2nd International Joint Conference on Water Distribution Systems Analysis & Computing and Control in the Water Industry
Valencia (Spain), 18-22 July 2022
doi: https://doi.org/10.4995/WDSA-CCWI2022.2022.14116

MEASURING DRINKING WATER TEMPERATURE CHANGES IN A DISTRIBUTION NETWORK

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Abstract

During distribution the drinking water temperature changes due to the temperature of the soil surrounding the drinking water distribution network (DWDN). A drinking water temperature below 25 °C at the tap is required to meet Legionella prevention standards and/or drinking water standards. With climate change, urbanisation and the energy transition towards more district heating networks, the urban subsurface will heat up further, and more exceedances of the 25 °C threshold are expected.

To understand the effectiveness of various measures to keep drinking water temperature below the threshold a modelling approach was followed. The drinking water temperature model (WTM) calculates drinking water temperatures at each customer from a hydraulic network model and heat conduction from the outside of the pipe wall, where the soil temperature is kept constant and the soil is thus assumed to be an infinite heat source. The WTM was validated with measurements in a DWDN on relatively small diameters (150 mm or smaller) and at locations far enough from the source so that equilibrium with the soil temperature was already reached (i.e. the influence of residence time was not validated). In reality, the soil is not an infinite heat source, but is affected by the drinking water temperature. We therefor developed an enhanced WTM (called WTM+) which uses an extra insulation layer (of soil material) around the drinking water pipe to account for the soil which is affected by the drinking water temperature. In order to determine a suitable length scale for this extra insulation layer, and to validate the WTM+, we measured drinking water temperatures in two real case studies.

Case study 1 is a single 1 km pipe where we manipulated flows, and thus residence time. Case study 2 is a DWDN with a variation in diameters and residence times. Designing and executing these measurements proved to be quite a challenge. In case study 1 the incoming drinking water temperatures and soil temperatures were not stable during the three weeks of measurements. The temperature changed typically less than 1.5 °C over 1 km, and the sensors had a resolution of only 0.1 °C. In case study 2 the measurements were done on a single day (morning, and repeated in the afternoon), and were quite stable. The drinking water temperature changed up to 8 °C over the course of the residence time. However, as the DWDN hydraulic network model is never perfect, the residence times are not all known accurately, and the surrounding soil temperatures, that may have varied quite a lot over the DWDN, were not measured. Nevertheless, the case studies did prove to be suitable for validating the WTM+, including the effect of residence time.

Keywords
Drinking water temperature, measurements, real DWDN.

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1. INTRODUCTION

During distribution the drinking water temperature changes due to the temperature of the soil surrounding the drinking water distribution network (DWDN). In the Netherlands and many other countries, a drinking water temperature below 25 °C at the tap is required to meet Legionella prevention standards and/or drinking water standards [1]. With climate change, urbanisation and the energy transition towards more district hearing networks, the urban subsurface will heat up further, and more exceedances of the 25 °C threshold are expected [1].

To understand the effectiveness of various measures to keep drinking water temperature below the threshold a modelling approach was followed. The drinking water temperature model (WTM, [2]) calculates drinking water temperatures at each customer from a hydraulic network model and heat conduction from the outside of the pipe wall, where the soil temperature is kept constant and the soil is thus assumed to be an infinite heat source. The WTM was validated with measurements in a DWDN on relatively small diameters (150 mm or smaller) and at locations most likely beyond the maximum heating time (i.e. the influence of residence time was not validated).

The WTM equations [2] show that in a Ø100 mm pipe the drinking water temperature increases with 90% of the initial temperature difference between drinking water and the pipe wall within less than 2 hours. However, this approach assumes infinite heat capacity of the soil and does not take into account heat exchange from drinking water to soil. In reality the soil is not an infinite heat source, but is affected by the drinking water temperature. As drinking water flows through these pipes year after year, the influence on the surrounding soil may not be neglected. This would mean that in the example above, the time for the drinking water temperature to increase may be (much) longer than 2 hours. We therefor introduced an enhanced WTM (called WTM+) which uses an extra insulation layer (of soil material) around the drinking water pipe to account for the soil which is affected by the drinking water temperature. In order to determine the size of this extra insulation layer, and to validate the WTM+ we measured drinking water temperatures in two real case studies. Case study 1 is a single pipe stretch of ca. 1 km where we manipulated flows, and thus residence time. Case study 2 is a DWDN with a variation in diameters and residence times. Designing and performing these measurements proved to be quite a challenge. This paper shows the results of the validation measurements.

2. BACKGROUND ON MODELLING AND VALIDATION APPROACH

The goal of the measurements was the validation of the WTM as a function of residence time [2, 3]:

$$T_{water}(t,\tau) = T_{boundary}(t) + \left(T_{water,0}(t) - T_{boundary}(t)\right) exp(-k\tau) \quad (1)$$

$$k = \frac{4 \cdot \alpha_{water}}{D_1{}^2 \left(\frac{1}{Nu} + \frac{\lambda_{water} \cdot ln\left(\frac{D_2}{D_1}\right)}{2\lambda_{pipe}} + \frac{\lambda_{water} \cdot ln\left(\frac{D_3}{D_2}\right)}{2\lambda_{soil}}\right)} \quad (2)$$

Where k is the overall heat transfer coefficient [2], which depends on characteristics of the water, and the insulating material of the pipe and pipe surroundings, and in the case of a flowing medium on the Nusselt number (Nu). For the boundary conditions it is assumed that $T_{water}(\tau=0) = T_{water,0}$ and $T(\tau=\infty) = T_{boundary}$,. Conditions are time variable, where t is time and τ is the travel time. Of course, k can also be time dependent when Nu changes over time. We will assume that the equation is still valid when $T_{boundary}$ is not uniform over the pipe circumference.

