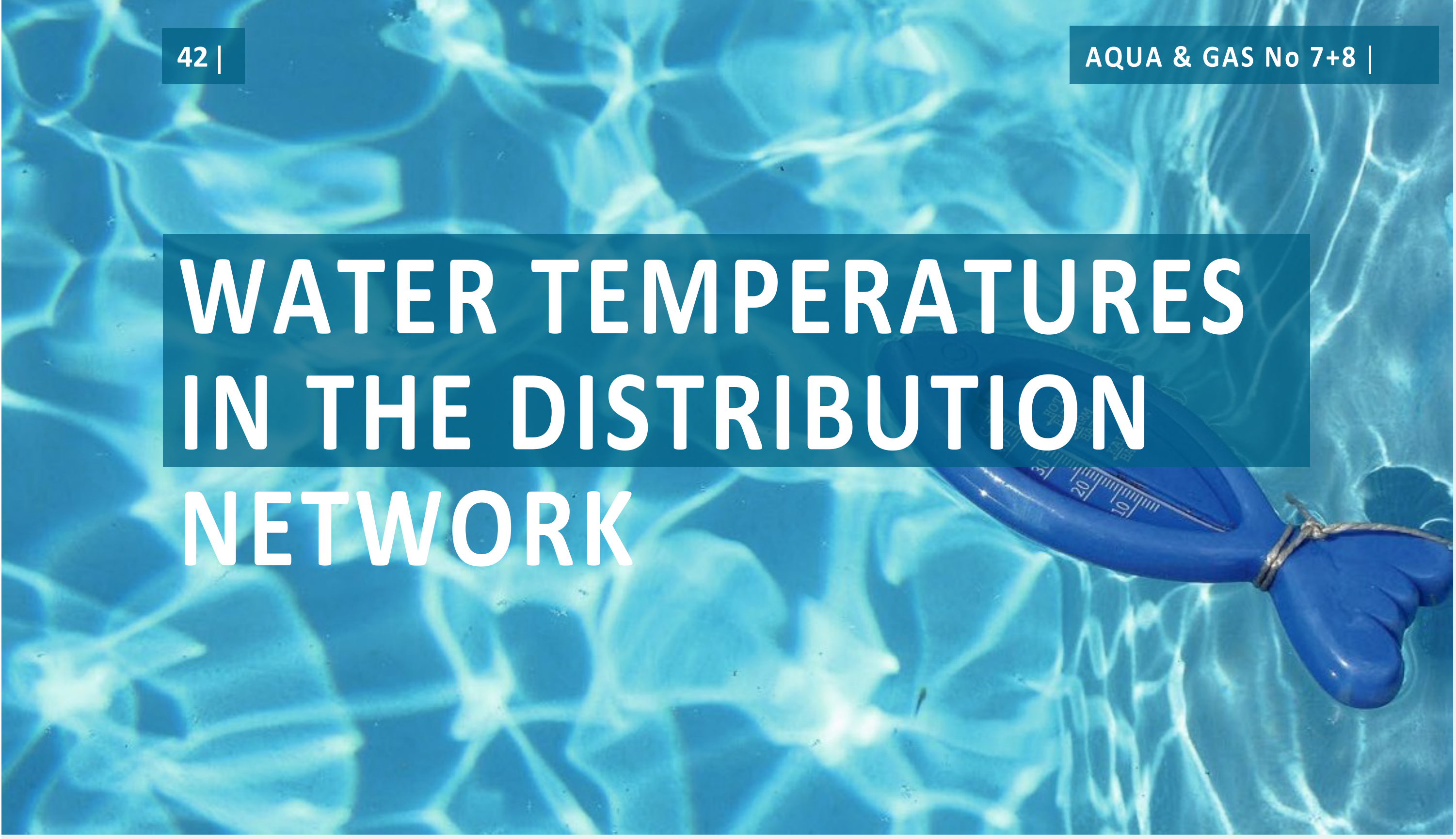

WATER TEMPERATURES IN THE DISTRIBUTION NETWORK

PRACTICAL REPORT FROM THE ZURICH WATER SUPPLY

Continuous temperature measurements in the drinking water distribution network of the Zurich water supply have shown that surprisingly high temperatures occur in unexpected places. In combination with soil temperature measurements, factors influencing the heat generation of drinking water in distribution networks were evaluated. A simple model helps to assess holistic approaches to the reduction of high temperatures in the network, such as cable depth, cable material or insulation material.

Caroline Marks; Silvano Murk; Jakob Helbing, City of Zurich Water Supply

RÉSUMÉ

TEMPÉRATURES DE L'EAU POTABLE DANS LE RÉSEAU DE DISTRIBUTION – RAPPORT PRATIQUE DU SERVICE DES EAUX DE ZURICH

Dans le cadre d'un projet pilote de surveillance en ligne du réseau de distribution d'eau potable, 13 capteurs de qualité, 6 stations de mesure hydraulique et 2 chaînes de mesure de la température du sol ont été installés chez le service des eaux de Zurich. Ce rapport traite de l'évaluation des mesures de température. La forte densité de capteurs dans la zone pilote montre le développement de chaleur dans le réseau de distribution et révèle les points chauds de la température de l'eau potable en été. Cependant, les températures de l'eau, en partie plus élevées que prévu, ne sont pas systématiquement en corrélation avec la charge thermique dans les zones urbaines. Le transfert de chaleur depuis le sol dans l'eau potable peut être représenté à l'aide d'un modèle simple. Les principaux facteurs d'influence que sont la température du sol, le diamètre ainsi que le matériau des conduites et la vitesse d'écoulement ont été pris en compte. Il s'avère que la température d'entrée de l'eau a moins d'influence sur l'évolution des températures dans le réseau que la température du sol. Pour mieux comprendre l'évolu- tion de la température sur toutes les stations de mesure, d'autres mesures de la température du sol sont nécessaires. En outre, la distribution d'eau devrait entrer en compte dans des plans urbains visant à réduire la chaleur lors des mois d'été.

