundwater level is introduced into the model to lower the DWT by choosing different influence levels higher than the range of -1.1 ~2.6℃ of groundwater level at a depth of 1.10m.

The soil cover type is also flexible in actual circumstances. We cannot simply judge that the pipe segment is under a single kind of pipe cover. When it is relatively long, it may combine different cover types and pass through the area with different pipe cover types. In order to determine the pipe wall temperature (T_{soil}) of pipe with different cover types, the partial influence level of each kind of pipe cover can be calculated according to the proportion of specific pipe cover length in the total length of the DWDS pipe segment. These partial influence levels can integrate as the sum of these partial influence levels to become a comprehensive influence level on the DWDS pipe segment with multiple kinds of pipe cover.



Figure 18 DWDS pipe with the cover of half grass cover and half tile cover

*The figure of 'DWDS pipe with the cover of half grass cover and half tile cover' is retrieved from Google Earth.

Figure 18 shows the circumstance of DWDS pipes passing through two different kinds of pipe cover: complete under grass cover (green belt/lawn) and complete under tile cover (pavement area of parking lot). The pavement of parking lots is seen as a similar material to a tile cover. For these two pipes, it can be roughly determined that half of the pipes are 'complete under grass cover' and the other half are 'complete under tile cover' by measuring the length of each cover type. The integrated influence level of half grass cover and half tile cover on these two pipes can be calculated as the sum of half influence level of 'complete under grass cover' and half influence level 'complete under tile cover':

$$\frac{Influence\ level\ of\ 'complete\ under\ grass\ cover'}{2} + \frac{Influence\ level\ of\ 'complete\ under\ tile\ cover'}{2}$$

Due to the pipe wall temperature (T_{soil}) with the type of 'complete under tile cover' is determined as the standard pipe wall temperature, the influence level of 'complete under tile cover' is 0 in this project. Therefore, the integrated influence level is:

$$\frac{-3.0\sim4.1℃}{2} + \frac{0}{2} = -1.5\sim2.1℃$$

The integrated influence level can be explained as the pipe wall temperature with the cover of half grass and half tile is 1.5~2.1℃ lower than pipe wall temperature with the cover of 'complete under tile cover'.

It has the same circumstance for the shade effect. Figure 18 also shows the DWDS pipes affected by shade. It can be observed that the shade on these two pipe segments, generated by surrounding trees is not continuous. Instead, there are intervals between trees which will also lead to intervals between shades. Hence, the integrated influence level of this circumstance, 'half shade', can be determined as:

$$\frac{-1\sim1.5℃}{2} = -0.50\sim0.8℃$$

The pipe wall temperature (T_{soil}) with 'half shade' is lower than pipe wall temperature without shade.

Finally, the pipe wall temperature (T_{soil}) of these two pipes can be roughly estimated in the range of:

$$19℃ - (1.5\sim2.1℃) - (0.5\sim0.8℃) = 16.1\sim17.0℃$$

19℃ is the standard pipe wall temperature (T_{soil}) in the default state.

Based on the statement above, the combination of different impact factors can be calculated by using the same method. The influence level of different combination of each impact factor are summarized in following table.

Table 16 Calculation of influence level of different impact factors on outer pipe wall temperature in different circumstances

Group	Background Temp (℃)	Impact Factors	Influence Level (℃)	Combination Result (℃)	Conprehensive Influence Level (℃)
Pipe segment with 1 impact factor	19	Complete under tile	Standard value	0	19.00
		Complete under grass	-(3.0~4.1)	-(3.0~4.1)	14.9~16.0
		Under grass near tile	-(1.1~1.8)	-(1.1~1.8)	17.2~17.9
		Under tile near grass	-0.4	-0.4	18.6
		Half grass and Half tile cover	[-(3.0~4.1)/2] + [0/2]	-(1.5~2.1)	16.9~17.5
		Influenced by shade	-(1.0~1.5)	-(1.0~1.5)	17.5~18.0
		Influenced by half shade	-(0.5~0.8)	-(0.5~0.8)	18.2~18.5
		Influenced by district heating pipe	+(0~6.1)	+(0~6.1)	19.0~25.1
		Influenced by groundwater level	< -1.1	< -1.1	< 17.9
Pipe segment with 2 impact factors	19	Under grass cover with influence of shade	-(3.0~4.1), -(1.0~1.5)	- (4.0~5.6)	13.4~15.0
		* The influence level of pipe segments influenced by shade (or half shade) with tile cover, the cover of under grass near tile, the cover of under tile near grass, the cover of half tile and half grass, can be calculated in the same, respectively.			
		Under grass cover with the influence of district heating pipe	-(3.0~4.1), +(0~6.1)	-4.1~+3.1	14.9~22.1
		* The influence level of pipe segments influenced by district heating pipe with tile cover, the cover of under grass near tile, the cover of under tile near grass, the cover of half tile and half grass, can be calculated in the same, respectively.			
		Under grass cover with the influence of groundwater level	-(3.0~4.1), < -1.1	< -4.1	<14.9
		* The influence level of pipe segments influenced by groundwater level with tile cover, the cover of under grass near tile, the cover of under tile near grass, the cover of half tile and half grass, can be calculated in the same, respectively.			

Group	Background Temp (℃)	Impact Factors	Influence Level (℃)	Combination Result (℃)	Conprehensive Influence Level (℃)
Pipe segment with 3 impact factors	19	Under grass cover with influence of shade and district heating pipe	-(3.0~4.1), -(1.0~1.5), +(0~6.1)	-5.6~+2.1	13.4~21.1
		* The influence level of pipe segments influenced by shade (or half shade) and district heating pipe with tile cover, the cover of under grass near tile, the cover of under tile near grass, the cover of half tile and half grass, can be calculated in the same, respectively.			
		Under grass cover with influence of shade and groundwater level	-(3.0~4.1), -(1.0~1.5), < -1.1	< -5.1	<13.9
		* The influence level of pipe segments influenced by shade (or half shade) and ground water level with tile cover, the cover of under grass near tile, the cover of under tile near grass, the cover of half tile and half grass, can be calculated in the same, respectively.			
		Under grass cover with influence of district heating pipe and groundwater level	-(3.0~4.1), +(0~6.1), < -1.1	< +0.8	<19.8
		* The influence level of pipe segments influenced by district heating pipe and ground water level with tile cover, the cover of under grass near tile, the cover of under tile near grass, the cover of half tile and half grass, can be calculated in the same, respectively.			
Pipe segment with 4 impact factors	19	Under grass cover with influence of shade, district heating pipe and groundwater level	-(2.97~4.09), -(1.00~1.50), +(0~6.05), <-1.13	<-0.67	<18.33
		* The influence level of pipe segments influenced by shade (or half shade), district heating pipe and ground water level with tile cover, the cover of under grass near tile, the cover of under tile near grass, the cover of half tile and half grass, can be calculated in the same, respectively.			

The calibration process includes pipe wall temperature (T_{soil}) setting of each DWDS pipe segment by comparing DWDS in QGIS map and google map to determine the impact factors of each segment, especially for two parts of Almere which include 35 measurement points as shown in figure 16.

4.4 Simulation results & Evaluation

The simulation period is 72 hours (3 days). The first 48 hours is an adaptation period to make the DWT of the whole DWDS system reach a stable level to eliminate DWT fluctuation. Data from the last 24 hours is used to compare measurement data and further analysis. The boundary temperature is the outer pipe wall temperature (as '[PARAMETR] - T_wall' shown in table 15). The outer pipe wall temperature of each pipe segment is set by the method introduced in section 4.3. It is constant in the simulation duration of 72 hours.

After several rounds of regulating pipe wall temperature (T_{soil}) in Almere, the calibration process was completed. Seventy measured values at different times were measured at 35 measuring points in Almere. Indeed, 70 simulation data corresponding to the measurement moment were chosen for comparison to observe the accuracy of simulation data. Figure 19 presents the result of the comparison of simulation data and measurement data. The horizontal axis is 'measurement result', and the vertical axis is 'simulation result'. The red dashed line names as 'perfect line', which means the simulation results are equal to measurement results. The grey dashed line names as 'irregular cold point', which help us to observe if there is any measurement value lower than the source water temperature (13.5℃, as shown in table 15). The gold dashed line names as 'irregular hot point', which help us to observe if there is any measurement value higher than the boundary pipe wall temperature by default (19.0℃, as shown in table 15).

In figure 19, the simulation result was classified into three groups. The classification standard is based on the difference between the measurement result and the simulation result of i) 0~0.5℃, ii) 0.5~1℃, iii) bigger than 1℃. Blue points mean that the points are matched very well with differences more minor than 0.5℃. Brown points mean that the values which

match well with a difference in the range of 0.5~1℃. Finally, green points mean that the points matched not well with a difference bigger than 1℃.

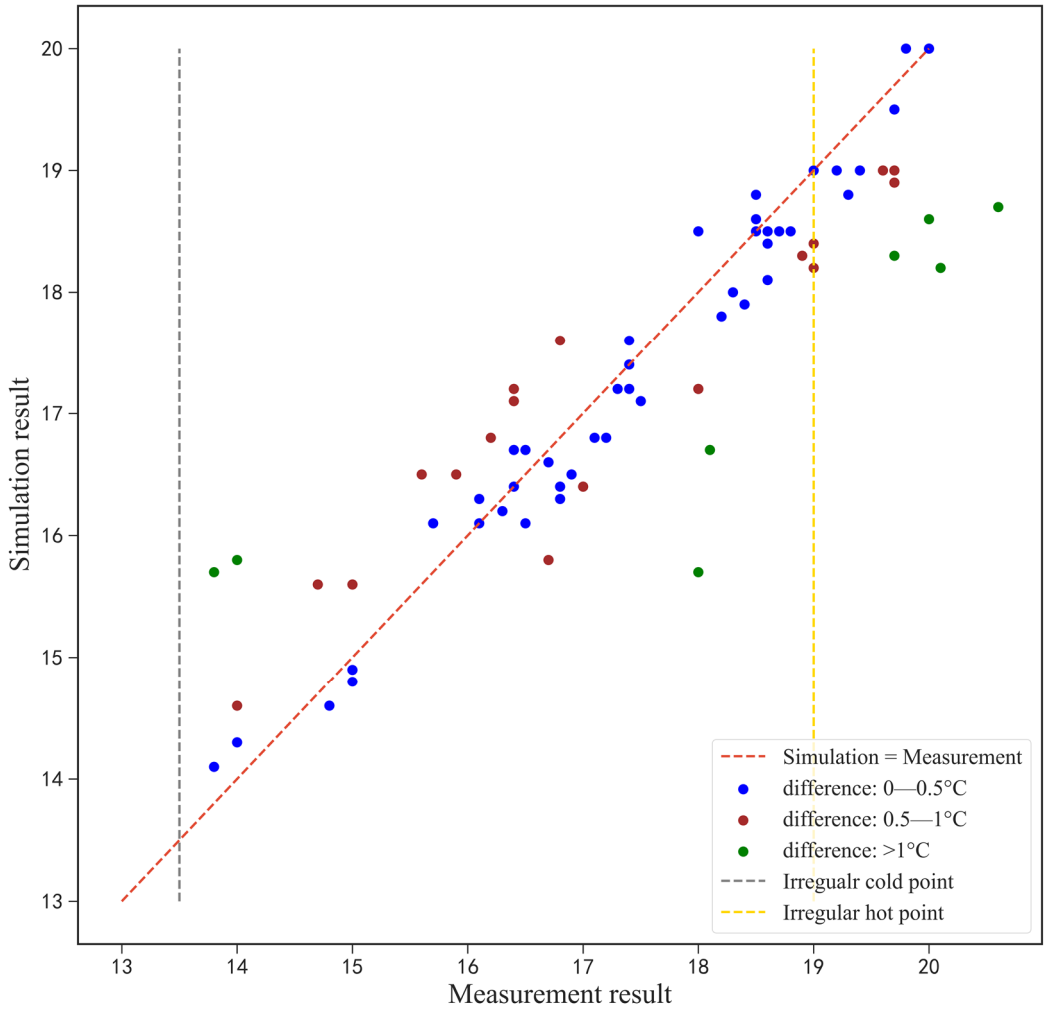


Figure 19 Comparison of simulation result and measurement result in Almere

Table 17 Evaluation of simulation result in Almere

Classification	Difference (℃)	Number	Percentage (%)
Matched very well	0~0.5	44	62.86%
Matched well	0.5~1	18	25.71%
Not matched well	>1	8	11.43%

Table 17 provides the percentage of each classification group. 88.57% of simulation results have a difference with measurement results smaller than 1℃, which can provide a rough description of the accuracy of this model. In addition, the root mean squared error (RMSE) can be calculated as:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(X_{measured,\ i} - X_{simulated,\ i}\right)^2} = 0.74$$

Where:

$\sum n$ —— Σ is summation notation (the absolute value is summed for every forecasted point in time);
$X_{measured}$ —— measurement value;
$X_{simulated}$ —— simulated value;
n —— number of values.

The RMSE of this model is smaller than 0.74℃, which means that the model has relatively good accuracy.

In the 'Not matched well' group with a difference bigger than 1℃ between measured data and simulated data presented in table 17, they can be named 'unexplained points'. The 'unexplained point' group can be divided into two parts: i) irregular cold points; ii) irregular hot points.

Irregular cold points mean that the measured data of DWT at some points is much lower than the simulation result and closed to DWT at the reservoir (13.5℃). Based on the model framework, it is hard to obtain a DWT of DWDS pipe lower than DWT at reservoir only when the pipe wall temperature (T_{soil}) is really low. For these irregular cold points, the impact factor of groundwater level was introduced into the calibration process. After several rounds of simulation, it can be estimated that the DWT will decrease 0.5~1℃ when the pipe wall temperature (T_{soil}) decreases 5℃ caused by groundwater level. The influence level of different groundwater level is hard to determine. Some data of soil temperature under this circumstance is needed. In addition, the impact of upstream DWT had also been considered, like in drinking water mains, and it did not work in the calibration process. Instead, the DWT will tend to the outer pipe wall temperature of corresponding segment. It can be summarized that the DWT highly depends on the outer pipe wall temperature of different pipe segments. Hence, it is hard to determine the reason how irregular cold points is generated.

The irregular hot point means that the measured data of DWT at some points is higher than the pipe wall temperature setting (T_{soil}) in EPANET-MSX as 19℃, which is the same as the soil temperature at a depth of 1.10m. An irregular hot point happened in the east part of Almere, which consisted of 19 measurement points and were not under grass cover and not affected by the district heating network (as shown in figure 17). Based on the impact factors analyzed in section 3, only the impact of district heating pipe can increase the DWT. Also, based on the frame of this simulation model, one of the boundary conditions is $T_{water}(t = \infty) = T_{outer\ wall}$ that the DWT (T_{water}) will be equal to pipe wall temperature (T_{soil}) with a time interval as infinity, as mentioned in section 4.1.1. (In EPANET-MSX, T_{soil} was used to represent $T_{outer\ wall}$). Therefore, the DWT cannot be higher than the pipe wall temperature setting of 19℃ without any impact from the district heating pipe. Through further conjecture and analysis, we found possible reasons: i) local radiation effects, which can lead to soil temperature fluctuation (e.g., high soil temperature during daytime and low soil temperature during night time); ii) Impact from surrounding underground construction may emit heat (like high voltage cable, heat pump, the information of this part is absent in model calibration process).

4.5 Discussion of simulation result

Some problems and deficiencies of this DWT simulation model had been observed during the calibration process. These problems can be divided into six parts.

● The difference between the valve operating status in the simulation model and reality DWDS will affect the accuracy of DWT prediction. In this model, the status of each valve is assumed as open. However, some valves are closed in an actual circumstance, leading to a relatively longer or shorter residence time and thus higher or lower DWT.