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With D_1 the inside pipe diameter, D_2 outside pipe diameter ($D_2 = D_1 + 2 \times d_{pipe}$, with d_{pipe} the pipe wall thickness), e.g. D_1 = 152.0 mm, D_2 = 160 mm. For pipes, Nu can be described as a function of the dimensionless Reynolds number (Re) and Prandtl number (Pr): $Nu = 0.027\ Re^{0.8}\ Pr^{0.33}$ for turbulent flows, and Nu = 3.66 for laminar flows. Furthermore, α_{water} is the thermal diffusion coefficient [0.14 m^2/s]; $\alpha_{water} = \lambda_{water}/\rho_{water}\ C_{p,\ water}$; λ_{water} is the thermal conductivity of water [0.57 W.m^{-1}.K^{-1}]; ρ_{water} is the density of water [1000 kg.m^{-3}]; $C_{p,water}$ is the heat capacity of water [4.19 J.kg^{-1}.K^{-1}] – with the parameter values given at 20 °C. In this paper we only consider plastic pipes, for which λ_{pipe} is the thermal conductivity of PVC [= 0.16 W.m^{-1}.K^{-1}]. D_3 the diameter where the boundary condition is valid, equal to the outside pipe diameter plus the surrounding soil ($D_3 = D_2$ + GpD). What the best value for D_3 is, is still to be determined. In this paper we only consider pipes that are installed in sand, for which λ_{soil} is the thermal conductivity of dry sandy soil [= 1.6 W.m^{-1}.K^{-1}]. Figure 1 shows the solution for Eq. (1) and (2) for a range of values for D_3.

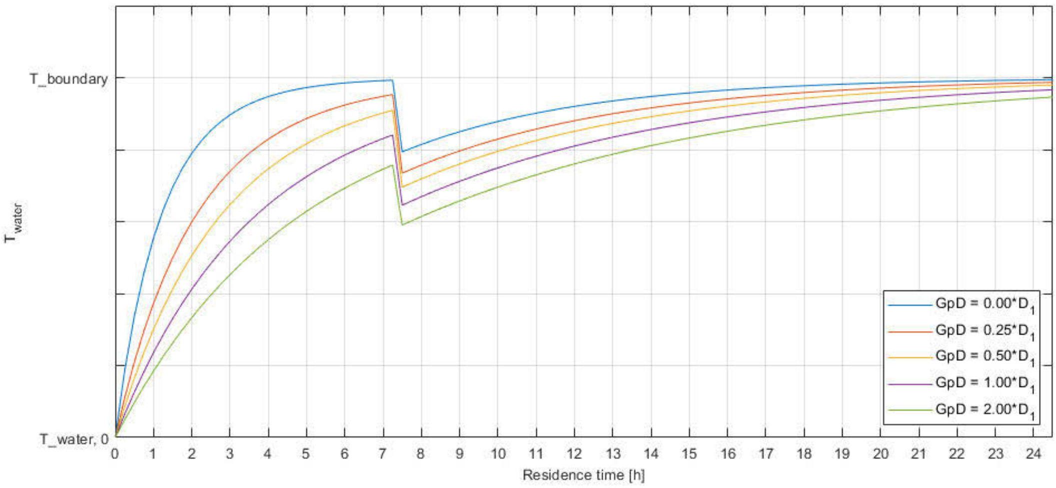

Figure 1. T_{water} against travel time (τ) for a Ø160 mm PVC pipe with various potential length scales for the extra insulation layer of soil.

In practice, time t implies a distance x ($=v/t$). The challenge in validating the WTM+ in practice is to find a DWDN where $T_{boundary}(t)$ is known over length x and time t. This is a potential problem because a) over the pipe length circumstances above and below ground are not constant over both time (under the influence of changing weather) and space (e.g. district heating pipes or electricity cables are installed alongside only part of the drinking water pipe, the drinking water pipe is installed under an incline and thus surrounding temperature changes over the pipe length), and b) it is not clear how to exactly determine the undisturbed soil temperature that is $T_{boundary}(t)$. The undisturbed soil temperature (i.e. not influenced by temperature of the drinking water pipe itself) can only easily be measured when there is no drinking water pipe, and by definition this can therefor not be measured at the location of the pipe under investigation. Another problem is that the temperatures can not be controlled, they can only be measured.

We tried to overcome these issues by following two paths on two case studies, which are described further in Section 3. The first case study entailed measurements of drinking water temperature in one single stretch of a drinking water pipe, without demand along the length. At this location we also measured soil temperatures at three locations along the pipe length, measured soil properties, mapped electricity cables and district heating pipes and a 2D soil temperature model [STM+, 4] was built to validate the STM+. After the validation the STM+ was used to describe $T_{boundary}(t)$. The length x was a constant, but with a variation in flow, τ was changed. Measurements took several weeks, and none of the parameters in Eq. (1) were kept constant. The second case study entailed measurements of drinking water temperature in a DWDN with various pipe diameters. At this location we did not measure soil temperatures, but

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used the STM [2, 3] to estimate T_{boundary}. Measurements were done at various distances (x) and thus times (τ), but τ was not controlled, but instead was estimated based on the hydraulic network model. Measurements took only one day, and we assumed that the parameters in Eq. (1) were constant over time, but not necessarily over space.

3. CASE STUDY DESCRIPTIONS

3.1 Case study 1: Single pipe system

The first case study is a single pipe, a Ø160 mm PVC pipe (D_1 = 152 mm, D_2 = 160 mm) in Rotterdam with a length of 925 m. This pipe is fed from a surface water PS (pumping station) through a stretch “S1” of 1650 m (D_1 = 1569 mm), “S2” of 1350 m (D_1 = 1369 mm), and”S3”of 570 m (D_1 = 150,6 mm), see Figure 2. The water in the measured pipe flows from location L1 to location L2 (stretch “S4” - 415 m) to location L3 (stretch “S5” 510 m). The flow at L3 was controlled with a hydrant. During a two weeks measurement period (19 May 2020 – 03 June 2020) the flow rate was regulated in order to get measurements for residence times of the water in the pipe from 1 to 24 hours.