INTRODUCTION

Since the beginning of the recording of climate data, a rising global average temperature has been observed, especially in recent years the increase has accelerated. In the canton of Zurich, too, the average annual temperature has risen by about 2 °C compared to the 1864 average [1]. Especially in the summer months, the heat island effect also causes increased temperatures in the cities compared to the surrounding countryside. The high level of surface sealing of urban areas due to dense development, which at the same time goes hand in hand with reduced ventilation, ensures strong warming during the day and limited cooling at night. This results in more hot days as well as more tropical nights in urban areas during the summer months [2]. In Switzerland, Germany and Austria, there is a requirement for water suppliers that the cold water temperature at the tapping point should not exceed 25 °C [3–5]. In general, the temperature of drinking water influences chemical, physical and microbiological processes. Microbiology in particular is crucial for short-term health hazards. However, there has been no clear influence of increased temperatures in drinking water on the microbio-

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logical stability, since not only the temperature but also the availability of nutrients determines microbiological growth. In addition, it is still unclear what long-term effects the increased temperatures in cities, together with the heat island effect, will have on the temperatures of drinking water in distribution networks. Furthermore, risks can also arise from elevated temperatures in domestic installations and, in general, warm drinking water is less appreciated by most consumers.

In order to be able to develop sustainable measures for the provision of cool drinking water, heat effects in the drinking water network must be understood . This presupposes that the temperature developments in drinking water are measured. For this reason, as part of a pilot project, Wasserversorgung Zürich has installed several measuring points directly in the drinking water network, where quality and hydraulic parameters are continuously monitored. Water temperature and other parameters can be measured. The main focus of the pilot project is to better understand and evaluate the various relationships and influences on drinking water temperature. In this report, the results of the measurement and initial conclusions from one and a half years of recording measurement data are presented and discussed.

METHODS

The pilot area for measuring quality and hydraulic parameters in the drinking water network is located in Zurich's Höngg district. At the end of 2021, new sensors for quality, hydraulic and soil temperature measurements were installed there in addition to three existing measuring points. In this section, the different types of sensors are first presented and then the basics for the theoretical discussion of heat transfer effects in the drinking water network are given.

MEASURING SHAFTS IN THE PILOT AREA

An overview of all measuring points in the Höngg pilot area is given in *Figure 1*. The dense measuring network with a total of 13 quality measuring points, 6 hydraulic measuring points and 2 floor temperature measuring points can be seen. The hydraulic measuring points are not considered further in this report and are only shown for the sake of completeness. In addition to temperature, conductivity, pH, redox potential, turbidity and dissolved oxygen as well as flow and pressure are measured at the quality measuring points. The data is recorded approximately every two minutes and transmitted every ten minutes via GSM to a data cloud of the manufacturer. A total of three different sensor types from *Intellitect* are used for quality measurements. Two sensor types allow direct inline measurement in the drinking water pipe and one sensor type is operated in the bypass. *Figure 2* shows examples of the three sensor types. The so-called *Direct Insertion* (DI) probe is suitable for the