● The parameter setting of 'ground_pen_depth' is assumed as constant in the simulation process, as mentioned below in table 15. However, with further research on the convective heat convective layer from drinking water inside the pipe to the surrounding soil outside, the parameter setting of 'ground_pen_depth' should depend on the pipe material diameter and flow velocity. Therefore, variable settings of the heat convective layer need to be considered with different pipe properties

● The impact of groundwater level on DWT is not clear enough. The only data related to groundwater level is collected in Boszoom with the groundwater level at a depth of 1.1m which equals the pipe installation depth, and the data of influence level of groundwater level at different depths is absent. However, Almere is a polder. Therefore, it uses active pumping to control the groundwater level.

● The outer pipe wall temperature ('T_{soil}' in equation; 'T_wall' in EPANET-MSX model) in this simulation process is assumed as constant for each pipe segment over 24h. However, after considering the temperature difference between day and night, the outer pipe wall temperature should be dynamic corresponded to the temperature fluctuation over day and night.

● The consideration of different impact factors is not sufficient enough. It is possible to introduce other impact factors of underground construction like storm tanks, cables underground, and other related infrastructures. Instead, the information of underground construction layout is unknown in Almere. This kind of information may be helpful to understand the irregular cold and hot points and increase the accuracy of the model.

● The diminishing marginal effect was not considered in the calibration process. For instance, a pipe segment is under grass cover, shade and affected by groundwater level with the pipe wall temperature of 20℃ in the default state. The default state of pipe wall temperature is set under tile cover. Therefore, the integrated influence level on this pipe can be roughly estimated as -4-1-2=-7℃. It is a sum of the influence level of each impact factor. Therefore, the pipe wall temperature of this DWDS pipe segment can be calculated as 20-7=13℃. However, the diminishing marginal effect of calculating the integrated influence level should be considered in the calculation. The analogy to the definition of diminishing marginal effect, the pipe wall temperature, which is affected by these impact factors, decreases 1℃ from 20℃ is more accessible than from 15℃. Therefore, superimposing the influence level of these three impact factors of grass cover, shade and groundwater level should be smaller than the sum of three types of influence levels. In other words, the actual pipe wall temperature with these three impact factors should be higher than 13℃. In general, calculating the diminishing marginal effect of superimposing different impact factors is a sophisticated process and could research further.

4.6 Chapter summary

Chapter 4 mainly presents the detailed information of three parts: i) The mechanism of DWT simulation model framework; ii) The calibration principle and operational methods; iii) Evaluation of the simulation result.

The process of this DWT simulation model can be summarized as an input file, an operation file and an output file. Moreover, the core of this model is the operational file with equations corresponded to three heat transfer processes. The heat transfer process are as follows.

- Heat conductive process from the outer pipe wall to the inner pipe wall;
- Heat convective process of the flowing water inside the pipe;
- Heat convective process outside the pipe.

The manual calibration method is implemented in this part. Impact factors of each pipe segment is determined by comparing the DWDS layout in QGIS map and street view from google map. After calibration, the accuracy of the simulation data is 88.57%, with a difference smaller than 1℃ compared with measured data. Furthermore, calculating a correlative coefficient to verify the accuracy of the simulation results. The root mean squared error is 0.74℃. Hence, the simulation results are close to measurement results with low errors. Therefore, the simulation model is calibrated with high accuracy.

Chapter 5 Measures to prevent high water temperature

Based on the mechanism of DWT simulation, the occurrence of hot-spot can be simulated when the DWT is greater or equal to 25℃, which is the specified tap water temperature stated in Drinking Water Directive (2018). Also, Blokker and Pieterse-Quirijns (2013) presented that DWT at the tap is similar to the soil temperature surrounding the DWDS pipe. Thus, the surrounding soil temperature is assumed as the same as pipe wall temperature in the simulation model. Therefore, it is necessary to look for some measures to prevent high water temperature in DWDS pipes. Chapter 5 will be divided into five parts to illustrate the process of measures design. Section 5.1 presents the design thinking of intervention conjectures and the example. Section 5.2 will introduce the influence level of different interventions for decreasing soil temperature. Section 5.3 will explain the thinking of introducing the different interventions as impact factors to simulate the DWT. Section 5.4 will assess/evaluate these measures and interventions for preventing high water temperature by considering their capability, construction cost, operational cost, convenience and other related factors. Ultimately, section 5.5 will provide the chapter summary.

5.1 Intervention conjecture & design

5.1.1 Design thinking of intervention conjecture

The main idea of preventing high DWT and controlling DWT from the point of pipe cover can be considered as decreasing the heat volume in the surrounding soil of the DWDS pipes by changing pipe cover material and such as soil types and ground cover material. With less heat volume in the soil surrounding DWDS, the soil temperature will be lower than the original temperature. As a result, the heat transfer volume from soil to pipe wall will lower, and the impact of pipe wall to DWT will be lower further. In addition, the cost (including construction part and maintenance part), feasibility and capability of decreasing DWT will be considered with the requirement of ensuring the original function of these pipe covers.

5.1.2 Design example

Based on the hot-spots simulation of DWT with the surrounding soil temperature of 25℃, the high DWT often occurs in the pipe installed under the tile cover, asphalt pavement, and some DWDS pipe segments will also be affected by district heating pipe.



Figure 20 Porous asphalt (left: regular asphalt; right: porous asphalt)

According to different functions of ground cover, the pipe cover can change from ‘complete under tile cover’ to grass cover or cover of pervious pavement. As for pipes installed under streets which are asphalt pavement with high DWT, it is impossible to change the cover of the street to grass. However, it can use porous asphalt (PA) instead of regular asphalt, as shown in figure 20. PA not only decreases the soil temperature, but it can also reduce the run-off during the precipitation period to avoid urban flooding (Cheng et al., 2019; Hashim et al., 2018; Fini et al., 2016). Furthermore, many tiny pores

in PA can allow water transfer through the asphalt layer to increase the soil moisture. In addition, PA with good performance on water infiltration can also improve traffic safety to avoid the generation of surface gathered water. In summary, the porous pavement has multi-functions with the advantages of reducing run-off flow (Hashim et al., 2018), reducing the effect of urban heat island (Ferguson et al., 2008), reducing soil temperature (Kevern et al., 2009), and DWT furtherly.

As for some areas, like parking lots, with tile cover and asphalt pavement, it can also be changed as permeable interlocking concrete pavements (PICP), like shown in figure 21. Permeable interlocking concrete pavements are concrete units with open, permeable spaces between the units (Bean et al., 2004). They provide enough space for planting vegetation in their open space and can bear both light and heavy traffic except for high-volume or high-speed roads (Smith, 2011).



Figure 21 Permeable interlocking concrete pavements

Indeed, change of surface cover type with permeable material and design can help decrease the soil temperature, affecting pipe wall temperature and water temperature directly.

5.2 Influence level of measures for decreasing soil temperature

Due to the project conditions, it is not available to measure the soil temperature under PA and PICP. Indeed, the influence level of each measure on soil temperature is estimated and referenced to the relevant literature and data obtained from Weesperkarspel and Boszoom as introduced before.

Based on the pavement structure of PA and PICP, it is easy to consider that the PICP has a better performance in reducing soil temperature than PA. The reason is that PICP includes big holes through the pavement layer. In other words, PICP has a better ability for filtration. Hence, the influence level of PICP can be estimated bigger than PA. However, Cheng et al. (2019) had tested the performance of temperature control in Taipei city and concluded the temperature difference between i) PA pavement and regular asphalt pavement, ii) PICP and regular concrete pavement during an extended dry period in summer and winter. The most significant decrease in surface temperature for PA (compared with regular asphalt) and PICP (compared with regular concrete) are 14.4℃ and 9.4℃ respectively, around 14:00 in summer (2018/08/07). The most considerable decrease in surface temperature in winter is 2℃ and 3.8℃ for PA and PICP, respectively, around 14:00 in winter (2019/02/18). However, it has to be aware that Taipei city has a subtropical monsoon climate which has a relatively high temperature around the whole year and is entirely different from the temperate maritime climate of the Netherlands. Therefore, the simulation in this section is mainly for simulating the DWT under the high temperature in Almere, which mainly happens in summer. Also, the average temperature of Taipei in summer is around 25.8~30.1℃ (Central weather bureau), and the long-term average temperature of the Netherlands in summer is around 15.4~18.8℃ (Royal Netherlands Meteorological Institute, Ministry of Infrastructure and Water Management). (Because there is not any average temperature data in Almere and the national data of the whole Netherlands are used here.) It can be inferred that the performance of PA and PICP for decreasing surface temperature will not be as apparent as in Taipei city.

Therefore, compared with the soil temperature decrease under grass compared with under tile in section 3.5.2. It is summarized as -4±0.5℃. The influence level of grass cover on soil temperature can be seen as -4±0.5℃ compared with soil temperature at a depth of 1.1m under tile cover. Also, the influence level of PA pavement and PICP would be smaller

than under grass cover. The influence level of PA and PICP follows the proportion of temperature decrease under PA and PICP cover mentioned in reference of Cheng et al. (2019). The soil temperature at a depth of 1.0~1.1m will decrease about 3±0.5℃ under PA pavement compared with regular asphalt pavement. Soil temperature will decrease by around 2±0.5℃ under PICP compared with regular concrete pavement. These two values are smaller than the influence level of grass cover compared with tile cover.

5.3 Introduce the intervention into the water temperature simulation model

The highest air temperature throughout a day is around 14:00 (Parton and Logan, 1981). However, the time lag between air temperature and soil temperature at a depth of 1m is about 2.5h which means that the highest soil temperature will occur at 16:30 (Florides and Kalogirou, 2005). Therefore, the DWT at 16:30 is chosen for comparison with and without measures to evaluate the performance of DWT decrease.

Based on the hot-spots simulation of DWT with the surrounding soil temperature of 25℃, the target districts are chosen, including any hot-spots. These districts will be simulated with and without PA, PICP and grass cover to compare the temperature reduction level of each node. In this way, the efficacy of each measure can be estimated. Four districts are chosen as the test area (shown in figure 22) A. As for the DWT of each node in these four test districts, the target nodes with DWT higher than 23℃ are seen as hot-spots which have a potential risk of water quality deterioration. After considering the heat transfer and residence time from DWDS pipe to tap, the DWT in DWDS pipes, which is 23℃, will be estimated easily increase to 25℃ at the tap and even over the threshold (25℃) of DWT formulated in Drinking Water Directive (2018) (Moerman et al., 2014).

Different locations limit the application of different measures and interventions in these four test districts. As for grass cover, it can only be used for urban landscapes and green belts, which are restrictive. The application of PA does not have any limitations and can be paved anywhere theoretically. PICP can be used for urban landscapes and parking lots which has the requirement of the surface load. However, the application of all these ground cover materials should correspond to urban planning and municipal design in reality.

PA, which does not have any limitation of implementation, is chosen as the base. Therefore, there are three circumstances shown as follow. In addition, figure 22 A shows the original nodes layout in test area without any measures.

1. Implementing PA as cover for every pipe segment, whether under street or greenbelt, parking lot (figure 22 B);
2. Implementing PA for pipe segments installed under street and PICP for pipes not installed under the street (figure 22 C);
3. Implementing PA for pipe segments installed under street and grass cover for pipes not installed under the street (figure 22 D).

As considering the influence level of PA, PICP and grass cover are -3±0.5℃, -2±0.5℃, -4±0.5℃, respectively. Hence, the maximum value (RA: -3.5℃; PICP: -2.5℃), the minimum value (RA: -2.5℃; PICP: -1.5℃) and the median value (RA: -3℃; PICP: -2℃) of each influence level is chosen to introduce in the simulation model which is also helpful for sensitive analysis in section 5.4.

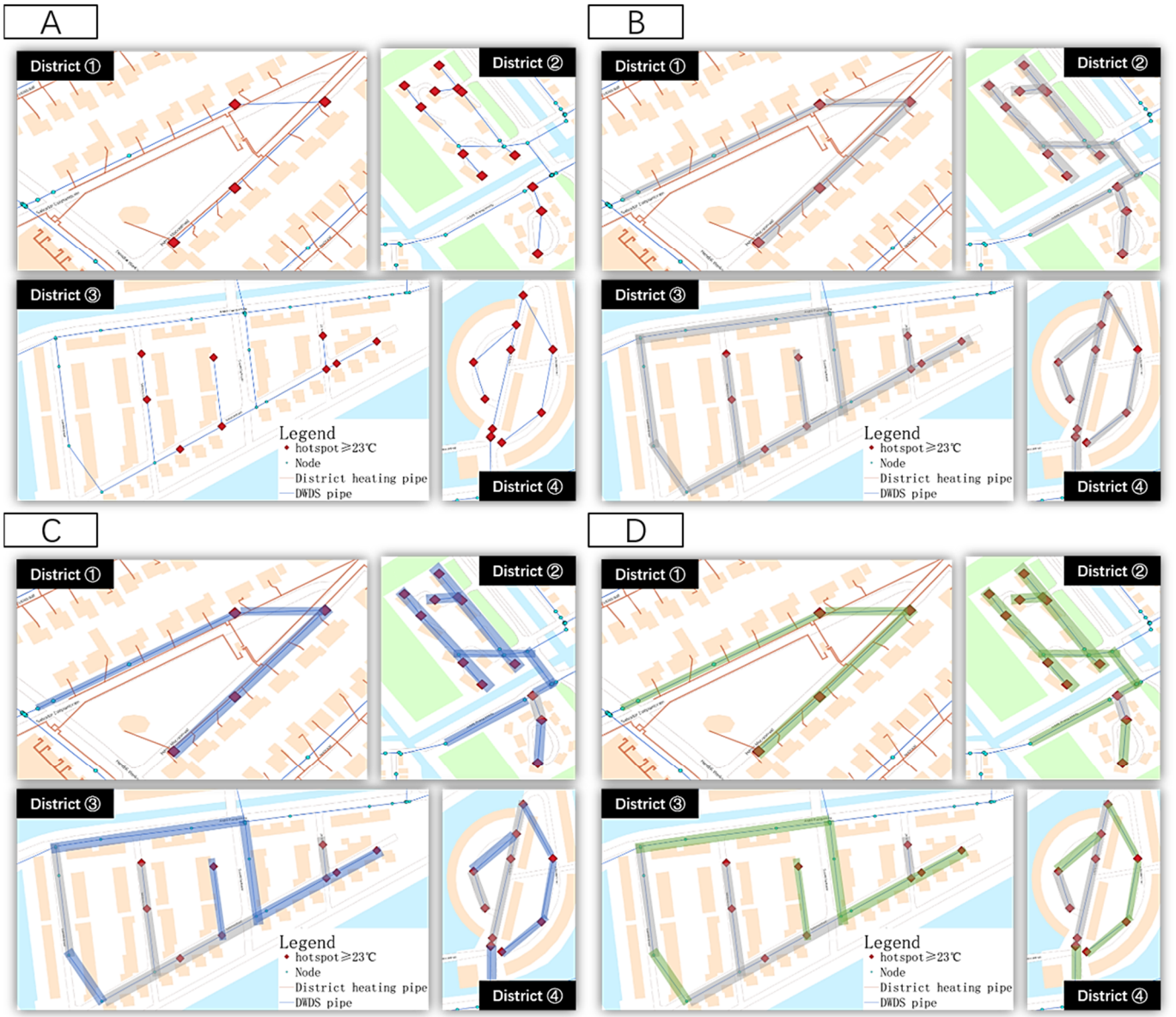


Figure 22 Four Test districts with hot-spots (DWT≥23℃)

* Pipe with grey shadow: cover of PA; Pipe with blue shadow: cover of PICP; Pipe with green shadow: cover of grass.