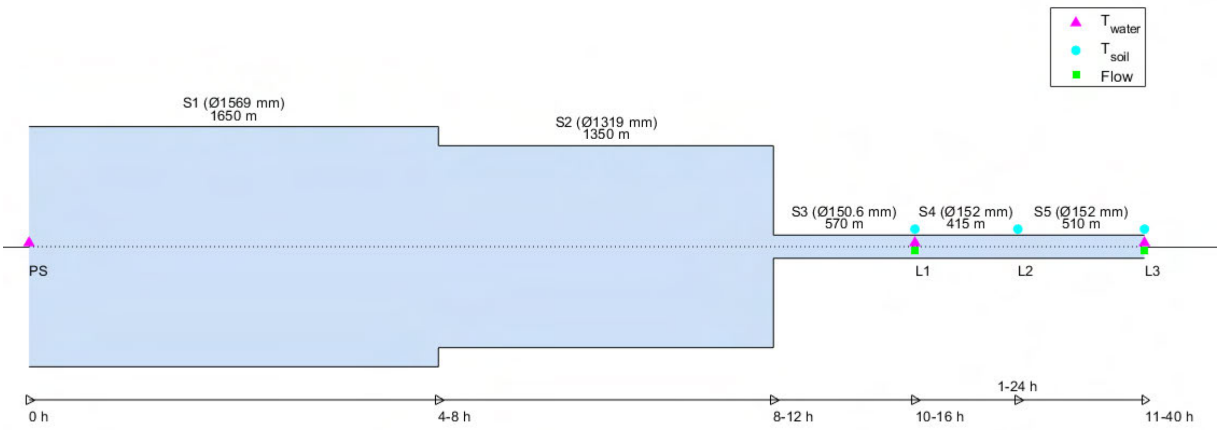

Figure 2. Measurement locations of case study 1. In green flow meter locations, in magenta and cyan drinking water temperature and soil temperature measurement locations. Stretch names with length and diameter are indicated above, and travel times are indicated below. PS is pumping station, L1, L2 and L3 are measurement locations.

The following was measured, with a logging frequency of once per 15 minutes:

- T_{water} was measured at the PS and at L1 and L3 (Figure 3). We may assume that T_{water} at the start of S3 is equal to T_{water} from the PS as S1 and S2 have large diameters and short residence times. However, T_{water} at the end of S3 (location L1) is not equal to T_{water} from the PS (Figure 3).
- T_{soil} (temperature of the soil) was measured at L1, L2 and L3, at various distances from the pipe.
- The flow was measured at L1 and L3. During the measurements there was limited demand from customers along the pipe, as there is only one residential customer, and some sports facilities that were closed during the Covid-19 pandemic. The demand at the customer location was measured, and it had a negligible effect on the flow at L1. The residence time between L1 and L3 was calculated from the pipe length, pipe diameter and flow at L3.

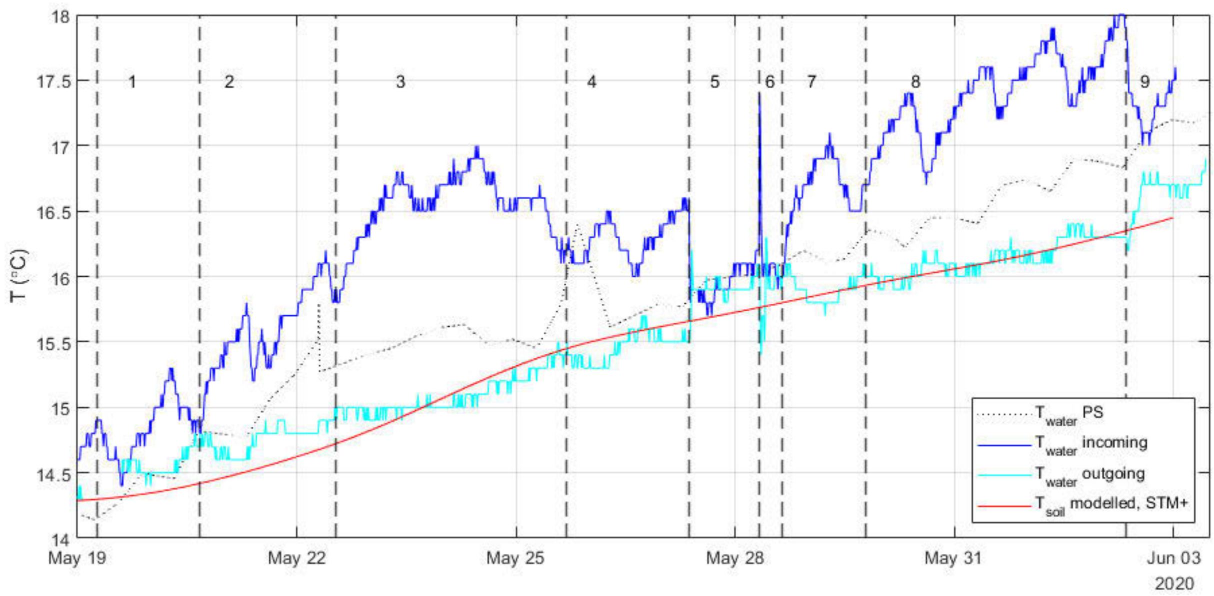

Figure 3 Measured drinking water temperatures and modelled soil temperature for the single pipe case study. Indicated are the starting times of the 9 tests (Table 1).

3.2 Case study 2: Drinking Water Distribution Network

Drinking water temperature measurements were done in the DWDN of Almere in the Netherlands. The Almere DWDN is ca. 700 km long, and consists mainly of PVC pipes, with nominal diameters of Ø63 (8%), Ø110 (51 %), Ø160 (15%), Ø200 (5%), Ø310 (6%) and > Ø400 mm (9%), [5]. The DWDN is fed by two feeding reservoirs, in the north and in the south part of the system that will be referred to in the paper as F1 and F2.