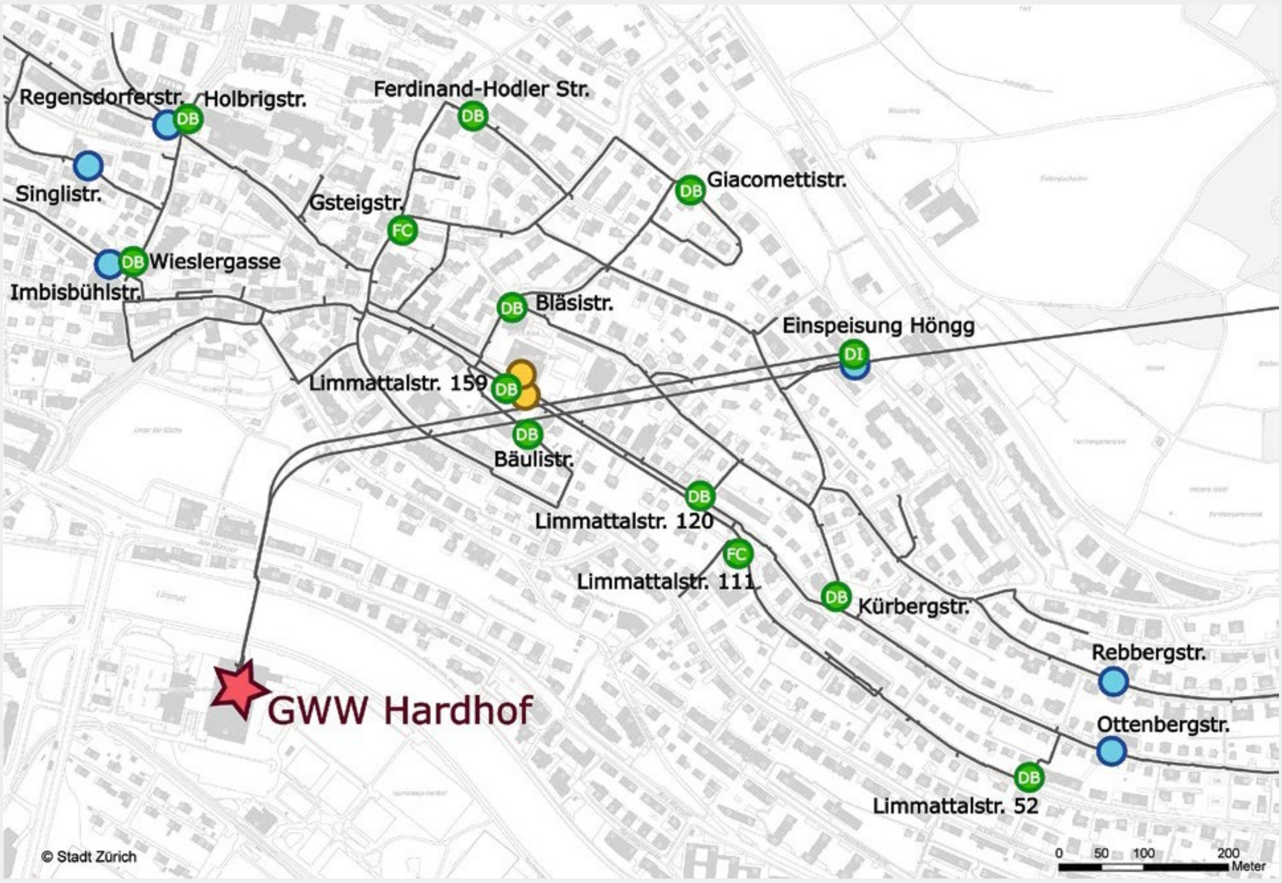

Fig. 1 Overview map of the sensor locations in the pilot area Höngg. The red star shows the Hardhof groundwater plant. The green dots refer to measuring points for quality measurements, the blue dots to measuring points for hydraulic measurements and the yellow dots to the two soil temperature measurements. The abbreviations in the green dots indicate the sensor type of the quality measurements. The main inflow into the pilot area is "Einspeisung Höngg" via the large supply line coming from the pumping station at Hardhof.

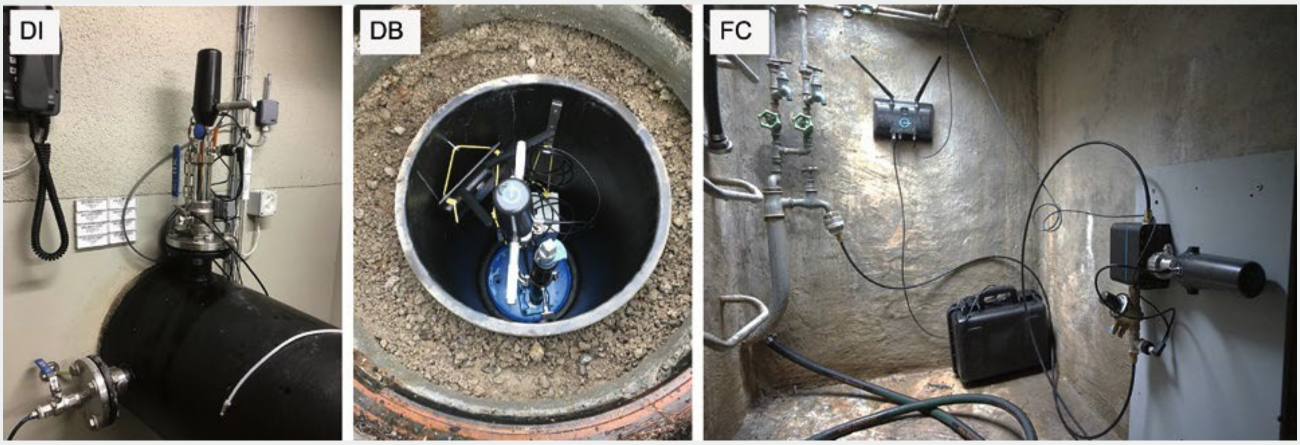

Fig. 2 Photos of the three installed sensor types for measuring water quality (from left). Direct Insertion (DI) for installation in walk-in shafts, Direct Bayonet (DB) for direct installation in the drinking water pipe in mini-shafts in the street space and Flow Cell (FC) for bypass measurement in connection shafts of drinking water wells.

stallation in large, walk-in shafts. Within the pilot area, it will only be used at the Höngg feed-in pipeline. The *Flow Cells* (FC) operated in the bypass are installed in well shafts of two drinking water wells at Gsteigstrasse and Limmattalstrasse 111. At all other quality measuring points, *Direct Bayonet* (DB) probes are installed in mini-shafts directly in the respective control lines in the road space. The two FCs have already been in operation for several years, all other sensors were installed at the end of 2021.

In addition to the quality measuring points for monitoring the drinking water quality in the distribution network, two measuring chains for recording the soil temperature were installed under asphalt at Limmattalstrasse 159 and on the opposite side of the road under Wiese as part of the pilot project. These soil temperature probes measure the soil temperature every ten minutes at depths of 0.2 m, 0.5 m, 0.9 m, 1.6 m and 2 m and store the measured values in a connected Data logger. The data is read out manually on site via a radio dongle.

MODELLING HEAT TRANSFER

The main factors influencing the development of drinking water temperature in the distribution network are shown schematically in *Figure* 3. Due to the sun's rays, the soil warms up, especially in summer. The heat transfer from the atmosphere to the soil as well as the influence of different surfaces such as asphalt and meadow are not examined in detail in this report. The focus is on the subterranean influencing factors soil temperature, pipe depth, pipe material and diameter as well as flow speed.

As long as the ambient soil temperature is higher than that of the water in the pipe, heat transfer from the soil to the water takes place. The evolution of the water temperature *over time* as a function of the heat transfer