Therefore, there are three kinds of input of PA (-3.5℃, -3℃. -2.5℃) for circumstance 1, three kinds of input of combining PA and PICP (both maximum: PA: -3.5℃, PICP: -2.5℃: both median: PA: -3℃, PICP: -2℃: both minimum: PA: -2.5℃, PICP: -1.5℃) for circumstance 2 and three kinds of input of combining PA and grass cover (both maximum: PA: -3.5℃, grass cover: -4.5℃: both median: PA: -3℃, grass cover: -4℃: both minimum: PA: -2.5℃, grass cover: -3.5℃) for circumstance 3. Thus, in total, nine settings are simulated by the model.

In addition, the control variable thinking is also implemented in this process. Therefore, the pipe cover is only changed in these four test districts. As for other areas outside these test districts, like the upstream area, the pipe cover does not change. Hence, the performance of reducing soil temperature only by comparing DWT with and without changing pipe cover in these four test districts.

5.4 Result evaluation and discussion

There are a total of 73 nodes in these four test districts. Therefore, the simulation results focus on the DWT of each node in these four test districts. The reason is that the DWT in DWDS pipes is the average temperature in the pipe segments, which highly depends on pipe length and is not appropriate for result comparison and analysis. Hence, the DWT of each node is chosen for the result evaluation.

Table 18 Statistics of simulation results under 3 settings of circumstance 1

Level of DWT decrease (℃)	Maximum input		Median input		Minimum input	
	Number	Percentage (%)	Number	Percentage (%)	Number	Percentage (%)
0<DWT reduce≤1	27	36.99	29	39.73	31	42.47
1<DWT reduce≤2	10	13.70	14	19.18	20	27.40
2<DWT reduce≤3	19	26.03	30	41.10	22	30.14
DWT reduce>3	17	23.29	0	0.00	0	0.00
Sum	73	100	73	100	73	100

Table 19 Statistics of simulation results under 3 settings of circumstance 2

Level of DWT decrease (℃)	Maximum input		Median input		Minimum input	
	Number	Percentage (%)	Number	Percentage (%)	Number	Percentage (%)
0<DWT reduce≤1	31	42.47	34	46.58	39	53.42
1<DWT reduce≤2	16	21.92	32	43.84	31	42.47
2<DWT reduce≤3	23	31.51	7	9.59	3	4.11
DWT reduce>3	3	4.11	0	0.00	0	0.00
Sum	73	100	73	100	73	100

Table 20 Statistics of simulation results under 3 settings of circumstance 3

Level of DWT decrease (℃)	Maximum input		Median input		Minimum input	
	Number	Percentage (%)	Number	Percentage (%)	Number	Percentage (%)
0<DWT reduce≤1	21	28.77	24	32.88	27	36.99
1<DWT reduce≤2	14	19.18	11	15.07	13	17.81
2<DWT reduce≤3	11	15.07	20	27.40	20	27.40
DWT reduce>3	27	36.99	18	24.66	13	17.81
Sum	73	100	73	100	73	100

* The columns of 'Maximum input', 'Median input' and 'Minimum input' in table mean that the maximum input of influence level (Grass cover: -4.5℃, PA: -3.5℃, PICP: -2.5℃), median influence level (Grass cover: -4℃, PA: -3℃, PICP: -2℃), and minimum influence level (Grass cover: -3.5℃, PA: -2.5℃, PICP: -1.5℃), respectively.

The simulation results of each circumstance with three kinds of setting (maximum influence, median influence, minimum influence) are classified into four levels according to their performance of decreasing DWT: i) 0<DWT reduce≤1℃; ii) 1<DWT reduce≤2℃; iii) 2<DWT reduce≤3℃; iv) DWT reduce>3℃. Table 18, 19 and 20 present the classification of the simulation result of circumstances 1, 2 and 3, respectively. As for more intuitive observation, the bar chart of each circumstance has been summarized in figure 23, 24 and 25, respectively.

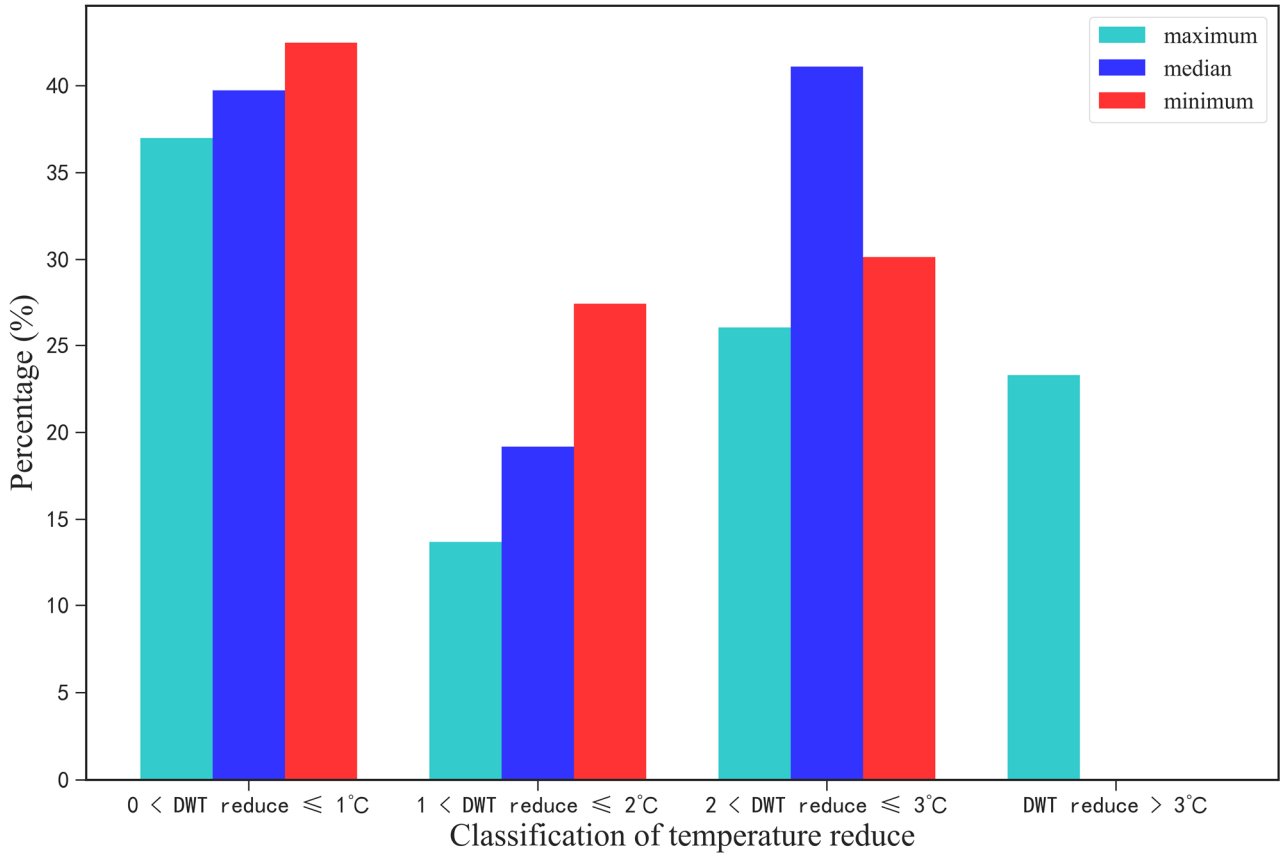


Figure 23 Simulation results under 3 settings of circumstance 1

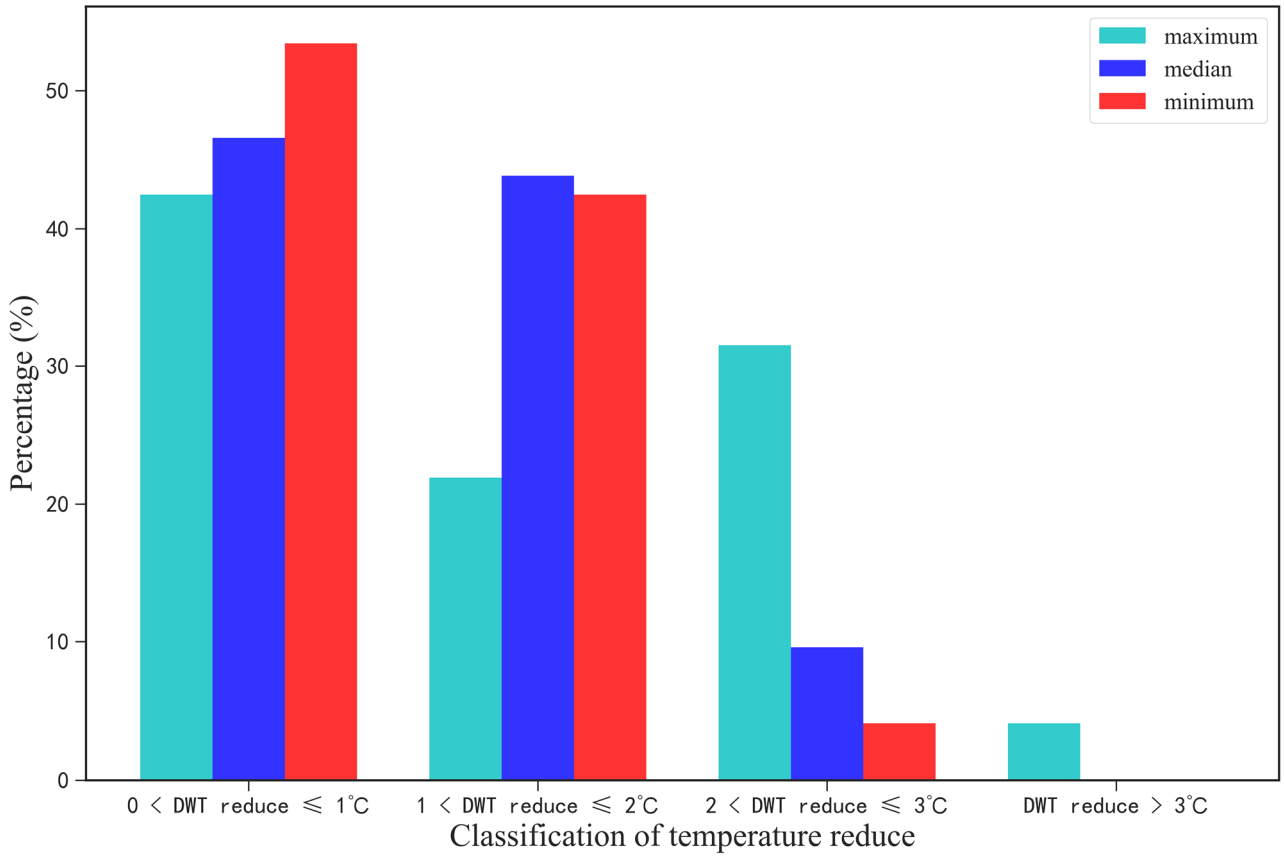


Figure 24 Simulation results under 3 settings of circumstance 2

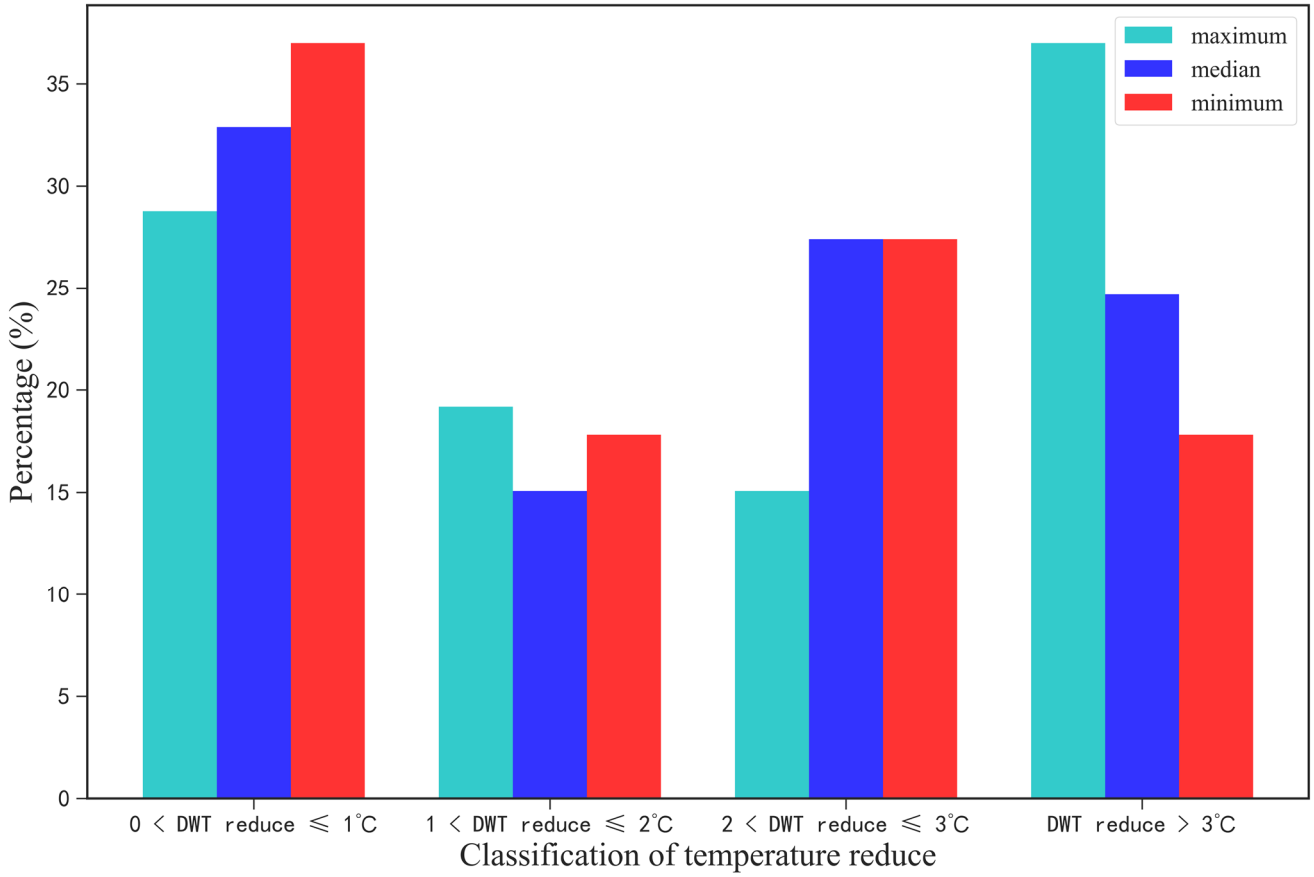


Figure 25 Simulation results under 3 settings of circumstance 3

* In figure 23, 24 and 25, the cyan bar represents the maximum input of influence level; the blue bar represents the median input of influence level; the cyan bar represents the minimum input of influence level.

The general trend of different circumstances is that with the bigger input of influence level in the simulation model, the better performance of DWT reduction can be obtained. The bigger input of influence level, the more results of DWT reduction located into the range of 2<DWT reduce≤3℃ and DWT reduce>3℃. Otherwise, more results of DWT reduction locate into the range of 0<DWT reduce≤1℃. For example, all DWDS pipe segments are under cover of PA in circumstance 1, but the performance of DWT decrease is different from node to node. The reason is that the level of DWT reduction depends on the length of pipe with low pipe wall temperature, which can also seem like a short cooling time. As the node on the inlet pipe of one district, the node does not have enough cooling time because of the short length of the pipe. Hence, the DWT decrease of this node will be slight and largely falls in the range of 0~1℃. Instead, water distributed to the end node on a DWDS pipe which will flow through a long distance in the pipe with low pipe wall temperature, could have enough cooling time. Therefore, the DWT decrease of this end node will be significant and largely falls in the range of 2~3℃ and 3~4℃.