There is a variation of backfill for the pipes where the older network parts (built between 1980 and 2000) have a mixture of sand and clay and the newer parts where the backfill is sand. Also, there is a variation in installation depth with the distribution mains in the older parts at -1.3 m and in the newer parts at -1.1 m. The transport mains are installed at ca. -1.5 m. The western part of Almere has a district heating network (DHN) that may influence the Drinking Water Distribution Network (DWDN). The effect of the DHN parallel to the DWN was calculated with STM+ to be negligible as the distance between the two is more than 2.5 m. Where DWDN and DHN pipes cross, the distance between the two is much closer, but for a limited length. So, crossings may lead to an increased drinking water temperature. Roughly speaking, the area with a DHN is the older part of the DWDN with larger pipe diameters and a looped system, where the newer DWDN is designed as a self-cleaning network with a more branched structure and smaller pipe diameters [6].

Two areas (A and B) were selected to take temperature measurements. Area A and B are comparable in residence time from the sources, they have a similar year of installation and thus a similar design philosophy (with similar pipe diameters, pipe materials and DWDN layout, in this case self-cleaning network design) and a similar number of residents. The individual measurement locations differ in experienced soil temperatures and in residence times from the source. The soil in area A experiences a slower heat transfer compared to area B, because there is a mixture of clay and sand in A and only sand in B; the pipes in area A are installed a little bit deeper than in area B; and area A has a DHN installed next to the DWDN, and in area B there is no DHN. This means that the expected soil temperatures (based on the STM) in area A without a DHN are lower than for area B (18.7 °C instead of 20.5 °C), but with a DHN the soil temperature in area A is comparable to that in area B (20.5 °C). The hydraulic model of Almere (provided by Vitens)

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was used to calculate the flows at the measurement day (the demand pattern of 31 August 2020 was used). The hydraulic network model shows a residence time between 5 to 24 hours at the measurement locations in area A and between 10 and 15 hours in area B.

Drinking water temperature measurements were done by Vitens employees on 31 August 2020 at 35 hydrants in area A and B at two moments of the day (one in the morning, between 8:00 and 12:30, and one in the afternoon, between 12:45 and 16:30) leading to a total of 70 values. Measurements were taken at hydrants, in order to avoid an influence of the premise plumbing system, and during the Covid-19 pandemic to not have to enter people's homes. The hydrants were opened only with a small flow of water, in order not to influence travel time of the water too much. The drinking water temperature at the sources F1 and F2 are $T_{water,F1}$ = 13.7 °C and $T_{water,F2}$ =13.3 °C on 31 Aug 2020, respectively (see Figure 4).

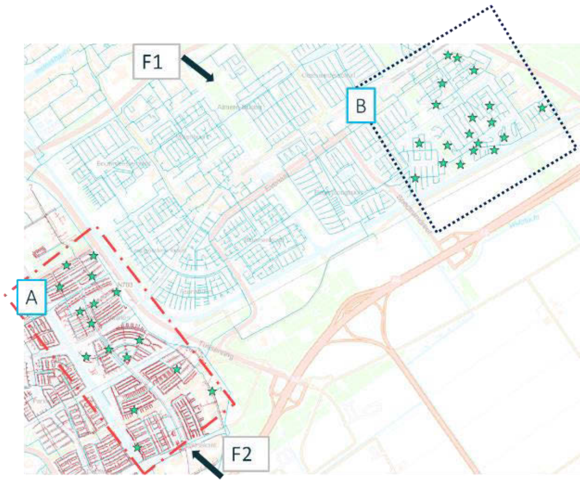

Figure 4 Almere DWDN in blue, and DHN in red. The measurement locations are indicated in green.

4. DATA ANALYSIS

4.1 Case study 1: Single pipe system

As during the measurement period (19 May 2020 – 03 June 2020) the boundary conditions ($T_{water,0}$ and $T_{boundary}$ in Eq. (1)) were not constant, we decided to introduce a normalized parameter (with values between 0 and 1) to be able to compare all measurements in a single graph. This leads to:

$$\Delta TN(\tau,t) = 1 - exp(-k(t)\tau(t)) = \frac{T_{water}(\tau,t) - T_{water,0}(t)}{T_{boundary}(t) - T_{water,0}(t)} \quad (3)$$

The parameters of Eq. (3) are determined as follows (and shown in Figure 3):

- $\tau(t)$: The residence time follows from the measured flows, and is listed in Table 1. The accuracy of the flow meter is 0.004 m³/h (1 litre with a log frequency of 15 minutes). During the test phases the flow is kept more or less constant, the accuracy and variability lead to a ΔQ equal to 0.012 m³/h. This leads with Eq. (4) and the flow rates of Table 1 to an uncertainty in the residence time of less than 2% (less than 1 minute for the short residence times of tests 5 and 6 and almost 30 minutes for the longest residence time of test 3), and therefor can be neglected. In this Eq. V is the pipe volume (16.8 m³ for a 152 mm, 925 m pipe):

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$$\frac{\Delta\tau}{\tau} = \frac{\frac{V}{Q - \Delta Q} - \frac{V}{Q}}{\frac{V}{Q}} = \frac{\Delta Q}{Q - \Delta Q} \approx \frac{\Delta Q}{Q} \tag{4}$$

- $T_{water,0}(t)$: drinking water temperature measured at location L1.
- $T_{water}(\tau, t)$: drinking water temperature measured at location L3, time-shifter to adjust for residence time τ. For example for test 4, in which the flow Q = 1.4 m³/h results in τ = 5 hours (L1 to L2) + 7 hours (L2 to L3). Therefore, $T_{water}(\tau, t) = T_{water}(t + 12)$, where the data during the transition time of 12 hours are discarded (adjustment for residence time). Table 1 shows the residence times needed for the adjustment, and the amount of datapoints left for the analysis after discarding the transition period. Figure 5 shows the time series after adjustment for residence time.
- $T_{boundary}(t)$: $T_{boundary}$ was estimated by using the STM+ [7] results at L3. The STM+ was validated with this particular case study, and then the STM+ was rerun to calculate the so called undisturbed soil temperature ($T_{boundary}$). This modelled temperature ($T_{\text{soil, modelled}}$) is also shown in Figure 3. For the tests we assume that during the residence time the $T_{boundary}$ that is experienced by the flowing water is the average of the soil temperature during this residence time: $T_{boundary}(t) = mean(T_{soil,modelled}(t{:}\, t + \tau))$