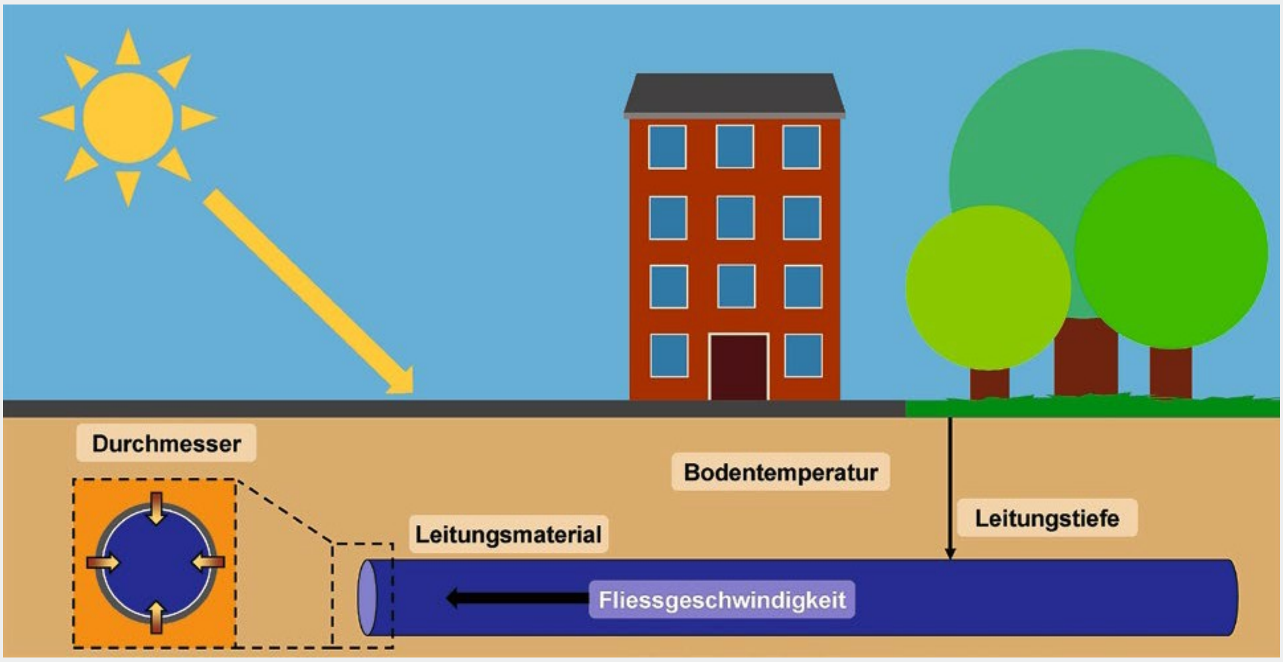

Fig. 3 Schematic representation of factors influencing the temperature development of drinking water in the pipeline network. The focus is on underground factors. The transfer of heat from the atmosphere to the ground is not considered in detail in this report.

Gear coefficients *k*, density $\rho_{\text{water and heat capacity}}$ cp, water of *water* as well as pipe radius *r* and temperature on the outer wall of the pipe *Taussen* can be described by a differential equation [6]:

$$\frac{ddTT_{WWWWWWWWWWW}}{WWWWW} = \frac{2kk}{\rho\rho_{WWWWWWWWWWWW}}(TT_{WWaaWWWWWWaa} - TT$$

The heat transfer coefficient *k* is influenced by the heat conduction through the pipe wall as a function of the wall thickness of the pipe wall and the thermal λ conductivity of the pipe wall *as well as by convective processes in the water as a function of the pipe diameter* $_{\text{dPipe,}}$ thermal conduct λ ivity *of water* and $_{\text{Nusselt}}$ number *Nu*:

$$kk = \frac{1}{\frac{DD_{RRRRhWWrrWWaarr}}{\lambda\lambda_{RRRRhWWrrWWaarr}} + \frac{D\ D_{RRRRhWW}}{\lambda\lambda_{WWWWWWWWWWWW}}}$$

There are different approximations for the *Nusselt* number depending on the flow conditions. Since turbulent flow conditions prevail in the pipelines within the pilot area, the analyses in this report are based on approximations for fully developed turbulent flows [7]:

$$NNNN = \frac{(\xi\xi/8)\ RRRR\ PPrr}{1 + 12.7\ (\xi\xi/8)1/2(^{PPrr2/3-1})}\left[1 + \left(\frac{ddRRRRhWW}{Ll}\right)\quad\right]$$

With the pressure loss coeffi ξ cient = (0.79 ln(*Re*) – 1.5)–^{2} and pipe length *l*. The *Reynolds number* Re = v dPipe/ vWater also *takes into account* the flow velocity v and kinematic viscosity *vWater, the* Prandtl number Pr = cp,water λ μ *water/water* refers to the dynamic viscosity $_{\mu\text{Water}}$.

RESULTS AND DISCUSSION

Figure 4 shows a map of the heat load in the settlement area superimposed on the drinking water pipes and the measuring points in the pilot area. The color scale of the background map indicates the physiologically equivalent temperature on a summer day at 2 p.m. The physiologically equivalent temperature describes the mean thermal sensation of a standard person and is mainly influenced by air temperature and humidity, wind speed and direct sunlight [8]. It is clearly recognizable that there are several hotspots with extreme overheating in the pilot area. Whether