As for DWT reduction performance of different kinds of pipe cover, circumstance 3 with PA and grass cover has the best performance on DWT reduction under the same setting (maximum, median, minimum). For instance, under the maximum setting of influence level, about 52% of nodes in four test districts have a DWT decrease of more than 2℃ in circumstance 3, which is more than the group of the same setting in circumstance 1 and circumstance 2. Also, similar results can be obtained in the other two median and minimum influence levels.

Although the simulation results show that changing the pipe cover to grass from regular tile cover has a relatively better effect of DWT decrease compared with changing to PA and PICP, it cannot be determined that the grass cover is more recommended. In addition to the effect of different pavement materials on DWT decreasing, the influence level of grass and pervious pavement on DWT also depends on the porosity and thickness of permeable materials in different circumstances (Kevern et al., 2009). Also, different soil and soil moisture compositions can affect soil temperature, which could influence DWT further. Besides, implementing different types of pipe cover should correspond to urban planning and design to fulfil the requirements of daily life for the public. Therefore, it is better to determine which kinds of permeable ground cover to use by local experiment.

Another critical factor that should be considered is the cost of different pervious pavements. The material costs of PA and PICP are 50 cents to $1 per square foot and $2~10 per square foot, respectively. The maintenance costs of PA and PICP both range from $0.01~0.02 per square foot per year for vacuum sweeping three to four times (Region, 2012). The price of sod ranges from $0.35 to $0.65 per square foot (HomeAdvisor). The maintenance cost of municipal lawn is variable with different requirements and labor costs, including lawn mowing, trimming, pesticide treatment and other related work. Other costs will vary with different construction circumstances, project size, base material (such as flay soil and stones).

Based on the above, although the grass cover is cheaper (in cost of material) and relatively more effective for decreasing soil temperature and DWT than pervious concrete, it should not be forgotten that a vital function of permeable pavement is to reduce the run-off flow. Therefore, the choice of permeable material needs to consider its primary purpose: reducing soil temperature or run-off flow.

5.5 Chapter discussion

In this part, the measures are considered from the point of pipe cover (or soil cover). Changing pipe cover measures can be named the 'negative measure', which is constant construction. Moreover, to further reduce the soil temperature and DWT, permeable pavement can be implemented with spraying water, especially in hot weather. Hence, spraying water can be seen as the ‘positive measure’ which is more flexible in regulating the soil temperature. The positive measure depends on the factual demand. Sprinkler, which is usually used for irrigating lawn in the urban green belt, can also be used for sprinkling water on the ground surface. It can be installed on the grass cover, porous asphalt (or concrete) and permeable interlocking concrete pavements. The water from sprinklers can infiltrate through the permeable pavement and reach the soil under the tile cover. The increase of soil moisture will decrease the thermal diffusion coefficient of soil. Hence, the surrounding soil of DWDS pipes will transfer less heat to the pipe wall during a particular period of spraying water (Al-Kayssi et al., 1990; Jin and Mullens, 2014; Roxy et al., 2014). In addition, water evaporation from the ground surface and air will also lower the surface temperature.

Another relatively cheaper way of spraying water can be fulfilled by water trucks. It does not need any construction of infrastructures like sprinklers and sprayers. Furthermore, using a watering truck is more flexible, depending on the weather condition and has a relatively low maintenance cost than installing sprinklers or sprayers in extensive areas. However, a water truck also has the disadvantage of not spraying water in large areas simultaneously. Therefore, it is only available to implement in relatively small areas with a constant low advancing velocity.

However, the current research of correlation between soil moisture content and soil temperature mainly focuses on the temperature of surface soil and shallow soil (the depth of 0~20cm) (Jin and Mullens, 2014; Roxy et al., 2014; Fini et al., 2016; Ferguson et al., 2008; Cheng et al., 2019). Therefore, more research is still needed on the impact of soil moisture on soil temperature at a depth of DWDS pipe installation, considering the variation of soil moisture at different depths.

5.6 Chapter summary

Chapter 5 presents the information of measures and interventions for controlling and reducing DWT from the point of pipe cover. There are three measures introduced to the simulation model of DWT, which are PA, PICP and grass cover. After comparing the DWT in 4 test districts in Almere, pipes with grass cover have better performance on decreasing DWT than PI and PICP, decreasing water temperature 3.5~4.5℃ maximum. Also, the material cost of grass cover is cheaper than PA and PICP, which means that grass cover could be the better choice from the point of decreasing soil temperature (Region, 2012). However, the implementation of lawn has more limitations than PA and PICP. In addition, the performance of DWT decrease in each circumstance is the only speculation based on current literature. The actual temperature dynamics at a depth of DWDS pipe installation with different types of permeable material is still needed more further research.

Chapter 6 Discussion

In this chapter, the issue about DWT is addressed with the sequence of theory, observation to practice. This chapter firstly evaluates the current research on the relation between DWT and drinking water quality. Secondly, the severity of high DWT in DWDS pipe is assessed based on current research. Thirdly, some recommended approach to cope with the occurrence of high DWT is discussed.

6.1 The relation between drinking water temperature and drinking water quality

The microorganism stability of water is strong linked with DWT, which is an essential factor influencing bacterial growth and competition process (Prest et al., 2016). Increasing DWT has typically been associated with bacterial abundance increase in DWDS (Servais et al., 1992; Kerneis et al., 1995; Francisque et al., 2009; Liu et al., 2013), especially with higher numbers in some indicator microorganisms such as coliforms and Aeromonas (Burke et al., 1984; LeChevallier et al., 1996). Francisque et al. (2009) found that heterotrophic plate count concentrations above 100 CFU/mL at temperatures above 18℃ are five times more than at lower DWT. Moreover, DWT can also influence the bacterial community composition by providing a competitive advantage for specific bacterial species in specific temperature ranges, including disease-causing species (Vital et al., 2007, 2012). For instance, Vital et al. (2012) showed that the specific DWT range for E. coli growth with an indigenous water community is 12~30℃. In this range, E. coli has the maximum growth rate and better competitive fitness than in other DWT ranges. Therefore, it can be confirmed that the probability of bacterial growth will increase with high DWT occurrence. The problem of bacteria growth in the drinking water can affect water quality, increasing hygienic risks and influencing the aesthetic of water and the operation of water infrastructures.

It is vital to note that DWT should be considered and studied as an integral part of the interaction among complicated physical, chemical and biological processes in DWDS pipes. Hence, the impact of DWT on drinking water quality should fulfill the full range of the drinking water standard and representative physical conditions, including chemical composition, biological stability, Assimilable Organic Carbon (AOC) / Total Organic Carbon (TOC) content, hydraulic volume, pipe infrastructure materials, etc. (Agudelo-Vera et al., 2020). Although evaluating the effect of DWT on drinking water quality is vital for determining the appropriate limit on DWT, the current research on the relationship between DWT and various biological growth (and chemical composition to some extent) is still not clear enough to determine that.

Moreover, typical DWT ranges are generally limited in a specific drinking water supply district or area. The bacterial composition of drinking water in DWDS pipes is also affected by seasonal shifts, which can mainly cause air temperature variation and change the DWT furtherly. Hence, it seems that the risk of problems associated with bacterial growth increases during summertime with relatively high DWT (Prest et al., 2016). As for this part, Pinto et al. (2014) had summarized the significant seasonal shifts in bacterial community composition in effluents of treatment utilities. Although the cause of bacterial composition change is not clear enough now, seasonal DWT variations could be involved in bacterial community characteristics of water in DWDS (Prest et al., 2016). Further research needs to determine the influence level of the impact of DWT changes caused by seasonal shifts on bacterial composition in DWDS. This research is preferred to launch in an international context to summarize the generalized conclusion from various DWT samples, water quality samples and local circumstances of DWDS in different regions (Agudelo-Vera et al., 2020).

6.2 The trend of high-water temperature occurred in DWDS

Due to the lack of large-scale monitoring of DWT in DWDS in many countries, high DWT seems rarely happens. Hence, the DWT standard is not legislated in these countries. However, with increasing global climate change and urbanization, it is expected that DWT will rise (Agudelo-Vera et al., 2015b; Levin et al., 2002).

With increasing trend of urbanization and climate change, the concept of urban heat island (UHI) has been researched for decades. However, with the research development of subsurface urban heat island (SUHI), recent results show that SUHI mainly affects the shallow subsurface, where DWDS pipes are installed (Menberg et al., 2013a, 2013b; Ferguson and Woodbury, 2007; Müller et al., 2014; Previati and Crosta, 2021; Shi et al., 2012; Huang et al., 2009). As the urbanization process, more and more infrastructures are constructed. Some infrastructures emit heat which can be seen as anthropogenic heat sources. Hence, the ground temperature in urban areas is higher than in rural areas. Warmer ground influences the DWT and water quality furtherly. Although the worst global warming will be felt many years from now, it is vital to consider the trend of DWT variation from now. The relation of DWT with the lifespan of DWDS pipes, its impact on drinking water infrastructure and water quality management should also be considered (Agudelo-Vera et al., 2020).

We believe that the occurrence of high DWT will be more frequent with the trend of global warming in future decades. However, due to the lack of DWT monitoring, it is hard to see the general trend of water temperature variation in past

years. Therefore, the trend of DWT increasing cannot be concluded from historical data. Moreover, the standard value of DWT is not easy to determine. The risk of Legionella proliferating in the domestic water supply system will increase when DWT exceeds 20℃ (Agudelo-Vera et al., 2020). Hence, the DWT in DWDS cannot be over 25℃ regulated by the Dutch government is also for inhibiting the proliferation of Legionella, especially during hot summertime (Drinking Water Directive, 2018). However, it is hard to guarantee the DWT below the regulated temperature during the drinking water supply and distribution processes. Firstly, the monitoring of DWT during water supply and distribution processes is still absent. More monitoring of DWT is needed in the whole water supply network and DWDS, especially for large cities with a complex network. The big-scale monitoring puts forward higher requirements for government investment, infrastructure networking and high-level informatization of society. Secondly, there is no effective operational measure to resolve noncompliance in some points and small districts. Although flushing can work locally to shorten the residence time of drinking water, it does not have enough pressure capacity to flush the whole system. Also, flushing can only provide short-term amelioration, which is not practical for long term improvement with the severe trend of global warming (Agudelo-Vera et al., 2020). Similarly, there is no operational intervention to resolve noncompliance occurring on a large scale or even on the whole network scale. The construction measures and social measures will be introduced in the next part.

In summary, the impact factors on DWT are put forward systematically for the first time in this thesis, which provides some directions for further research of drinking water temperature more or less.

6.3 Improved approach to control water temperature and improve water quality

Based on the current research of DWT and the trend of DWT variation, improved approaches to control DWT are addressed in this section. This section will discuss in two aspects: i) monitoring and prediction; ii) construction measures and social management.

6.3.1 Monitoring and prediction method

Monitoring DWT in DWDS and the domestic water supply system could not be fulfilled by on-site measurement, which may be expensive, inefficient, too late to find and solve relative problems. It should be achieved by the implementation of smart meters and water infrastructures networking. Smart water meters will be more and more widely used with the increased requirement for water quality and human health. At the same time, the implementation of smart meters cooperated with the networking process development of municipal infrastructures can accomplish the target of monitoring DWT at each node of the DWDS network. After constructing the network system of smart meters, water quality indexes, including DWT, can be monitored together. In addition, with the help of the monitoring program and threshold setting of DWT, the system can send out a warning when DWT exceeds the threshold. The prediction and even early warning system can help engineers and researchers to find the accident location and irregular data timely and resolve the problem as fast as possible.

Compared with constructing the DWT monitoring network, prediction of DWT as an early warning system is also available. The prediction could be built on the DWT simulation model introduced in chapter 4. After calibrating the model of city Almere, we summarized several possible reasons for measurement points, matched not well with the simulation result. Hence, based on the current model framework, we can also provide approaches to improve the accuracy of the DWT simulation model. This thesis only explains the calibration process of regulating the outer pipe wall temperature of DWDS. The model calibration of city Almere is completed by setting the temperature of different pipes according to the actual circumstance. Although the simulation result shows relatively good conformity with measurement data, the calibration strategy is still single and rough to cope with the complex DWDS in urban areas.

Based on the understanding of the coefficient setting in EPANET-MSX and the difference between ‘[CONSTANT]’ and ‘[PARAMETER]’ (explained below table 15), we only set outer pipe wall temperature (T_wall) as ‘[PARAMETER]’, which is not constant for each pipe segments. Therefore, it is possible to set other coefficients as ‘[PARAMETER]’ to improve the model accuracy. For instance, ‘ground_pen_depth’ represents how big the scope of DWT inside effect on surrounding soil linked with the heat convective process outside the pipe. The heat convective process outside will happen when the surrounding soil temperature is lower than DWT. The setting of the ‘ground_pen_depth’ value is constant as 0.2m in the simulation process, explained in section 4.3.5. However, the coefficient of ‘ground_pen_depth’ could be set as different values for different pipe segments. The setting values of ‘ground_pen_depth’ depends on the soil texture, soil humidity, pipe diameter and flow velocity inside the pipe. However, the relation of penetration depth and its impact factors mentioned above is not clear enough now. Therefore, we did not pay more attention to this coefficient. In addition, the complex water distribution network includes many different kinds of pipe diameter. Indeed, it is not easy to set specific values of ‘ground_pen_depth’ for each segment. In addition, the thermal conductivity of pipe could also be set as different values for different pipe materials. Indeed, other coefficients related to DWDS pipe properties can be regulated with the same thinking.

As for improving the simulation model by regulating the model framework, the DWT simulation model can also be improved to divide the outer pipe wall temperature (T_wall) setting of different temperatures with different time periods like day and night. The pipe wall temperature (T_wall) setting is constant during the whole day in the current model. Hence, it may limit the simulated result and influence the accuracy. Based on the measurement data collected in Weesperkarspel during 2020/05/21~2020/07/01, one day has been divided into daytime and nighttime with the standard: daytime: 7:00-19:00; night time: 0:00-7:00 & 19:00-24:00. The highest temperature during daytime and lowest temperature during nighttime was chosen to find the most significant temperature difference. Figure 26 shows the result. It reveals that 20% of the air temperature difference between day and night is higher than 0.5℃. Also, there is one point with the temperature difference between day and night bigger than 1℃. Furthermore. it needs to consider that the Netherlands is a country with an oceanic climate that has a small temperature difference during day and night. However, in the north of China, some other countries and regions have a big air temperature difference during day and night (which can reach 20℃ in some areas) and lead to significant soil temperature differences underground. Indeed, it is preferred to introduce the time parameter of daytime and nighttime in the DWT simulation model to set the soil temperature of different periods separately.