The normalized temperature difference ΔTN (Eq. (3)) is then calculated for every datapoint, i.e. for every 15 minutes. Also, the uncertainty in ΔTN is considered. This uncertainty is related to the accuracy of the drinking water temperature measurements. The measurement accuracy in $T_{water,0}$ and $T_{water}(t)$ is ± 0.05 °C and the uncertainty for $T_{boundary}$ is assumed to be small compared to the measurement uncertainty. With ε_w = 0.05 °C, the uncertainty in ΔTN is determined as (see appendix)
$\bar{E} = \frac{\varepsilon_w(2T_{boundary} - T_{water,0} - T_{water})}{(T_{boundary} - T_{water,0})^2 - \varepsilon_w{}^2}$. This means that when $(T_{boundary} - T_{water,0})$ is small, the uncertainty in ΔTN is large. As ΔTN is between 0 and 1, we will discard datapoints where $\bar{E} > 0.25$. Figure 5 shows the time series after adjustment for residence time and without the datapoints with $\bar{E} > 0.25$.

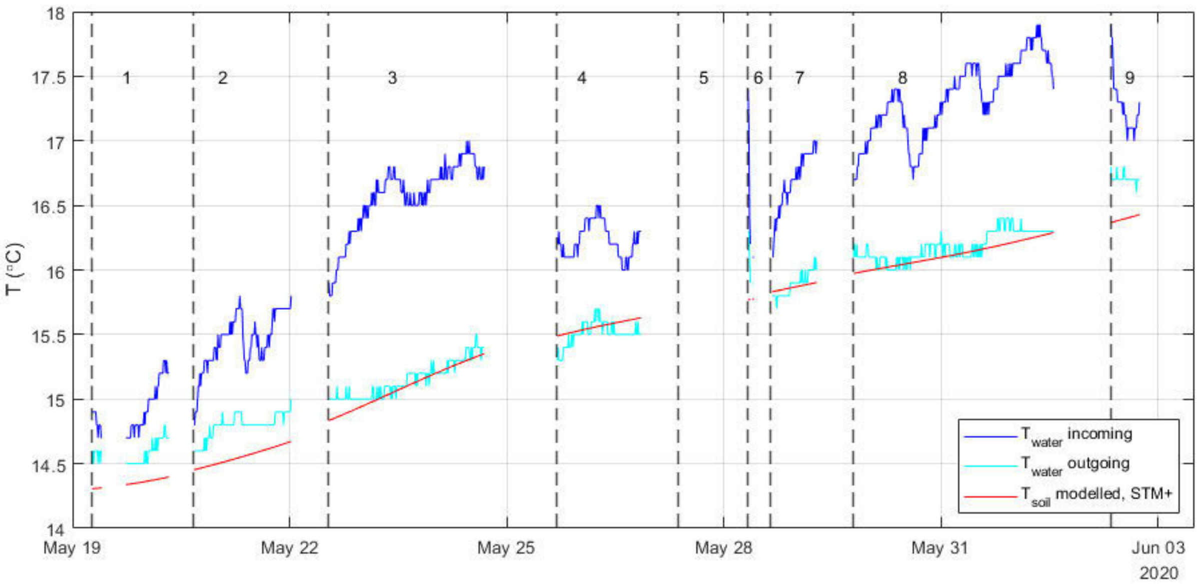

Figure 5. As Figure 3, but here T_{water} outgoing is adjusted for residence time. And datapoints where $\bar{E}$ > 0.25 are discarded.

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Table 1 Overview of data in the drinking water temperature measurements for various residence times. Changing the hydrant flow took 15-30 minutes. Test 1 started on 18 May, but some measurements were lost. Therefor we used data from 19 May onwards. Test 6 was started 15 minutes after test 5 ended. However, a passer-by closed the hydrant. The next morning during the check test 6 was started again. The measurements at L1 were stopped at 03-June 0:45. Between brackets the number of datapoints after removing high uncertainty measurements.

ID	Starting time	End time	Amount of datapoints after adjusting for residence time	Flow rate [m^3/h]	Residence time [h]
1	19-May-2020 6:30 (18-May-2020 12:00)	20-May-2020 16:00	103 (73)	2.1	8.0
2	20-May-2020 16:15	22-May-2020 12:30	130 (130)	1.4	12.0
3	22-May-2020 13:00	25-May-2020 16:30	207 (207)	0.7	24.0
4	25-May-2020 16:45	27-May-2020 08:30	112 (112)	1.4	12.0
5	27-May-2020 09:15	27-May-2020 20:00	41 (1)	16.7	1.0
6	28-May-2020 08:00	28-May-2020 15:00	21 (9)	8.5	2.0
7	28-May-2020 15:30	29-May-2020 18:45	62 (60)	1.4	12.0
8	29-May-2020 19:00	02-Jun-2020 07:45	266 (266)	0.9	18.6
9	02-Jun-2020 08:15	03-Jun-2020 10:00	39 (39)	2.8	6.0

Case study 2: Drinking Water Distribution Network

The parameters of Eq. (1) are determined as follows:

- τ: The residence time follows from the hydraulic network model. Here, the demand patterns of 31 August 2020 were applied, but the model was not calibrated for this particular day, so there may be some valve positions that are incorrect which may lead to errors in travel time.
- $T_{boundary}$: $T_{boundary}$was estimated by using weather data, processed with the STM [2, 3] and STM+ [4]. There were no soil temperature measurements available. Five different boundary conditions were suggested:
  - T_{TM} is the soil temperature around transport mains. T_{TM} = 18.0 °C. This is the STM calculated temperature at -1.7 m (Figure 6), in peri-urban area (clay/sand under grass);
  - T_{TM_DHN} is the soil temperature around transport mains with crossing DHN. T_{TM_DHN} = 20.1 °C. This is the STM calculated temperature at -1.7 m, in peri-urban area (clay/sand under grass) + 2.1 °C from the primary network DHN as from the STM+ [4];
  - T_{TM} is the soil temperature around distribution mains in the older part of Almere. T_{DM} = 18.7 °C. This is the STM calculated temperature at -1.35 m (Figure 6), in peri-urban area (clay/sand under grass);
  - T_{TM} is the soil temperature around distribution mains with crossing DHN, in the older part of Almere. T_{DM_DHN} = 19.5 °C. This is the STM calculated temperature at -1.35 m, in peri-urban area (clay/sand under grass) + 0.8 °C from the secondary network DHN as from the STM+ [4];
  - T_{TM_B} is the soil temperature around distribution mains in the newer part of Almere. T_{DM_B} = 20.5 °C. This is the maximum drinking water temperature that was measured in area B (Figure 7), and is the average of the STM calculated temperatures at -1.15 m (Figure 6) for peri-urban (clay/sand under grass) and urban (sand, under tiles with various shade conditions).