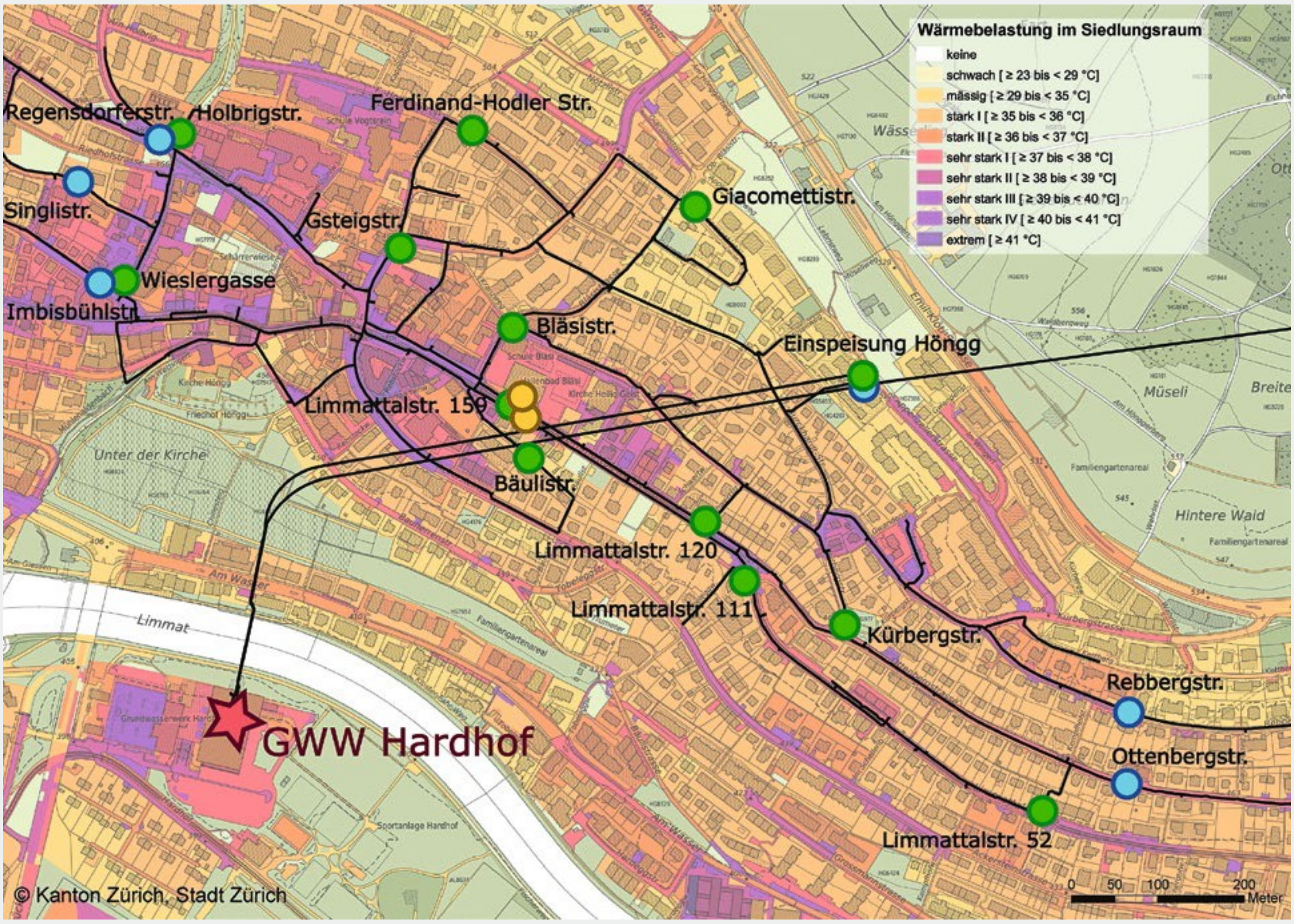

Fig. 4 Map of the heat load in the settlement area superimposed with the drinking water pipes and measuring points in the pilot area Zurich Höngg. The colour scale of the background map indicates the heat load in the settlement area in the form of the physiologically equivalent temperature on a summer day at 2 p.m. The quality of green spaces is not considered further in this report and therefore does not appear in the legend. The color assignment of the different measurement locations is explained in the caption to Figure 1.

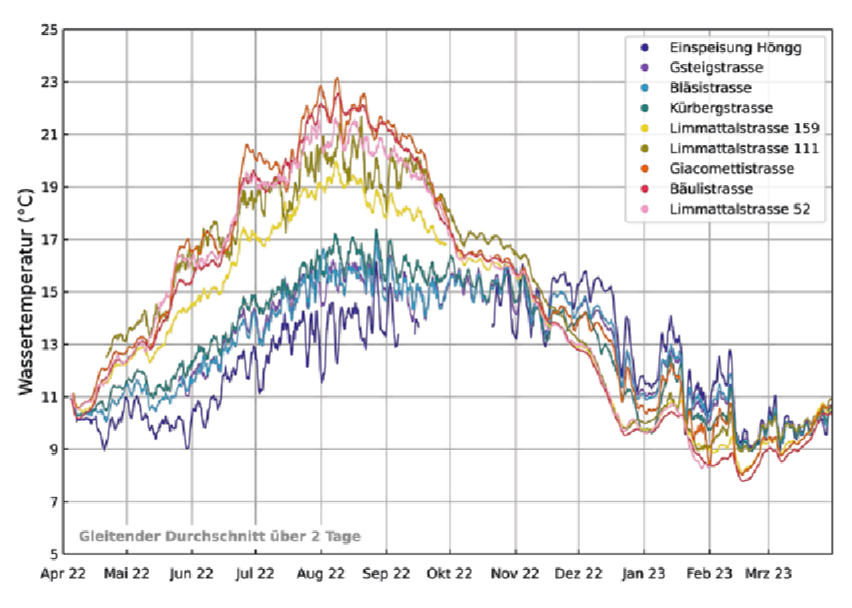

Fig. 5: Drinking water temperature at selected measuring points in the period April 2022 to March 2023. The moving average over two days is shown. Data gaps in individual time series have arisen due to failures of the respective sensors.

Until now, it was unclear whether these hotspots of heat pollution in settlement areas correlate with a warming of drinking water.

In order to assess the relationship between heat pollution in settlement areas and temperature development in the drinking water network, the measured temperatures at the measuring points were qualitatively evaluated in a first step. *Figure 5* shows the development of water temperatures at selected locations from the pilot area, which represent the variance of temperature development in the network. Shown is the moving average over two days for the Period April 2022 to March 2023. As mentioned above, the Höngg feed-in point is on the main inflow pipeline for the pilot area and thus represents the initial temperature. In the course of the summer, a warming can be seen in all stations compared to the temperature of the Höngg feed-in. The three stations Gsteigstrasse, Bläsistrasse and Kürbergstrasse show the lowest warming compared to the original temperature. These three stations are the closest to the tributary among those shown. A little further away, Limmattalstrasse 159 shows a little more warming. The hotspots

In terms of drinking water temperature in the pilot area, Limmattalstrasse 52, Limmattalstrasse 111, Bäulistrasse and Giacomettistrasse have average temperatures between 21 and 23 °C in midsummer. These four measuring points are located in streets with few consumers and show correspondingly low flows. The maximum temperature measured in the period shown was 24 °C (7.8.2022 at 04:43 at Limmattalstrasse 52). It is interesting to observe that the correlation changes from mid-November, and the measurements in the distribution grid show lower temperatures than in the main inflow feed-in Höngg.