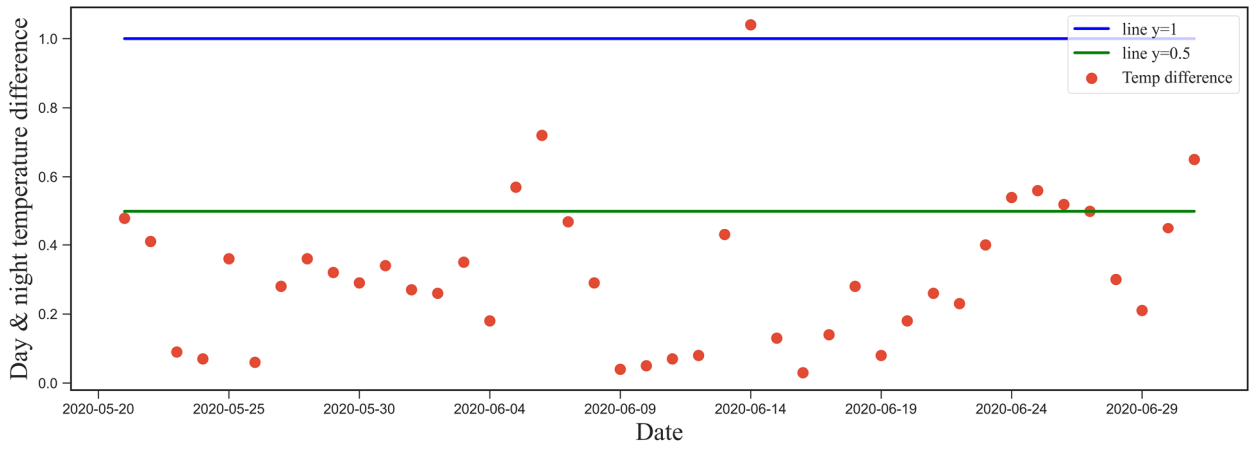


Figure 26 Temperature difference under tile cover over day and night during 2020/05/21~2020/07/01 at Weesperkarspel

* Two reference line of y=0.5 and y=1 is added which is more convenient to find if there were some big difference

In addition, after completing the prediction system and early warning system of DWT based on the current simulation model, the public broadcast system can also be managed. Authorities could inform people to note the risk of drinking water quality and avoid them drinking tap water via short message, radio, television and internet service.

6.3.2 Construction measures and social management

This thesis firstly summarizes the impact factors on DWT in DWDS systematically, though there are more impact factors not considered in the case study. It can become a guideline for developing measures to reduce water temperature from various aspects. Besides the measures considered from the point of ground cover (or pipe cover), other four kinds of measures and interventions can be involved to decrease DWT and guarantee drinking water quality: i) low impact development (LID) construction, ii) utility tunnel, iii) process disinfection and iv) new material for pipe production.

Firstly, the measures to control DWT can be combined with LID construction. Changing impervious pavement to the pervious pavement (PA, PICP, lawn) presented in chapter 5 is also an aspect of LID. Moreover, the pipe cover can be related to LID construction like grass swale, presented in appendix 9. Pipe cover with grass swale has a similar function to pipe cover under grass, but grass swale has better performance on infiltration. The precipitation and rainwater collected in the grass swale can infiltrate into the soil to further increase soil moisture and decrease soil temperature. In addition, the three-dimensional greening can provide more shade area and inhibit the effect of urban heat island, which can facilitate to reduce DWT.

Secondly, it seems that the utility tunnel is also an available solution to decrease DWT. The utility tunnel is a comprehensive corridor for underground urban pipelines, a tunnel space built underground in urban areas to integrate all kinds of engineering pipelines, such as electricity, communication, gas, heating, water supply and sewer pipes. It is equipped with special inspection ports and hoisting ports. The thermal conductivity of air is smaller than the soil, which means that air is better for temperature heat preservation and isolation. Moreover, integrating pipelines into the tunnel is convenient for building the monitoring system and maintenance of these pipelines. However, the implementation of unified planning, unified design, unified construction and management of monitoring systems are essential factors considered in utility

tunnel design. Hence, the construction of a utility tunnel needs high fixed and operational costs. It also needs enough underground space in urban areas and complex design, which is unavailable for some cities.

Thirdly, process disinfection is also an important aspect to guarantee water quality during the distribution process. For instance, DWDS pipes can be installed with point-of-treatment, such as small packaged UV systems. Such systems are commercially available and increasingly common in countries such as South Korea (Agudelo-Vera et al., 2020). This method is possible to cope with the water quality deterioration caused by the DWT rise. Moreover, additional disinfection can provide extra protection for drinking water, especially after a long supply and distribution process. However, the social acceptance, profitability, and regulatory implications of such an approach are still absent and far-reaching.

Fourthly, an available direction for future development is developing a new material that has good performance for temperature insulation. The heat conductive coefficient of the new material is low, which is ineffective for heat transfer. The new material can be used in pipe manufacturing and pipe cover, respectively. For extant pipelines, the new material can be covered for insulation, especially in urban areas with a high risk of DWT rise. Moreover, cost should also be considered in this approach as a practical index.

The measures mentioned above were not discussed in detail due to the work load and limitation of current simulation model. Some research has been conducted showing there is potential (Curiel-Esparza and Canto-Perello, 2005; Canto-Perello and Curiel-Esparza, 2006; Shafique and Kim, 2017; Qin et al., 2018; He et al., 2019).

Additionally, another construction method like installing DWDS pipe deeper is also effective for enhancing the ability to cope with soil temperature fluctuation. Nevertheless, changing the depth of DWDS pipes includes lots of excavation works and pressure regulating for the new DWDS network. It may not be available for many places after considering the soil texture, street reconstruction, investment and social cost. Another vital aspect, which is valuable to present, is to take various costs into account. Firstly, the fixed investment of a project should be determined. Then, under the constraint of the total cost, we should calculate the sum of the construction cost of each measure, which cannot be higher than the total cost. Then, the maintenance cost should be considered. In some regions with high labour costs, the high maintenance frequency and maintenance cost should be avoided, such as lawn.

Furthermore, choosing feasible measures should correspond to the actual circumstance of different areas, including DWT reducing performance, the function of the ground surface, construction cost and feasibility, maintenance cost and feasibility, daily requirement and public acceptance.

Finally, with the future development of urban environment (e.g., more expansive use of geothermal energy, expanded installation of urban heating system, etc.) and a better understanding of water-energy nexus, the further alternations of DWT issue in the built environment and their effect on drinking water quality are necessary to research more.

Chapter 7 Conclusion

In conclusion, this thesis systematically elaborates the overall process to cope with the emergence of high water temperature in the drinking water distribution system. It includes the following parts: i) summarizing and classifying impact factors on drinking water temperature, ii) calibrating the water temperature simulation model with these impact factors to predict the hotspots in the water distribution system, and iii) proposing feasible measures to control drinking water temperature from the point of pipe cover.

The conclusion can be summarized in the following three parts, corresponding to three research questions presented in section 1.3.

- Measurement of drinking water temperature and soil temperature in two cases (six weeks of measurements at Weesperkarpel and three weeks of measurements at Boszoom, the Netherlands) certifies that the soil temperature surrounding the distribution pipes mainly affects the water temperature inside. This means that the soil temperature surrounding pipes can be set as the boundary temperature to simulate water temperature because the residence time of drinking water in distribution pipes is longer than the time of heat transfer process between drinking water and soil. The measurement data also provides four kinds of impact factors on soil temperature, which can further influence drinking water temperature: i) pipe cover; ii) shade; iii) other municipal infrastructures (district heating pipe); iv) groundwater level. From the standpoint of pipe cover, the impact factors can be further divided into five species: 'complete under grass cover', 'complete under tile cover', 'under grass near tile cover', 'under tile near grass cover', and 'half under grass and half under tile cover'. Moreover, the influence level of each impact factor on soil temperature surrounding water pipes is determined as a range by statistical processing and visualization of the measured data.

- The simulation model of drinking water temperature building in EPANET-MSX allows calculating the temperature of each pipe and junction in the water distribution system with a constant soil temperature surrounding each pipe over 24h. Moreover, the simulation model has been tested by a case study in the city of Almere. after calibration, the accuracy of the simulation model can reach around 88% with difference less than 1°C between the simulation result and corresponded measured results sampled from hydrant.

- This thesis presents three measures from the aspect of pipe cover: i) porous asphalt, ii) pervious interlocking concrete pavement, and iii) grass cover. After determining the influence level of each measure from measured data and some references, three circumstances with different combinations of measures are tested by the drinking water temperature model at some districts with hotspots in Almere. The result shows that the grass cover has the best performance of decreasing drinking water temperature among three measures. However, grass cover can only be applied in few specific cases. (e.g., urban greenbelt) and cannot be paved for the surface with bearing function. Therefore, no matter which measure is chosen, it should correspond to urban planning and design to fulfil the requirements of daily life for the public.

Furthermore, some aspects for further research of drinking water temperature are listed below.

- More data on soil temperature and drinking water temperature should be measured and collected under different covers and depths. More data makes it possible to summarize the correlation between water temperature and the variety of pipe covers. In addition, this information can provide more reference to calibrate the temperature simulation model and increase the accuracy.
- The simulation model of drinking water temperature should be tested in more cities or areas, which can further verify the feasibility of this model. Moreover, the model of any temperature-related water quality could be coupled with the water temperature model to simulate water quality in a water distribution system.
- The influence level of measures such as different types of pervious pavement on subsurface soil temperature and drinking water temperature should be measured on-site to summarize their performance separately or comprehensively.

In addition, daily monitoring of drinking water temperature should be implemented instead of only monitoring water quality at the effluent of the water treatment plant. The drinking water temperature can be measured at hydrants or particular taps installed on some junctions of the water distribution network for measuring, accumulating more data for further research. Also, a public warning system can be built combined with the daily monitoring projects on water temperature. When some areas emerge irregular high water temperature, the regulatory authority will inform the household and people potentially affected by the risk of water quality to pay attention to related issues. Moreover, operational measures like local flushing could be launched in distribution pipes of small areas.

In summary, the mechanism of water temperature on chemical and biological stability of water quality will be more explicit with further research and the higher requirement on drinking water safety. Also, the water temperature in the drinking

water distribution system is an emerging research topic in more and more countries worldwide. Therefore, government, researchers and the public should pay more attention to drinking water temperature and related water quality problems in the future.

Reference

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.; Avvedimento, S.; Boxall, J.; Creaco, E.; de Kater, H.; Di Nardo, A.; Djukic, A.; Douterelo, I.; Fish, K.E.; Iglesias Rey, P.L.; Jacimovic, N.; Jacobs, H.E.; Kapelan, Z.; Martinez Solano, J.; Montoya Pachongo, C.; Piller, O.; Quintiliani, C.; Ručka, J.; Tuhovčák, L.; Blokker, M. (2020). Drinking Water Temperature around the Globe: Understanding, Policies, Challenges and Opportunities. *Water 2020*, 12, 1049.

Agudelo-Vera, C. M., Blokker, E. J. M., & Pieterse-Quirijns, E. J. (2015). Early warning system to forecast maximum temperature in drinking water distribution systems. *Journal of Water Supply: Research and Technology—AQUA*, *64*(5), 496-503.

Agudelo-Vera, C. M., Blokker, 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., Blokker, M., & Pieterse-Quirijns, I. (2014). Early warning systems to predict temperature in the drinking water distribution network. *Procedia Engineering*, *70*, 23-30.

Agudelo-Vera, C., Blokker, M., van der Wielen, P., Raterman, B., & Dorland, E. (2015b). Drinking water temperature in future urban areas. KWR.

Al-Kayssi, A. W., Al-Karaghouli, A. A., Hasson, A. M., & Beker, S. A. (1990). Influence of soil moisture content on soil temperature and heat storage under greenhouse conditions. *Journal of Agricultural Engineering Research*, *45*, 241-252.

Average Cost of Sod Grass Per Pallet & Square Foot. HomeAdvisor. Available online: https://www.homeadvisor.com/cost/landscape/sod-prices/ (accessed on 20 June 2021)

Bean, E. Z., Hunt, W. F., & Bidelspach, D. A. (2004). Study on the surface infiltration rate of permeable pavements. In *Critical transitions in water and environmental resources management* (pp. 1-10).

Benyahya, L., St-Hilaire, A., Quarda, T. B., Bobée, B., & Ahmadi-Nedushan, B. (2007). Modeling of water temperatures based on stochastic approaches: case study of the Deschutes River. *Journal of Environmental Engineering and Science*, *6*(4), 437-448.

Benz, S. (2016). Human Impact on Groundwater Temperatures. Bauingenieur, Geo-und Umweltwissenschaften, KIT, PhD Thesis.

Benz, S.A., Bayer, P., & Blum, P. (2017a). Global patterns of shallow groundwater temperatures. *Environmental Research Letters*, *12*(3), 034005.

Benz, S. A., Bayer, P., & Blum, P. (2017b). Identifying anthropogenic anomalies in air, surface and groundwater temperatures in Germany. *Science of the Total Environment*, *584*, 145-153.

Benz, S. A., Bayer, P., Goettsche, F. M., Olesen, F. S., & Blum, P. (2016). Linking surface urban heat islands with groundwater temperatures. *Environmental science & technology*, *50*(1), 70-78.

Benz, S. A., Bayer, P., Menberg, K., Jung, S., & Blum, P. (2015). Spatial resolution of anthropogenic heat fluxes into urban aquifers. *Science of The Total Environment*, *524*, 427-439.

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

Blokker, E. J. M., van Osch, A. M., Hogeveen, R., & Mudde, C. (2013). Thermal energy from drinking water and cost benefit analysis for an entire city. *Journal of water and climate change*, *4*(1), 11-16..

Burke, V. J. M. D. K., Robinson, J., Gracey, M., Peterson, D., & Partridge, K. (1984). Isolation of Aeromonas hydrophila from a metropolitan water supply: seasonal correlation with clinical isolates. *Applied and Environmental Microbiology*, *48*(2), 361-366.

Campbell, D. T. (1960). Blind variation and selective retentions in creative thought as in other knowledge processes. *Psychological review*, *67*(6), 380.

Canto-Perello, J., & Curiel-Esparza, J. O. R. G. E. (2006). An analysis of utility tunnel viability in urban areas. *Civil Engineering and Environmental Systems*, *23*(1), 11-19.

Carraro, L., Toffolon, M., Rinaldo, A., & Bertuzzo, E. (2020). SESTET: a spatially explicit stream temperature model based on equilibrium temperature. *Hydrological Processes*, *34*(2), 355-369.

Çengel, Y. A. (2020). Heat Transfer-A Practical Approach.

Cheng, Y. Y., Lo, S. L., Ho, C. C., Lin, J. Y., & Yu, S. L. (2019). Field testing of porous pavement performance on runoff and temperature control in Taipei City. *Water*, *11*(12), 2635.

Climate monthly average (氣候月平均). Central weather bureau (交通部中央氣象局). Available online: https://www.cwb.gov.tw/V8/C/C/Statistics/monthlymean.html (accessed on 12 June 2021)

Curiel-Esparza, J., & Canto-Perello, J. (2005). Indoor atmosphere hazard identification in person entry urban utility tunnels. *Tunnelling and underground space technology*, *20*(5), 426-434.

Drinking Water Directive (Drinkwaterbesluit) (2018). Available online: https://wetten.overheid.nl/BWBR0030111/2018-07-01 (accessed on 9 June 2021)

Earle, R. L. (2013). *Unit operations in food processing*. Elsevier.

Ferguson, B., Fisher, K., Golden, J., Hair, L., Haselbach, L., Hitchcock, D., ... & Waye, D. (2008). Reducing urban heat islands: compendium of strategies-cool pavements.

Fini, A., Frangi, P., Robbiani, E., & Ferrini, F. (2016). Pervious vs. impervious pavements for sidewalks: effects on soil characteristics and physiology of two establishing urban tree species. *ISA-Arbor. com*.

Florides, G. A., & Kalogirou, S. A. (2005). Annual ground temperature measurements at various depths.