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- $T_{water,0}$: drinking water temperature measured at locations F1 and F2 (13.7 and 13.3 °C respectively).
- $T_{water}(\tau)$: drinking water temperature measured at hydrants (Figure 7).

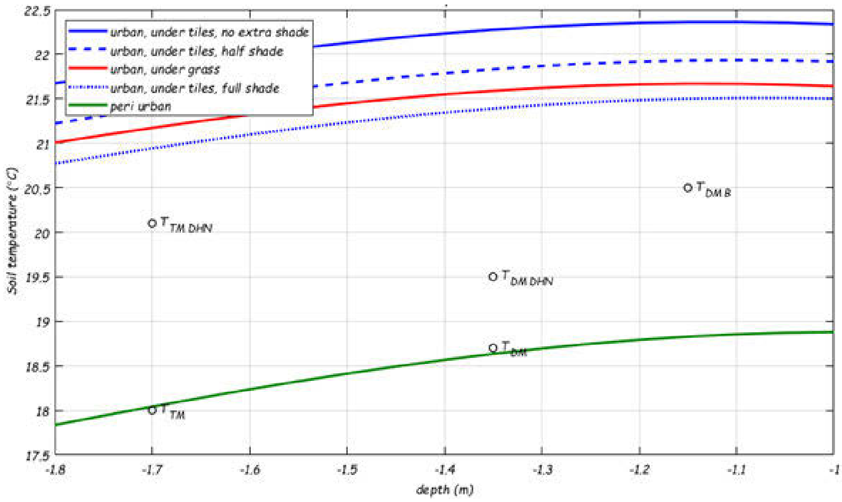

Figure 6. Modelled soil temperature (STM) at various depths for 31 August 2020, for KNMI data of Schiphol airport and circumstances around Almere DWDN. T_{TM}: Temperature around transport mains, $T_{TM\ DHN}$: Temperature around transport mains with crossing of DHN, T_{DM}: Temperature around distribution mains (area A) , $T_{DM\ DHN}$: Temperature around distribution mains with crossing of DHN (area A) , $T_{DM\ B}$: Temperature around distribution mains (area B).

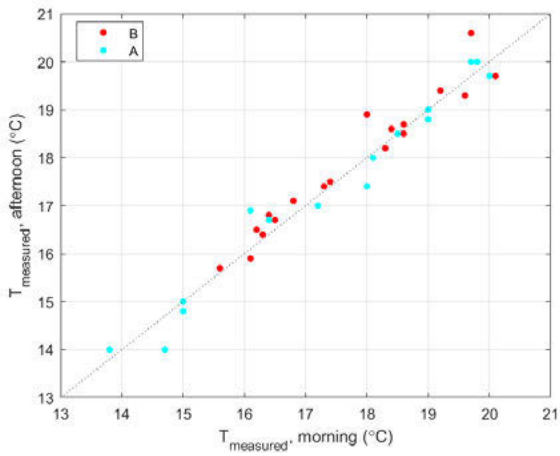

Figure 7. Measured drinking water temperatures in the morning and afternoon in areas A and B.

5. RESULTS OF MEASUREMENTS

5.1 Case study 1: Single pipe system

Figure 3 and Figure 5 show the measured and modelled temperatures. There are some remarkable results:

1) In Figure 3 temperatures are shown simultaneously, without taking into account the travel time between the locations. This makes it difficult to visually compare the temperatures. It looks like the outgoing water temperature is often lower than the modelled soil

temperature, but after correction for the travel time, this is hardly ever the case (considering the 0.1 °C accuracy) as is shown in Figure 5.

2) Typically the drinking water temperature increases from PS to L1, most likely in stretch S3, and then decreases between L1 and L3. It would be worthwhile to also model the upstream drinking water temperature changes. The difference between drinking water temperature at L1 and L3 was < 2.0 °C.
3) During the test with only one and two hours residence time (tests 5 and 6) there is no increase or decrease of the drinking water temperatures between PS and L1, nor between L1 and L3.
4) The difference between the drinking water temperature at the source and the modelled soil temperatures is small (but be aware of the travel time that needs to be considered when comparing the two). The fact that there was a temperature increase between PS and location L1 lead to better testing circumstances. If the soil temperatures between PS and the beginning of the test side (L1) would have been the same as the soil temperatures around the case study pipe (between L1 and L3), than the test would probably not have given any useful results.
5) The temperature of the incoming water at location L1 (dark blue line) shows an influence of the time of day, most probably due to the change in flow (high demands, high flows during the morning and little flow during the night). The temperature of the outgoing water at location L3 (cyan line) has a much more constant value over the day. This is due to the fact that during the tests the flow between L1 and L3 was constant and for the longer residence times the drinking water temperature was almost in equilibrium with the soil temperature. For the shorter residence times, the measurements were not long enough to show a diurnal pattern.
6) At the start of tests 5, 6 and 9 it can be seen that there is a very quick change in the incoming temperature at location L1 (dark blue line); this is not the case for the other tests. It is suggested that these tests have a quicker heat transfer, involving convective heat transfer due to turbulent flows. For this case study a travel time of 7 hours means a Reynolds number of 5,000. It is assumed that for $Re > 5{,}000$ the flow is turbulent, where $Nu = 0.027 \times Pr^{0.33} \times Re^{0.8}$, while for smaller Re (laminar flows), $Nu = 3.66$. This means that k in Eq. (1) is different for laminar and turbulent flows.