A comparison between the climate map (Fig. 4) and the measured drinking water *temperatures* (Fig. 5) shows that at *some measuring points the heat load in the street space corresponds to the temperature* development in the drinking water network. The measuring points Limmattalstrasse 52 and 111 are both located in zones with very high heat loads and belong to to the observed hotspots in terms of drinking water temperature. However, this relationship does not apply to all measuring points. For example, high drinking water temperatures were measured at Giacomettistrasse, whereby the measuring point is located in an area with moderate heat load. Conversely, the heat load at the Gsteigstrasse and Bläsistrasse measuring stations is very high, while the heating of the water compared to the initial temperature is rather low. All in all, it can be said that there is no direct correlation between overheating in the boiling area and drinking water temperature.

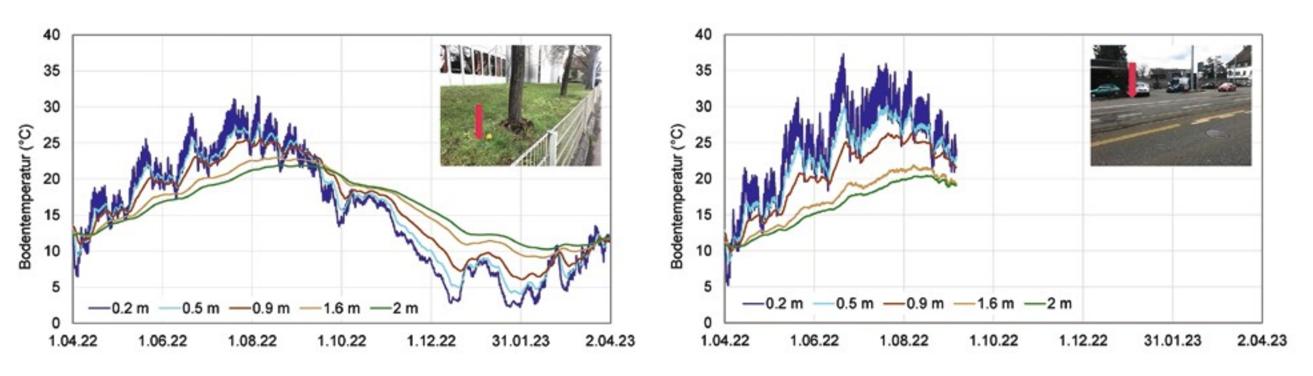

Fig. 6 Soil temperature in 0.2 m, 0.5 m, 0.9 m, 1.6 m and 2 m below ground surface at Limmattalstrasse 159 (under asphalt) and on the opposite side of the road (under meadow) for the period April 2022 to March 2023. The red arrows in the photos indicate the approximate location of the measuring chains. Due to a defect in the data logger, the series of measurements under asphalt is incomplete.

in the distribution network. Other influencing factors must therefore be taken into account.

One factor that influences the drinking water temperature in the distribution network is the floor temperature. *Figure 6* shows the moderate soil temperatures at the two sites near Limmattalstrasse 159 under asphalt and under meadow for the same period as the water temperatures in *Figure 5*. Due to a defect, the data for the logger under asphalt (which is located in the immediate vicinity of the quality measuring station Limmattalstrasse 159) is incomplete. The plot makes it clear that daily fluctuations in soil temperature are dampened with increasing depth. Especially at depths of 1.6 m and 2 m, only the progression of individual warm and cold periods can be detected. Furthermore, the maxima of individual warm and cold phases as well as those of the entire annual curve are time-delayed with increasing depth. This means that a heat input from above makes itself felt in the plane of the line depth (approx. 1.6 m) only after a few days noticeable.

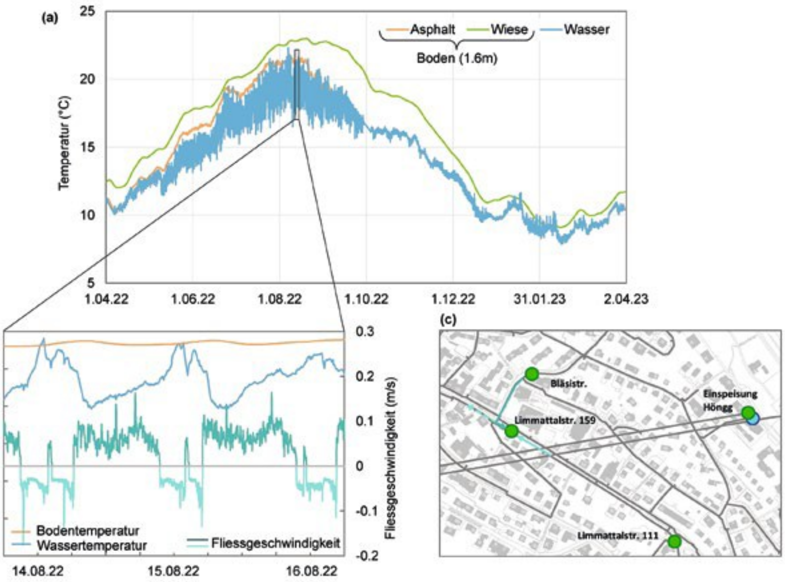

Fig. 7 (a) Soil and water temperature at a depth of 1.6 m measured at Limmattalstrasse 159 in the period April 2022 to March 2023. (b) Soil and water temperature as well as flow velocity and direction at Limmattalstrasse 159 for two days in August 2022. (c) Map section with display of flow directions at Limmattalstrasse 159.