Francisque, A., Rodriguez, M. J., Miranda-Moreno, L. F., Sadiq, R., & Proulx, F. (2009). Modeling of heterotrophic bacteria

counts in a water distribution system. *Water research*, *43*(4), 1075-1087.
Ferguson, G., & Woodbury, A. D. (2007). Urban heat island in the subsurface. *Geophysical research letters*, *34*(23).
Hashim, W., Noor, M. N. M., Shaffie, E., Rahman, Z. A., & Arshad, A. K. (2018, April). Cooling time of porous asphalt pavement affecting compaction process due to various raining condition. In *IOP Conference Series: Earth and Environmental Science* (Vol. 140, No. 1, p. 012070). IOP Publishing.
He, B. J., Zhu, J., Zhao, D. X., Gou, Z. H., Qi, J. D., & Wang, J. (2019). Co-benefits approach: Opportunities for implementing sponge city and urban heat island mitigation. *Land use policy*, *86*, 147-157.
Hemmerle, H., Hale, S., Dressel, I., Benz, S. A., Attard, G., Blum, P., & Bayer, P. (2019). Estimation of Groundwater Temperatures in Paris, France. *Geofluids*, *2019*.
Herb, W. R., Janke, B., Mohseni, O., & Stefan, H. G. (2008). Ground surface temperature simulation for different land covers. *Journal of Hydrology*, *356*(3-4), 327-343.
Huang, S., Taniguchi, M., Yamano, M., & Wang, C. H. (2009). Detecting urbanization effects on surface and subsurface thermal environment—A case study of Osaka. *Science of the total environment*, *407*(9), 3142-3152.
Ingerson-Mahar, M., & Reid, A. (2013). Microbes in pipes: the microbiology of the water distribution system.
van der Hoek, J. P., Bertelkamp, C., Verliefde, A. R. D., & Singhal, N. (2014). Drinking water treatment technologies in Europe: state of the art–challenges–research needs. *Journal of Water Supply: Research and Technology—AQUA*, *63*(2), 124-130.
Janssen, L.P.B.M. & Warmoeskerken, M.M.C.G., (1991). Transport phenomena Data Companion. *Delftse Uitgevers Maatschappij b.v.*, Delft, the Netherlands.
Jin, M. S., & Mullens, T. (2014). A study of the relations between soil moisture, soil temperatures and surface temperatures using ARM observations and offline CLM4 simulations. *Climate*, *2*(4), 279-295.
Kerneïs, A., Nakache, F., Deguin, A., & Feinberg, M. (1995). The effects of water residence time on the biological quality in a distribution network. *Water Research*, *29*(7), 1719-1727.
Kevern, J. T., Schaefer, V. R., & Wang, K. (2009). Temperature behavior of pervious concrete systems. *Transportation Research Record*, *2098*(1), 94-101.
Koninklijk Nederlands Meteorologisch Instituut – Ministerie van Infrastructuur en Waterstaat. Retrieved 28 November 2020 from https://www.knmi.nl/nederland-nu/klimatologie
Koreimann, C., Grath, J., Winkle, G., Nagy, W., & Vogel, W. R. (1997). Groundwater monitoring in Europe. Office for Official Publications of the European Communities.
KWR Water Research Institute (2019) Effectiveness of measures against heating drinking water in pipes (Dutch: Effectiviteit maatregelen tegen opwarming drinkwater in leidingen), available online: http://api.kwrwater.nl//uploads/2021/01/KWR-2019.080-Effectiviteit-maatregelen-tegen-opwarming-drinkwater-in-leidingen.pdf
LeChevallier, M. W., Welch, N. J., & Smith, D. B. (1996). Full-scale studies of factors related to coliform regrowth in drinking water. *Applied and environmental microbiology*, *62*(7), 2201-2211.
Levin, R. B., Epstein, P. R., Ford, T. E., Harrington, W., Olson, E., & Reichard, E. G. (2002). US drinking water challenges in the twenty-first century. *Environmental Health Perspectives*, *110*(suppl 1), 43-52.
Liu, G., Verberk, J. Q. J. C., & Van Dijk, J. C. (2013). Bacteriology of drinking water distribution systems: an integral and multidimensional review. *Applied microbiology and biotechnology*, *97*(21), 9265-9276.
Martincova, M., Dosa, M., Pekarova, P., & Holko, L. (2011). Water–soil–air temperature relationships in the Jalovecky creek catchment. *Die Bodenkultur*, *89*(62), 1-4.
Menberg, K., Bayer, P., Zosseder, K., Rumohr, S., & Blum, P. (2013a). Subsurface urban heat islands in German cities. *Science of the total environment*, *442*, 123-133.
Menberg, K., Blum, P., Schaffitel, A., & Bayer, P. (2013b). Long-term evolution of anthropogenic heat fluxes into a subsurface urban heat island. *Environmental science & technology*, *47*(17), 9747-9755.
Mihalakakou, G. (2002). On estimating soil surface temperature profiles. *Energy and Buildings*, *34*(3), 251-259.
Moerman, A., Blokker, M., Vreeburg, J., & Van Der Hoek, J. P. (2014). Drinking water temperature modelling in domestic systems. *Procedia Engineering*, *89*, 143-150.
Müller, N., Kuttler, W., & Barlag, A. B. (2014). Analysis of the subsurface urban heat island in Oberhausen, Germany. *Climate research*, *58*(3), 247-256.
Parton, W. J., & Logan, J. A. (1981). A model for diurnal variation in soil and air temperature. *Agricultural Meteorology*, *23*, 205-216.
Pinto, A. J., Schroeder, J., Lunn, M., Sloan, W., & Raskin, L. (2014). Spatial-temporal survey and occupancy-abundance modeling to predict bacterial community dynamics in the drinking water microbiome. *MBio*, *5*(3), e01135-14.
Powell, J. C., Hallam, N. B., West, J. R., Forster, C. F., & Simms, J. (2000). Factors which control bulk chlorine decay rates. *Water Research*, *34*(1), 117-126.
Prest, E. I., Hammes, F., van Loosdrecht, M., & Vrouwenvelder, J. S. (2016). Biological stability of drinking water: controlling factors, methods, and challenges. *Frontiers in microbiology*, *7*, 45.
Previati, A., & Crosta, G. B. (2021). Characterization of the subsurface urban heat island and its sources in the Milan city area, Italy. *Hydrogeology Journal*, 1-14.
Qin, Y., He, Y., Hiller, J. E., & Mei, G. (2018). A new water-retaining paver block for reducing runoff and cooling pavement. *Journal of Cleaner Production*, *199*, 948-956.
Region, W. S. (2012). Comparison of Permeable Pavement Types: Hydrology, Design, Installation, Maintenance and Cost. *Transportation*.
Riedel, T. (2019). Temperature-associated changes in groundwater quality. *Journal of hydrology*, *572*, 206-212.
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.
Roxy, M. S., Sumithranand, V. B., & Renuka, G. (2014). Estimation of soil moisture and its effect on soil thermal characteristics at Astronomical Observatory, Thiruvananthapuram, south Kerala. *Journal of earth system science*, *123*(8), 1793-1807.
Servais, P., Billen, G., Laurent, P., Levi, Y., & Randon, G. (1992). Studies of BDOC and bacterial dynamics in the drinking water distribution system of the Northern Parisian suburbs. *Revue des sciences de l'eau/Journal of Water Science*, *5*, 69-89.
Shafique, M., & Kim, R. (2017). Application of green blue roof to mitigate heat island phenomena and resilient to climate change in urban areas: A case study from Seoul, Korea. *Journal of Water and Land Development*.
Shang, F., Uber, J. G., Rossman, L. A., & Janke, R. (2008). EPANET multi-species extension user's manual. *Risk Reduction Engineering Laboratory, US Environmental Protection Agency, Cincinnati, Ohio*.
Shi, B., Tang, C. S., Gao, L., Liu, C., & Wang, B. J. (2012). Observation and analysis of the urban heat island effect on soil in Nanjing, China. *Environmental Earth Sciences*, *67*(1), 215-229.
Smeets, P. W. M. H., Medema, G. J., & Van Dijk, J. C. (2009). The Dutch secret: how to provide safe drinking water without chlorine in the Netherlands. *Drinking Water Engineering and Science*, *2*(1), 1-14.
Smith, D. R. (2011). Permeable interlocking concrete pavements. *Interlocking Concrete Pavement Institute (ICPI), Herndon, VA*.
St-Hilaire, A., Morin, G., El-Jabi, N., & Caissie, D. (2000). Water temperature modelling in a small forested stream: implication of forest canopy and soil temperature. *Canadian Journal of Civil Engineering*, *27*(6), 1095-1108.
Temperature normal values – long-term average 1991-2020 (Normale waarden temperatuur – langjarig gemiddelde 1991-2020). Royal Netherlands Meteorological Institute, Ministry of Infrastructure and Water Management (Koninklijk Nederlands Meteorologisch Instituut, Ministerie van Infrastructuur en Waterstaat). Available online: https://www.knmi.nl/nederland-nu/weer/waarschuwingen-en-verwachtingen/normalentabel (accessed on 12 June 2021)
Uhl, W., & Schaule, G. (2004). Establishment of HPC (R2A) for regrowth control in non-chlorinated distribution systems. *International journal of food microbiology*, *92*(3), 317-325.
Verweij, W., Van der Wiele, J., Van Moorselaar, I., & Van der Grinten, E. (2010). Impact of climate change on water quality in the Netherlands. *RIVM rapport 607800007*.
Vital, M., Füchslin, H. P., Hammes, F., & Egli, T. (2007). Growth of Vibrio cholerae O1 Ogawa Eltor in freshwater. *Microbiology*, *153*(7), 1993-2001.
Vital, M., Hammes, F., & Egli, T. (2012). Competition of Escherichia coli O157 with a drinking water bacterial community at low nutrient concentrations. *Water research*, *46*(19), 6279-6290.
World Health Organization. (2017). Guidelines for drinking-water quality: first addendum to the fourth edition.
Zheng C. (1989). *土壤温度的变化特点及其规律* (Doctoral dissertation).
Zlatanovic, 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.

Appendix

Appendix 1: The detailed information of measurement in Weesperkarspel

The figure A1 is the photo of the measurement point with the process of dredging soil, installing sensors, connecting sensors and data logger and soil backfilling. Figure A2 shows the circumstance of the measurement point after installing sensors for four weeks. The measurement points are half under grass cover and half under tile cover. However, the grass cover had been destroyed after installing the temperature sensors, the grass cover of the measurement points had almost become a bare land cover in a small-scale.



Figure A1 Process of sensors installation on 2020/05/20

* From left to right: i) soil evacuation; ii) sensors installation; iii) connection sensors with data loggers; iv) soil back fill



Figure A2 Circumstance after 4 weeks of sensors installation

*The grass which was originally grown on the soil surface was almost destroyed and the ground became uncovered.

Appendix 2 The detailed information of location L1 in Boszoom

1>Location L1 is in the shade in the morning, less and less shade from 11:00 am and full in the sun from 1:00 pm.

2>The pipes are on a slope: from the road it descends by approximately 6 degrees to the ditch like shown in figure A3. When the sensors were installed, this was compensated (as far as possible), so that the sensors are approximately flush with the drinking water pipe horizontally.

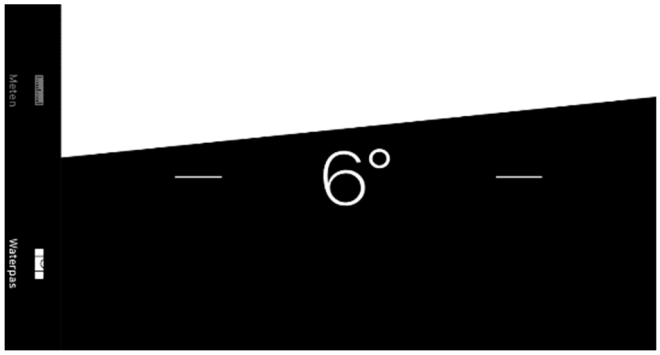


Figure A3 Sketch of the slope between the road and ditches at location L1

3> The groundwater level was not seen during the excavation work. It is therefore deeper than where the pipes installation is (at the depth of about 1.1m).

4> The diameter of the heat network pipes could not be measured on either the left or right side of the drinking water pipe. The digging trench was already very large (a lot of soil had to be moved), and time did not allow further excavation. The photo of the trench is shown in figure A4.



Figure A4 Digging trench at location L1

5> The district heating, data cables and drinking water pipe are at the same depth compared with the level line of drinking water pipe, at the depth of about 1.1m), and therefore not at the same depth with respect to ground level (because of the slope). However, the high voltage cable is higher than the drinking water pipe, and directly above it.

6> The vegetation cover on the digging trench is grass initially.

7> Wall temperature indications are provided with a Fluke 62 Mini IR Thermometer (UAN 080016) which is shown as diver ‘Dx’ in figure 8.

8> Measured temperature of fresh soil was 10.4°C on a sunny day (outside temperature was approximately 18-20°C).

9> Clamp on flow meter is placed on the drinking water pipe near location L1, south of the temperature sensor with tapping saddle in connection with the expected flow direction: the temperature sensor has no influence on the flow measurement concerns eddies, unless the flow is the other way around

10> Temperature sensors used with the loggers are PT-100 sensors.

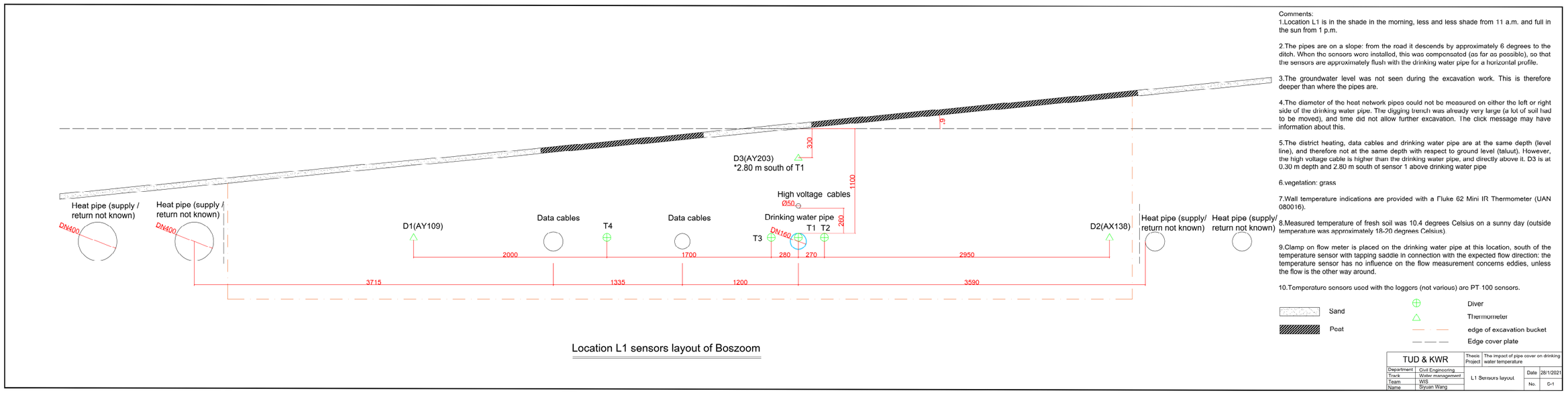


Figure A5 Technical drawing of sensors layout at location L1 of Boszoom

Appendix 3 The detailed information of location L2 in Boszoom

1> Location L2 is in the shade until 11:00 a.m., in the sun from 11:00 a.m. to 2:00 p.m., and more and more shade from 2:00 p.m.

2> The pipes are on a slope: from the road it descends by approximately 6 degrees to the ditch. When the sensors were installed, this was compensated (as far as possible), so that the sensors are approximately flush with the drinking water pipe for a horizontal profile. Where the drinking water pipe is located, the slope is less strong: approximately 2 degrees. The drinking water pipe is therefore under a 'dike' like shown in figure A6.

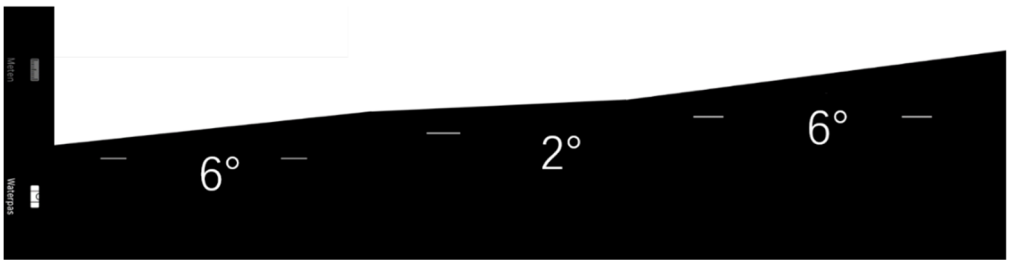


Figure A6 Sketch of the slope between the road and ditches at location L2

3> The groundwater level was not seen during the excavation work. It is therefore deeper than where the pipes installation is (at the depth of about 1.1m).