7) Table 1 shows that the results of test 5 and 6 have led to a very limited dataset. Partly due to the fact that the tests were only short (and test 6 was shorter than intended because a passer-by closed the hydrant), and partly due to the fact that the temperature differences between incoming temperature and the soil temperature are small, and therefor datapoints with very high uncertainty needed to be discarded.

5.2 Case study 2: Drinking Water Distribution Network

The temperature measurements in the DWDN showed a wide range between 14 and 21 °C (Figure 7). There is no significant difference between the measured temperatures in areas A and B. The maximum measured temperature in area B is higher than in area A (Figure 8), which can be a coincidence, or due to the fact that the soil temperatures around the pipes in area B ($T_{\mathrm{DM\_B}}$) are higher than in area A (T_{DM}). This suggests that the influence of the DHN (in area A) is limited. However, more analysis is required here. The differences between the morning and afternoon measurements were limited, less than 1.0 °C (Figure 7), and Figure 9 shows that the distribution of the results in the morning and afternoon is the same for area A; for area B the afternoon temperatures are slightly higher.

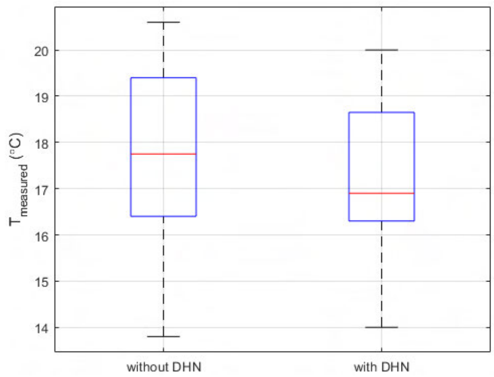

Figure 8. Range of measured drinking water temperatures in area without DHN (area B) and with DHN (area A).

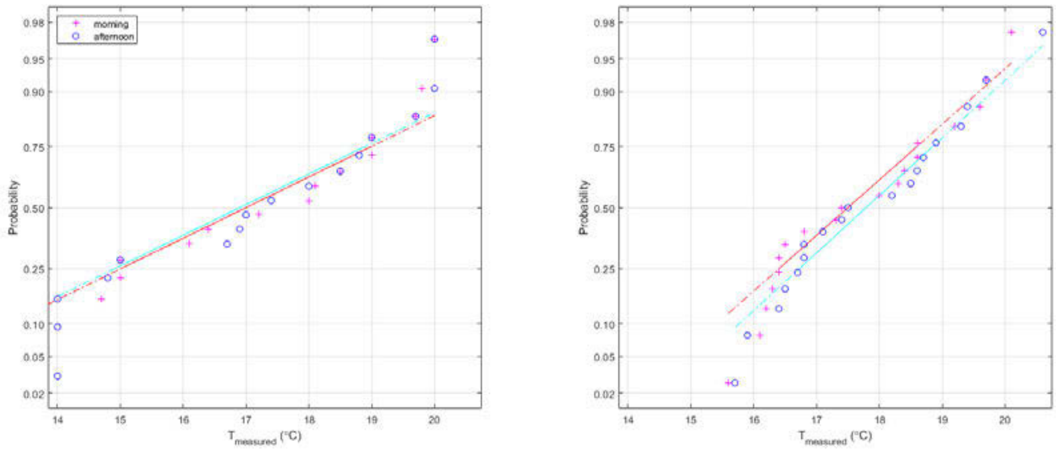

Figure 9. Normal probability plot of measured temperatures in area A (left) with DHN, and B (right) without DHN. In purple/red the morning data, in cyan/blue the afternoon data.

6. DISCUSSION

With respect to designing a good test, we present some lessons learned:

- Case study selection: It was a big challenge to find a good test site for the single pipe test, i.e. a pipe of sufficient length where travel time could be manipulated between 1 and 24 hours and where the soil temperature would not vary much over the pipe length. The DWDN test can be performed in any DWDN.
- Certainty of travel times: In the single pipe case it was possible to manipulate and exactly know the travel times. In the DWDN the hydraulic model was needed to estimate the travel times, which introduced some uncertainty. The measurement locations in the DWDN were such that there was a range of travel times, leading to a wide range of temperatures. More or less by accident there were hardly any measurement locations with a larger travel time beyond the maximum heating time, i.e. there were no measurement locations beyond where the influence of travel time could be assessed. Differences between WTM+ and measurements are potentially due to inaccuracies in the modelled flows (maybe due to inaccurate valve statuses), where the inaccuracies are not easy to estimate.
- Certainty of soil temperatures: In the single pipe test setup it was possible to measure soil temperatures, and soil heat capacity, and therefore validate the STM+ for the test location. This allowed to determine the $T_{boundary}$ with higher certainty than for the DWDN test site.
- Certainty of drinking water temperatures: For the single pipe the difference between drinking water temperature at the beginning of the pipe and the soil temperature was <

2.0 °C, with a resolution of 0.1 °C. The DWDN showed a larger range of temperatures, between 14 and 21 °C. Testing the same locations both in the morning and in the afternoon increased the reliability of the test results.

- Test duration: The single pipe test took a few weeks, so each test would lead to a good amount of datapoints. The test in the DWDN took just one day, and a limited number of datapoints were thus collected. Because the temperature differences in the single pipe system were relatively small and drinking water and soil temperatures varied a lot over time, there was a need for a high number of datapoints (and the test duration for the 1 and 2 hour travel times turned out to be too short). Because the temperature differences in the DWDN were relatively large, and were found in a broad range, the limited number of datapoints is acceptable.
- WTM+ validation: In the single pipe test, there was only a single pipe diameter, and the soil temperatures around the pipe were more or less the same over the entire pipe length. This ensured that the WTM+ for this single pipe was relatively simple, and validation should be straight forward. However, the drinking water and soil temperatures were not stable over time and some extra data preparation is required before the WTM+ can be validated. It would be worthwhile to also model the upstream drinking water changes. For the test in the DWDN multiple pipe diameters are involved, so the measurements need to be compared to a WTM+ over a trajectory of various pipe diameters and soil temperatures.
- Overall value of the tests: The case studies did prove to be suitable for validating the WTM+, including the effect of residence time (T.B.P.).
- How to measure: in the single pipe system, the drinking water temperature was measured by inserting a sensor in the pipe; in the DWDN at the hydrant. In both cases the influence of the service line and premise plumbing were not present.