Due to the proximity of the quality measuring point and the soil temperature measuring chain at Limmattalstrasse 159, a direct comparison can be made between the soil temperature at a depth of 1.6 m and the temperature in the drinking water pipe running next to it. This is shown in *Figure 7 (a)*. Since the soil temperature at the measuring point could not be recorded over the entire year, the soil temperature measured at a depth of 1.6 m was plotted on the other side of the road under meadow. It can be seen that the soil temperature in the course of spring and summer represents a kind of upper limit for the drinking water temperature. The section in *Figure 7 (b)* shows the detailed temperature profile of water and soil on two individual days in August 2022. Furthermore, the flow velocity and direction of the drinking water is plotted. *Figure 7 (c)* schematically shows the flow conditions. During the day, water flows from Bläsistrasse via Limmattalstrasse 159 in the direction of Limmattalstrasse 111 (dark *green curve, Fig. 7 (b) as* well as *dark green curve*

green arrow, Fig. 7 (c)). At night, the Direction of flow *(light green curve* and *corresponding arrow)*, so that water can flow again from the direction of Limmattalstrasse 111 flows back. However, it does not flow back into Bläsistrasse (no changes of direction were observed there), but further along Limmattalstrasse (indicated by the *light green dashed arrow*). The time course of water temperature and Flow velocity shows that with the nocturnal change of direction and slightly lower flow speeds, the water temperature rises to the level of the ground temperature. In the morning, accompanied by a change of direction and increasing water consumption (correspondingly higher throughput

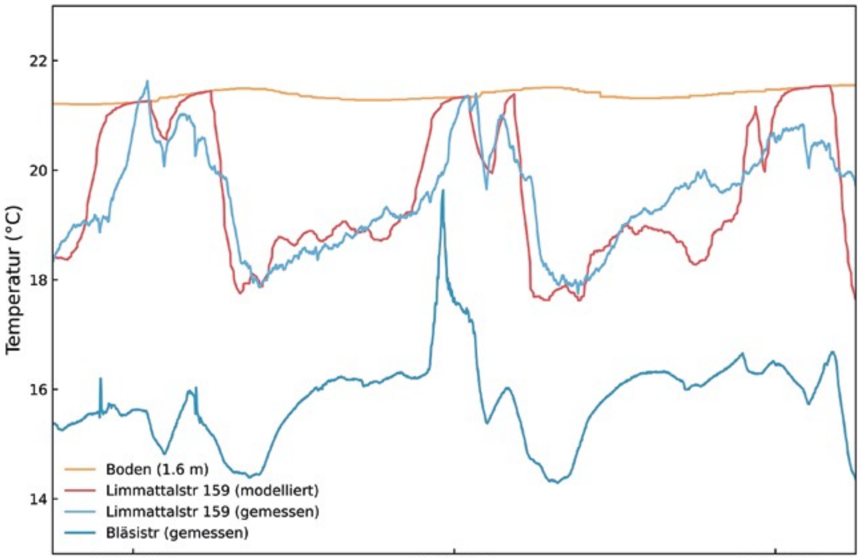

Fig. 8 Comparison between measured and modelled water temperature at Limmattalstrasse 159. The water temperature at Bläsistrasse was used as the initial temperature and the outside pipe temperature was equated as the assumption of the ground temperature.

rivers), the water temperature decreases by several degrees Celsius in less than three hours. It is therefore already qualitatively recognizable that soil temperature, flow velocity and time spent in the network have a significant influence on the development of water temperature.

For a first quantitative analysis, the water temperature at Limmattalstrasse 159 was estimated based on the formulas given above. For the direction of flow during the day, the water temperature at Bläsistrasse was considered as the initial temperature. For the change of direction of flow at night, an additional time spent on the Limmattalstrasse line was taken into account. The direct flow path between the two measuring points as well as the respective diameters and materials of the pipe lines specify further boundary conditions. Furthermore, due to the proximity between the soil temperature measurement and the pipeline, it is assumed that the outside pipe temperature corresponds to the measured soil temperature. The heat conduction within the soil between the soil measuring point and the pipe was neglected in the first approximation. *Figure 8* shows the measured and modelled water temperature as well as the initial temperature measured at the Bläsistrasse and the soil temperature. There is a good agreement between the model and the measurement, since the measurements measured at Daily profiles with small deviations can be predicted by the model. At other measuring points, the agreement between predicted and measured temperatures is less good (not shown). In other words, there are still too many unknowns there to achieve a realistic agreement. In particular, it is still unclear how much soil temperature changes over the pilot area and to what extent heat conduction within the soil plays a role. Furthermore, due to the many branches in the network, the flow rates cannot be determined for all lines despite the high sensor density. In order to make it possible to predict hotspots in the drinking water pipes, further insights into the variability of soil temperature across the pipeline network would be needed on the one hand and more precise data on the respective flow rates on the other.

WAYS TO REDUCE THE TEMPERATURE OF DRINKING WATER

The influencing factors known from the formulas can be used to evaluate various approaches to reducing the temperature of drinking water in the distribution network. Regardless of the actual initial temperature of the drinking water as well as the temperature of the soil surrounding the pipe, it is possible to calculate how long it takes for the drinking water to increase by 95% of the difference between water and soil temperature (warm-up time $t_{0.95}$). For a certain flow velocity v *in the pipe, the warm-up time* $t_{0.95}$ can be converted into a warm-up section $x_{0.95}$: $x_{0.95} = v\ t_{0.95}$. This warm-up section is shown in *Figure 9* as a function of the volumetric flow through a pipe for different materials and diameters. The range of the volumetric flow as well as the selected diameters and pipe materials represent the conditions prevailing in the pilot area. The material values for water were taken into account for an average water temperature of 15 °C. In the following sections, the individual factors influencing temperature reduction are discussed in more detail.