4>The diameter of the heat network pipes could only be measured to a limited extent to the left of the drinking water pipe, and not to the right of the drinking water pipe. The click message could contain information about this. The photo of the trench is shown in figure A7.



Figure A7 Digging trench at location L2

5> The district heating, electricity and drinking water pipe are at the same depth compared with level line of drinking water

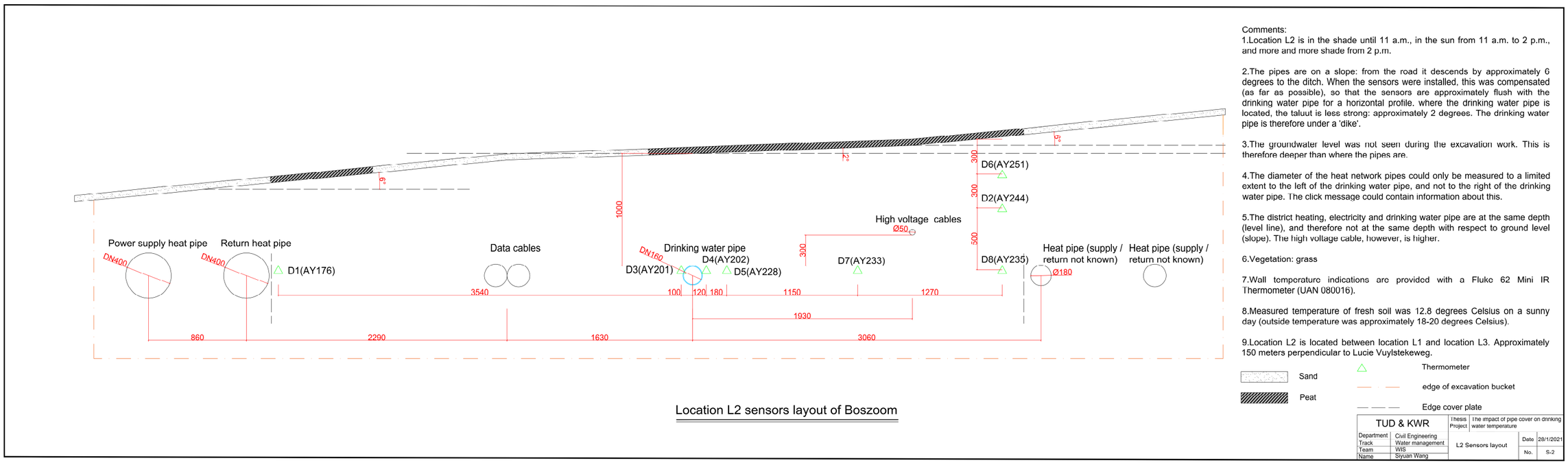
pipe, and therefore not at the same depth with respect to ground level (because of the slope). The high voltage cable, however, is higher than drinking water pipe.

6> The vegetation cover on the digging trench is grass initially.

7> Wall temperature indications are provided with a Fluke 62 Mini IR Thermometer (UAN 080016) which is shown as diver ‘Dx’ in figure 9.

8> Measured temperature of fresh soil was 12.8 ℃ on a sunny day (outside temperature was approximately 18-20℃).

9> Location L2 is located between location L1 and location L3. Approximately 150 meters perpendicular to Lucie Vuylstekeweg which is road near the location L2.



Location L2 sensors layout of Boszoom

Comments:
1.Location L2 is in the shade until 11 a.m., in the sun from 11 a.m. to 2 p.m., and more and more shade from 2 p.m.

2.The pipes are on a slope: from the road it descends by approximately 6 degrees to the ditch. When the sensors were installed, this was compensated (as far as possible), so that the sensors are approximately flush with the drinking water pipe for a horizontal profile. where the drinking water pipe is located, the taluut is less strong: approximately 2 degrees. The drinking water pipe is therefore under a 'dike'.

3.The groundwater level was not seen during the excavation work. This is therefore deeper than where the pipes are.

4.The diameter of the heat network pipes could only be measured to a limited extent to the left of the drinking water pipe, and not to the right of the drinking water pipe. The click message could contain information about this.

5.The district heating, electricity and drinking water pipe are at the same depth (level line), and therefore not at the same depth with respect to ground level (slope). The high voltage cable, however, is higher.

6.Vegetation: grass

7.Wall temperature indications are provided with a Fluke 62 Mini IR Thermometer (UAN 080016).

8.Measured temperature of fresh soil was 12.8 degrees Celsius on a sunny day (outside temperature was approximately 18-20 degrees Celsius).

9.Location L2 is located between location L1 and location L3. Approximately 150 meters perpendicular to Lucie Vuylstekeweg.

Figure A8 Technical drawing of sensors layout at location L2 of Boszoom

Appendix 4 The detailed information of location L3 in Boszoom

1> Location L3 is in direct sunlight for a large part of the day, but around noon it may be that shade from the surrounding trees.

2> The pipes are on a slope: from the road it descends by approximately 7 degrees to the ditch like shown in figure A9. When installing the sensors, compensation was (as far as possible) for this, so that the sensors are approximately flush with the drinking water pipe for a horizontal profile.

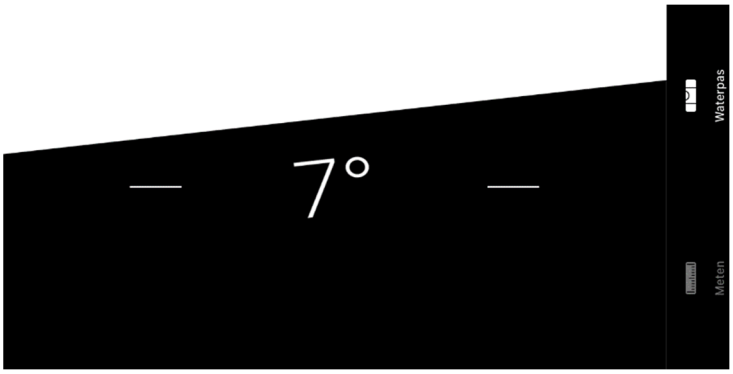


Figure A9 Sketch of the slope between the road and ditches at location L3

3> The groundwater level was approximately equal to the depth of the water mains. It is therefore possible that all sensors are just in the groundwater as shown in figure A10.



Figure A10 Digging trench at location L3

*Sensors are submerged in groundwater

4> The diameter of the supply to the heat network is smaller than the diameter of the return pipe (It is strange since you

would expect the supply pipe to have more insulation than the return pipe).

5> The heat network pipes lie in a sand bed; the rest of the soil is Peat / Clay / Earth.

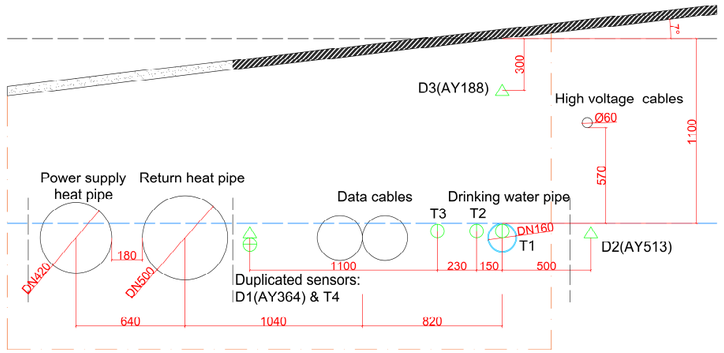
6> When the outside drinking water pipe temperature was measured (11.5°C), the temperature sensor (2062_01) of the water in the pipe indicated 12.3 °C.

7> The district heating, electricity and drinking water pipes are at the same depth (level line), and therefore not at the same depth with respect to ground level. The high voltage cable, however, is higher (so the distance between the center of the drinking water pipe line and the center of the high voltage cable is about: $\sqrt{50^2 + (110 - 53 + 6/2 + 16/2)^2} = 84.40cm$.

8> The vegetation cover on the digging trench is grass initially.

9> Wall temperature indications are provided with a Fluke 62 Mini IR Thermometer (UAN 080016) which is shown as diver 'Dx' in figure 10.

10> Temperature sensors used with the loggers are PT-100 sensors.



Comments:
1.Location L3 is in direct sunlight for a large part of the day, but around noon it may be that shade from the trees (just) falls over the location.

2.The pipes are on a slope: from the road it descends by approximately 7 degrees to the ditch. When installing the sensors, compensation was (as far as possible) for this, so that the sensors are approximately flush with the drinking water pipe for a horizontal profile.

3.The groundwater level was approximately equal to the depth of the water mains. It is therefore possible that all sensors are just in the groundwater.

4.The diameter of the supply to the heat network is smaller than the diameter of the return pipe (strange, since you would expect the supply pipe to have more insulation than the return pipe).

5.The heat network pipes lie in a sand bed, the rest of the soil is Peat / Clay / Earth.

6.When the outside drinking water pipe temperature was measured (11.5 degrees), the temperature sensor (2062_01) of the water in the pipe indicated 12.3 degrees Celsius.

7.The district heating, electricity and drinking water pipes are at the same depth (level line), and therefore not at the same depth with respect to ground level. The high voltage cable, however, is higher (so the distance between the center of the drinking water line and the center of the high voltage cable is $\sqrt{[50^2+(57+6/2+16/2)^2]}=84.40$cm. D3 is at 0.30 m depth and 1.60 m south of sensor 1 above drinking water pipe

8.Vegetation: grass

9.Clic report indicates for heat network that the pipes have a diameter of 300 mm and 500 mm and were installed in 1985 (but no reliable data).

10.Wall temperature indications are provided with a Fluke 62 Mini IR Thermometer (UAN 080016).

Sand
Peat
Diver
Thermometer
edge of excavation bucket
Edge cover plate
Groundwater level

Location L3 sensors layout of Boszoom

TUD & KWR		Thesis Project	The impact of pipe cover on drinking water temperature		
Department	Civil Engineering	L3 Sensors layout		Date	28/1/2021
Track	Water management				
Team	WIS			No.	S-3
Name	Siyuan Wang				

Figure A11 Technical drawing of sensors layout at location L3 of Boszoom

Appendix 5 Pipeline with a cover of ‘complete under grass’ (left) and ‘complete under tile’ (right)

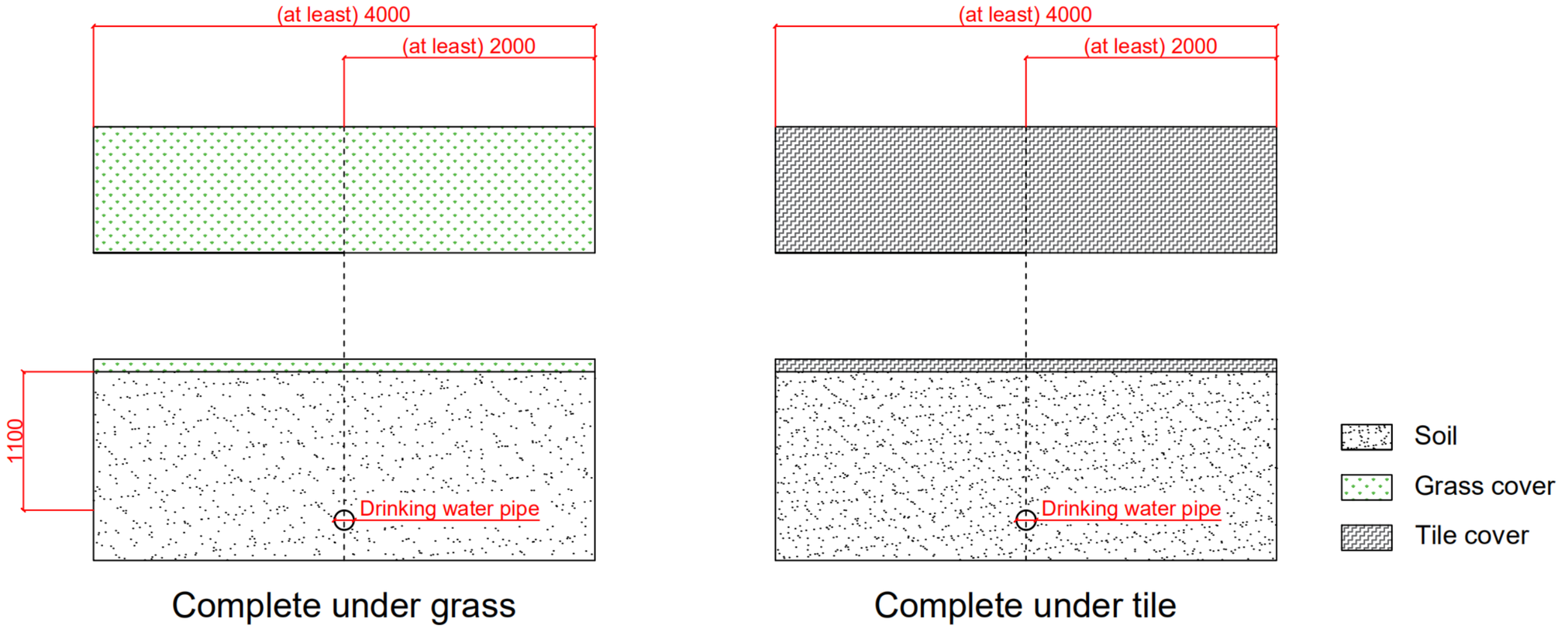


Figure A12 Pipe line with a cover of ‘complete under grass’ (left) and ‘complete under tile’ (right)

Appendix 6 Pipeline with a cover of ‘under grass near tile’ (left) and ‘under tile near grass’ (right)

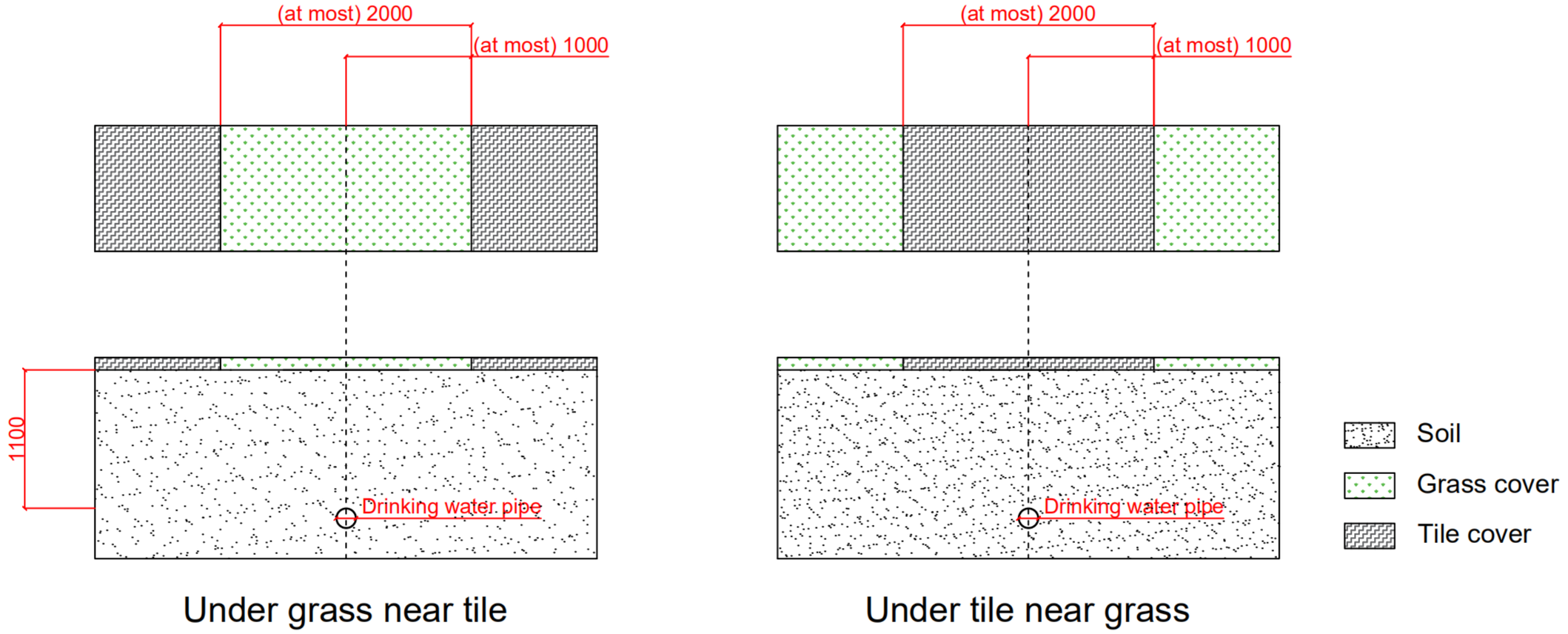


Figure A13 Pipe line with a cover of ‘under grass near tile’ (left) and ‘under tile near grass’