Based on the experiences, we recommend the following:

- When selecting a test site we advise to use one with large temperature differences, i.e. a ground water source, and doing the measurements either in winter or summer, when soil temperatures are most different from the ground water temperatures. In this case a resolution of 0.1 °C will not be a problem.
- When taking measurements in a DWDN we advise to use a well calibrated hydraulic network model, select the measurement locations based on expected WTM+ results with a variety of travel times (in the required range of travel times), and at enough locations to be able to not be bothered by a few outliers.

7. ACKNOWLEDGEMENTS

This work is part of the TKI Project Engine

(https://www.tkiwatertechnologie.nl/projecten/engine-energie-en-drinkwater-in-balans/), which is paid for by the ten Dutch drinking water companies, Energie Nederland, Gasunie, Convenant Rotterdam and the Dutch government. We would like to thank Henk de Kater (Evides), and Ben Los (Vitens) for their efforts in the measurement campaigns in Kralingen and Almere.

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Appendix

$$\Delta TN = \frac{T_{water} - T_{water,0}}{T_{boundary} - T_{water,0}} = \frac{T_w - T_{w,0}}{T_b - T_{w,0}} \tag{5}$$

$$E_1 = \frac{T_w + \varepsilon_w - T_{w,0} + \varepsilon_w}{T_b + \varepsilon_s - T_{w,0} + \varepsilon_w} - \frac{T_w - T_{w,0}}{T_b - T_{w,0}} \tag{6}$$

$$= \frac{(T_w - T_{w,0} + 2\varepsilon_w)(T_b - T_{w,0}) - (T_w - T_{w,0})\,(T_b - T_{w,0} + (\varepsilon_w + \varepsilon_s))}{(T_b - T_{w,0})\,(T_b - T_{w,0} + (\varepsilon_w + \varepsilon_s))}$$

$$= \frac{2\varepsilon_w(T_b - T_{w,0}) - (\varepsilon_w + \varepsilon_s)(T_w - T_{w,0})}{(T_b - T_{w,0})\,(T_b - T_{w,0} + (\varepsilon_w + \varepsilon_s))}$$

ε_w: error in water temperature measurement, ε_s: error in soil temperature measurement.

E_1: maximum error in ΔTN to plus side, E_2: maximum error in ΔTN to min side.

$$E_2 = \frac{T_w - T_{w,0}}{T_b - T_{w,0}} - \frac{T_w - \varepsilon_w - T_{w,0} - \varepsilon_w}{T_b - \varepsilon_s - T_{w,0} - \varepsilon_w} \tag{7}$$

$$= \frac{-(T_w - T_{w,0} - 2\varepsilon_w)(T_b - T_{w,0}) + (T_w - T_{w,0})\,(T_b - T_{w,0} - (\varepsilon_w + \varepsilon_s))}{(T_b - T_{w,0})\,(T_b - T_{w,0} - (\varepsilon_w + \varepsilon_s))}$$

$$= \frac{2\varepsilon_w(T_b - T_{w,0}) - (\varepsilon_w + \varepsilon_s)(T_w - T_{w,0})}{(T_b - T_{w,0})\,(T_b - T_{w,0} - (\varepsilon_w + \varepsilon_s))}$$

$$\bar{E} = \frac{E_1 + E_2}{2} \tag{8}$$

$$\bar{E} = \frac{2\varepsilon_w(T_b - T_{w,0}) - (\varepsilon_w + \varepsilon_s)(T_w - T_{w,0})}{2(T_b - T_{w,0})} \times \left(\frac{1}{T_b - T_{w,0} + (\varepsilon_w + \varepsilon_s)} + \frac{1}{T_b - T_{w,0} - (\varepsilon_w + \varepsilon_s)}\right) \tag{9}$$

$$\bar{E} = \frac{2\varepsilon_w(T_b - T_{w,0}) - (\varepsilon_w + \varepsilon_s)(T_w - T_{w,0})}{2(T_b - T_{w,0})\,(T_b - T_{w,0} + (\varepsilon_w + \varepsilon_s))\,(T_b - T_{w,0} - (\varepsilon_w + \varepsilon_s))} \times (T_b - T_{w,0} - (\varepsilon_w + \varepsilon_s) + T_b - T_{w,0} + (\varepsilon_w + \varepsilon_s)) \tag{10}$$

$$\bar{E} = \frac{2\varepsilon_w(T_b - T_{w,0}) - (\varepsilon_w + \varepsilon_s)(T_w - T_{w,0})}{2(T_b - T_{w,0})\left((T_b - T_{w,0})^2 - (\varepsilon_w + \varepsilon_s)^2\right)} \times 2(T_b - T_{w,0}) \quad (11)$$

$$\bar{E} = \frac{2\varepsilon_w(T_b - T_{w,0}) - (\varepsilon_w + \varepsilon_s)(T_w - T_{w,0})}{(T_b - T_{w,0})^2 - (\varepsilon_w + \varepsilon_s)^2} \quad (12)$$

If ε_s small: (13)

$$\bar{E} = \frac{\varepsilon_w(2T_b - T_{w,0} - T_w)}{(T_b - T_{w,0})^2 - \varepsilon_w^2}$$

If $\varepsilon_s = \varepsilon_w$: (14)

$$\bar{E} = \frac{2\varepsilon_w(T_b - T_w)}{(T_b - T_{w,0})^2 - 4\varepsilon_w^2}$$

2022, Universitat Politècnica de València
2nd WDSA/CCWI Joint Conference