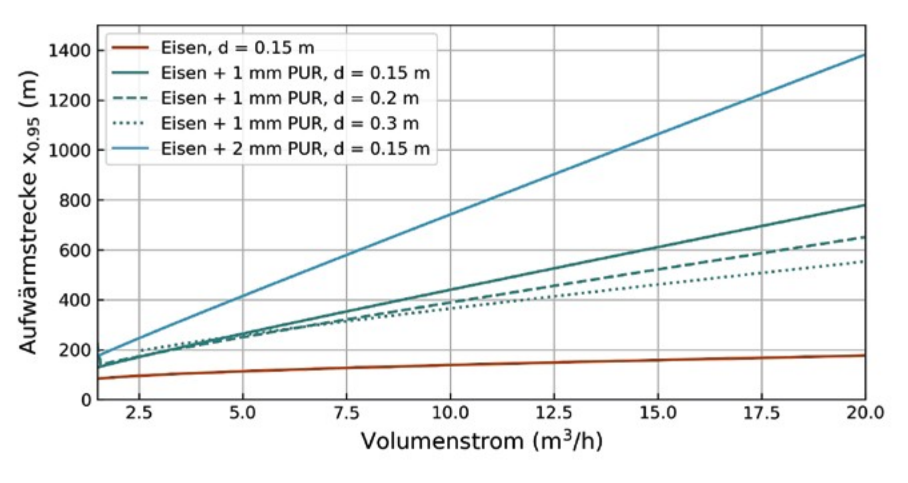

Fig. 9 Distance that the drinking water would have to travel in the distribution network in order to heat up by 95% of the temperature difference between water and soil, depending on the respective volume flow through a pipe with a fixed diameter. The solid lines show the influence of different pipe materials (PUR: polyurethane), the petrol-colored lines show the influence of different diameters.

LOWERING THE INITIAL TEMPERATURE

In Zurich, most treated lake water is made available as drinking water, which has a temperature of between 6 and 12 °C (average 7–8 °C) at the plant exit all year round. In addition, groundwater is pumped, which can reach temperatures of up to 18 °C in the summer months (average 15 °C). An obvious idea for lowering the temperatures in the distribution network is to lower the initial temperature. This would mean distributing drinking water from the lake waterworks in summer. However, *Figure 9* shows that, depending on the pipe material, diameter and volume flow, the drinking water has already heated up by 95% of the temperature difference between water and soil after very short distances of mostly less than 800 m. For the comparison between lake and groundwater, assuming a soil temperature of 23 °C, this would mean that the lake water, which was originally 8 °C cool, warms up to 22.25 °C and the significantly warmer groundwater from 18 °C to 22.75 °C. The originally large temperature difference between the two drinking waters would therefore hardly exist within a short time (or a short distance). Lowering the initial temperature would therefore only be very local around the respective plants to achieve the desired
Achieve effect .

SOIL TEMPERATURE

Figure 6 shows that the soil temperature increases with increasing depth.

and thus the upper limit for drinking water temperature during the summer months decreases. Another way to reduce the drinking water temperature in the distribution network would therefore be to lay the pipes at greater depths in order to limit the maximum temperature. However, this would be a very long-term and costly measure.

With regard to overheating in cities, there are various approaches to cooling down heat islands in urban areas (e.g. increased greening, different floor coverings) [2]. To the best of our knowledge, however, these measures have so far only been evaluated above ground. With regard to rising temperatures in drinking water, heat-reducing measures should not only be evaluated above ground in the future, but a possible effect on cooling the soil should also be taken into account and evaluated.

PIPE MATERIAL

The pipe material directly affects the heat transfer between the soil and drinking water. Cast iron is a popular material, but it is also a good conductor of heat. *Figure 9* shows that even a few millimeters of additional PUR coating have a strong insulating effect. At critical points such as pipes with a small diameter and/or low flow, additional insulation could help to keep drinking water cool for longer.

CABLE DIAMETER

With a smaller diameter, the area over which heat transfer from the ground can take place decreases. Furthermore, assuming that consumption remains constant (i.e. no major changes in the observed flow rates at individual locations), the pipeline flows are used to determine the affects the flow velocity. More precisely, halving the diameter means quadrupling the flow velocity. The flow velocity, in turn, influences the residence time of the water in the pipe and thus defines the period of time in which the water can heat up. At the same time, a higher flow velocity means higher turbulence and, as a result, better heat transfer. Figure *9* shows that the influence of smaller pipe diameters is limited and, depending on the volume flow, can lead to larger, but also to smaller warm-up distances. It is therefore not possible to make a general recommendation as to whether it makes sense to reduce or increase the diameter of the cable.

CONCLUSION/OUTLOOK

The first evaluations of the sensors of the Zurich water supply in the Höngg pilot area show how the temperature of drinking water in the distribution network develops over the course of a year. In the summer months, a strong warming compared to the initial temperature could be observed in some cases. A comparison with climate maps of the heat load in settlement areas shows that there is no general correlation between above-ground heat islands and the drinking water temperature measured in the pipelines. These results, in combination with modelling approaches, can help to evaluate factors influencing the drinking water temperature. Overall, it can be seen that in the warmer half of the year, the soil temperature as the upper limit for the drinking water temperature is a decisive factor. For this reason, measures to reduce heat in urban areas should explicitly include soil temperature. Farther-Drinking water distribution networks should be taken into account in action plans against heat. More soil temperature measurements are needed to further understand the development of soil temperature in urban areas. This should make it possible to develop a spatially resolved soil temperature model to predict water temperature. As a further measure, it is advisable to additionally insulate cables at critical points. The effect of a lower initial temperature is strongly localized. Likewise, a reduction in the pipe diameter does not always ensure cooler drinking water. Overall, it makes sense to explicitly take into account the development of drinking water temperature in long-term network planning in order to be able to take appropriate measures as early as possible.

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