Appendix 7 Analysis of measurement data at location L2 in Boszoom from 2020/05/12 to 2020/0603

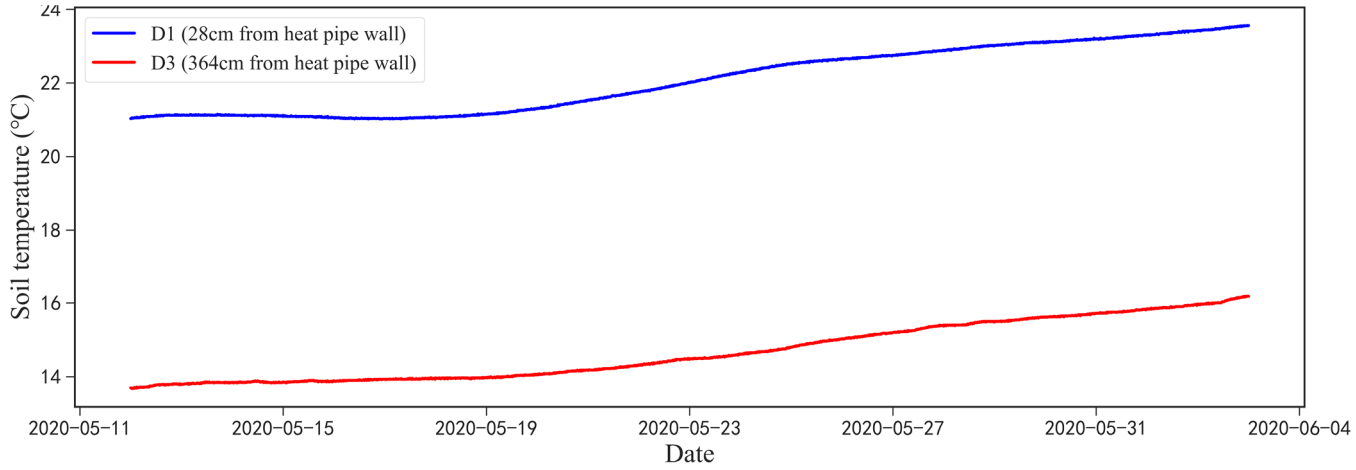


Figure A14 Measurement data of sensor D1 and D3 at location L2 in Boszoom from 2020/05/12 to 2020/0603

Figure A14 shows the temperature change with an upward trend collected by sensor D1 and D3 at location L2 in Boszoom during the period of 2020/05/12 to 2020/06/03. It can be found that the soil temperature around heat pipe (D1) is much higher than the soil temperature around the DWDS pipe (D3).

Table A1 Temperature difference between sensor D1 and D3 at location L2 in Boszoom

	D_D1-D3 (℃)
distance	354cm
max	7.75
min	7.08
average	7.40

* 'D' means 'difference'; 'D_D1-D3' means the difference between sensor D1 and sensor D3.
* The value of variance and average is calculated with the soil temperature data measured during the period of 21/05/2020 ~01/07/2020

The influence level of heat pipe can increase the soil temperature around 7.08℃~7.75℃ with the distance from heat pipe wall of about 28cm.

Appendix 8 Parameter setting of EPANET-MSX file

Table A2 Parameter configuration of the operation file by EPANET-MSX

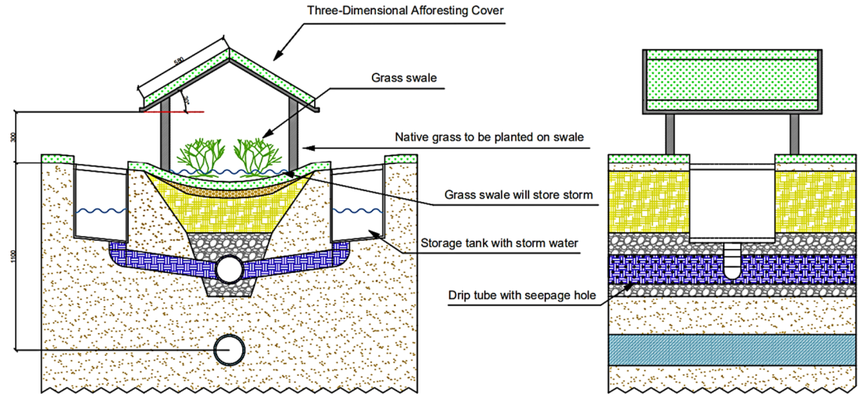
[TITLE]	**Adds a descriptive title to the data set**			
[OPTIONS]	**Sets the values of computational options**			
Classification	**Unit**	**Description**		
AREA_UNITS	M2	Surface concentration is mass/m2		
RATE_UNITS	SEC	Reaction rates are temperature/s		
SOLVER	EUL	5-th order Runge-Kutta integrator		
TIMESTEP	60	60 sec (1 min) solution time step		
[SPECIES]	**Names the chemical species being analyzed**			
Classification	**Name**	**Unit**	**Description**	
BULK[1]	T_water	C	Temperature in Celsius degree	
BULK	res_time	s	Residence time in sec	
[COEFFICIENTS]	**Names the parameters and constants used in chemical rate and equilibrium expressions**			
Classification	**Name**	**Value**	**Unit**	**Description**
CONSTANT[2]	T_wall	19	[C]	Temperature of soil, around the pipe wall, e.g. 19.
PARAMETER	T_wall	variable value	[C]	Temperature at pipe wall, To use to simulate hot spots
CONSTANT	Pr	7	[-]	Prandtl number, water at 20 C
CONSTANT	rho_water	1e3	[kg/m3]	Density of water
CONSTANT	Cp_water	4.19e3	[J/kg.K]	Specific heat capacity of water
CONSTANT	lambda_water	0.57	[W/m.K]	Thermal conductivity coefficient of water
CONSTANT	lambda_PVC	0.16	[W/m.K]	Thermal conductivity coefficient of PVC (pipe material)
CONSTANT	lambda_soil	1.6	[W/m.K]	Thermal conductivity coefficient of soil
* Thickness of the pipe wall is not in EPANET, it depends on pipe material and pipe strength and pipe diameter. We estiamte that pipe wall thickness / pipe diameter = 7% (PE will be more, ca. 15%, PVC will be less, ca. 3%) based on KWR 2012.017 info on pipe wall thickness				
CONSTANT	pipewall_ratio	0.052	[-]	Pipe wall thickness/diameter of pipe for calculate
CONSTANT	ground_pen_depth	0.20	[m]	The penetration depth into the soil where temperature is influenced by water temp
* Nusselt numbers vary with Reynolds number, for turbulent flows, Nu is presented as a formula and defined in [TERMS] section				
CONSTANT	Re_cutoff_1	10	[-]	Cutoff value for low Reynolds numbers (stagnant)
CONSTANT	Re_cutoff_2	2300	[-]	Cutoff value for high Reynolds numbers (turbulent)
CONSTANT	Nu_stagnant	5.8	[-]	Nusselt value for low Reynolds numbers (stangnant flow)
CONSTANT	Nu_laminar	3.66	[-]	Nusselt value for medium Reynolds numbers (lamainar flow)
[TERMS]	**Defines intermediate terms used in chemical rate and equilibrium expressions**			
Name	**Expression**		**Unit**	**Desicription**
Lambdda_pipe	lambda_PVC		[-]	Temperature conduction coefficient of pipe wall determined by diifferent pipe material
Nu_turbulent	0.027 * Pr^0.33 * Re^0.8		[-]	Nusselt number for Re > 2300 (turbulent flow)

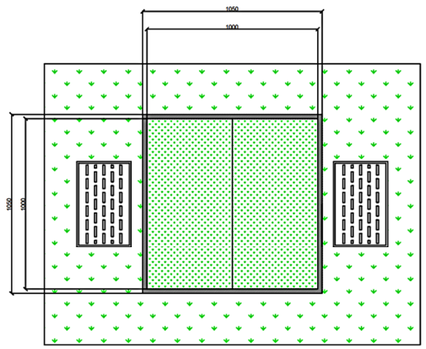
Nu	STEP(Re_cutoff_1 - Re) * Nu_stagnant + STEP(Re - Re_cutoff_1) * STEP(Re_cutoff_2 - Re) * Nu_laminar + STEP(Re - Re_cutoff_2) * Nu_turbulent		[-]	Determine the Nusselt number for different pipe by "STEP" calculation
diam_1	D		[m]	Inner pipe diameter
diam_2	diam_1 + pipewall_ratio * diam_1		[m]	Outer pipe diameter, including pipe wall thickness
diam_3	diam_2 + 2 * ground_pen_depth		[m]	Outer pipe diameter plus penetration depth of soil where temperature is influenced by DWT
* 'log' is natural logarithm (ln)				
h_1	Nu * lambda_water		[W/m.K]	Thermal conductance - water (* pipe_length*pi excluded)
h_2	2*lambda_pipe/log(diam_2/diam_1)		[W/m.K]	Thermal conductance - pipe wall (* pipe_length*pi excluded)
h_3	2*lambda_soil/log(diam_3/diam_2)		[W/m.K]	Thermal conductance - soil around pipe (* pipe_length*pi excluded)
h_total	1/(1/h_1 + 1/h_2 + 1/h_3)		[W/m.K]	The overall heat transfer coefficient
kk	4 * h_total /(rho_water * Cp_water * diam_1 * diam_1)		[-]	The cofficient of equation (2) before ((T_outer wall - T_water))
[PIPES]	**Supplies the rate and equilibrium expressions that govern species dynamics in pipes**			
Classification	**Name**	**Expression**	**Unit**	**Description**
* Residence time				
RATE	res_time	1	[s]	Residence time of each pipe and node
* Temperature of water				
RATE	T_water	kk * (T_wall - T_water)	Celcius degree	The differential equation of temperature change
[QUALITY]	**Supplies initial conditions for selected species throughout the network**			
Classification	**Name**	**Quality**	**Value**	**Description**
GLOBAL	/	T_water	13.5	Using the 'GLOBAL' specifier to set values throughout the network
NODE	Reservoir 1	T_water	13.5	Set the value of water temperature for different reservoirs, tanks, etc.
[PARAMETERS]	**Allows parameter values to be assigned on a pipe-by-pipe basis**			
* Set different value of specific pipe with parameter which has defined in [coefficient]				
[REPORT]	**Specifies reporting options**			
Classification	**Name**	**Status**	**Description**	
NODES	/	ALL	Presents all nodes in the report	
LINKS	/	ALL	Presents all links in the report	
SPECIES	T_water	YES/NO	'YES': Report results for water temperature to all nodes and links; 'NO': Do not report water temperature in result	
SPECIES	res_time	YES/NO	'YES': Report results for residence time to all nodes and links; 'NO': Do not report residence time in result	

Notification:

1. Bulk phase species are chemical or biological components or parameters like temperature that exist within the bulk water phase and are transported through the system with the average water velocity (Shang et al., 2008);
2. It is available to set 'PARAMETR' or 'CONSTANT' in [COEFFICIENTS] of any aspect which is needed in simulation process. 'CONSTANT' presents some unvaried coefficient by pipes and 'PARAMETER' presents the coefficient varied by pipes which could be adjusted on a pipe specific basis in the [PARAMETERS] section of the file.

Appendix 9 Measure for control drinking water temperature with grass swale





Native plants or other vegetation

Drinking water pipe

Gravel base

Steel framework

Mulch material

Grass cover

Bio-retention soil

Sand material

Drip tube

Comments:

1. This measure combines LID concept with drinking water pipe. Grass swale could be constructed upon the drinking water pipe with a three-dimensional greening which is about 30cm above grass swale.

2. A grassed swale is a graded and engineered landscape feature appearing as a linear, shallow, open channel with trapezoidal or parabolic shape. The swale is vegetated with flood tolerant, erosion resistant plants.The design of grassed swales promotes the conveyance of storm water at a slower, controlled rate and acts as a filter medium removing pollutants and allowing storm water infiltration. When properly designed to accommodate a predetermined storm event volume, a grassed swale results in a significant improvement over the traditional drainage ditch in both slowing and cleaning of water. Based on the specific design, the ground structure of grass swale consists of mulch material, bio-intention soil and gravel base which is for planting vegetation, inhibiting pollution penetration and drip tube installation respectively. Each layer is separated by filter fabric. Combined with the water tank which can store storm water, link with drip tube (drainage pipe) and permeate to soil and ground water level further.

3. Three-dimensional greening refers to a greening method that makes full use of different site conditions to choose climbing plants and other plants to plant, attach or pave on various structures and other spatial structures, including overpasses, building walls, slopes, river banks, Greening on roofs, courtyards, flower stands, scaffolds, balconies, corridors, columns, fences, dead trees and various rockery and building facilities.

4. The combination of grass swale and three-dimensional greening has three main functions:
   - The grass cover of grass swale and three-dimensional greening frame provide a double grass cover on drinking water pipe;
   - The three-dimansional frame will provide extra shade when it is constructed on drinking water pipe;
   - Grass swale could store storm water when it rains, the water stored in swale is helpful to decrease run-off flow and soil temperature which may affect drinking water temperature further. Storm water with shade and cover from three-dimensional greening frame will decrease the evaporation rate and maintains for a relative long time in grass swale with better performance for controlling soil temperature.

   In summary, all the functions contribute to prevent the occurrence of high water temperature.

5. The three-dimensional frame adopts a modular design. Each frame can be seen as a module and covers an area of about 1 square meter, and the length and width of its impact area can be flexibly adjusted by assembling different numbers and layouts of modeules according to the actual situation. The maintenance of the three-dimensional frame is also convenient which can fix or replace some parts of them when some modules are broken.

In conclusion, the system built by grass swale and three-dimensional greening frame could control drinking water temperature effectively with properties of ecological, sustainable, multi-functional and easy maintenance.

Measure 1: Grass swale with three-dimensional greening with storage tank

Thesis Project	The impact of pipe cover on drinking water temperature	Proportion	1:25
		Date	15/05/2021
		No.	M-2
Faculty	Civil Engineering	Measure 1: Grass swale with three-dimensional greening with storage tank	
Track	Water management		
Name	Siyuan Wang		
Stu. ID.	5100852		

Figure A15 Grass swale with three-dimensional greening with storage