Early warning system to forecast maximum temperature in drinking water distribution systems

C. M. Agudelo-Vera, E. J. M. Blokker and E. J. Pieterse-Quirijns

ABSTRACT

Climate change poses new challenges in preventing the exceedance of the maximum allowed temperature in the drinking water distribution system (DWDS). The objective of this article is to evaluate the feasibility of forecasting the maximum temperature in the DWDS. Two options were analysed: (1) using the records of the last day as forecast for the coming 2 days and (2) using 2-day weather forecast data. The maximum water temperature in the DWDS was modelled for a Dutch city for a warm period during summer 2006. Actual meteorological records and historical weather forecasts were used. Results for the daily maximum temperature for June–July 2006 based on the high resolution limited area model predictions showed a 0.09 °C average mean error and a maximum error of 0.3 °C, while using the last day record as forecasted showed a mean error of 1.09 °C and a maximum error of 2.5 °C. These results indicate that it is possible to predict the daily maximum water temperature in the DWDS using the weather forecast information or using actual records as a short-term prediction. These types of simulations can serve as an 'early warning system' to monitor drinking water temperature for taking measurements to avoid exceeding the maximum allowed temperature.

Key words | climate change, drinking water quality, drinking water temperature, early warning system, soil temperature

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INTRODUCTION

Although worldwide several initiatives addressing adaptation measures for climate change are being taken (Veraart *et al.* 2014), disruptive events such as heatwaves pose threats to public health. Negative health effects of exposure to heatwaves are well known (Kovats & Hajat 2008). However, the risks due to heating of drinking water distribution systems (DWDS), leading to water quality deterioration, are less known. In the Netherlands, 12 heatwaves have taken place in the last 25 years. In 2006, the heatwave lasted 16 days, with a maximum temperature of 35.7 °C (KNMI 2014). In the Netherlands, a heat wave is defined as a period of at least 5 consecutive days in which the maximum temperature in De Bilt exceeds 25 °C, provided that on at least 3 days in this period the maximum temperature in De Bilt exceeds 30 °C. De Bilt is the location of a meteorological station in the middle of the country. Clark *et al.* (2006) described how the intensity, duration, and frequency of summer heatwaves are expected to be substantially greater over all continents. The largest changes are found over Europe, North and South America, and East Asia.

In urban areas, the effect of the urban heat island effect has to be considered as well. A recent study in an urban area in Germany reported a 'subsurface urban heat island' of 9 °C at 70 cm depth (Müller *et al.* 2014). The heat island effect, which is a product of geometry, design, density, building materials used, latent heat, and decreased evapotranspiration due to reduced vegetation, combined with climate change, makes urban environments more susceptible to heatwaves. Specifically in urban areas, with concentrated populations and multiple heterogeneous land cover characteristics, tools are needed to monitor and predict drinking water temperature in the network at small spatial scales.

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Currently, thermal remote sensing is used to observe and investigate the surface urban heat island (SUHI), which refers to the relative warmth of the urban surfaces. The SUHI intensity is defined as the difference between the urban and rural surface temperatures (Klok *et al.* 2012). In the Netherlands, an analysis of the SUHI showed the influence of different surface materials and soil types on the surface temperature. The daytime SUHI intensity of Rotterdam can be as large as 10 °C, with variations between the different neighbourhoods, creating 'hot-spots' within the city. While mitigation measures can reduce the impact of the heat island effect and climatic changes, these measures take time to implement and have an impact. In the meantime, there is a need to monitor drinking water temperature in the DWDS and prevent drinking water quality problems during heatwaves, especially in high-density urban areas.

Water temperature is an important determinant of water quality. Temperature influences physical and chemical processes, such as absorption of chemicals and chlorine decay (Powell *et al.* 2000; Uber 2010). In the Netherlands, drinking water is distributed without additional residual disinfectant and the temperature of drinking water at the customer's tap is not allowed to exceed 25 °C (Drinking Water Directive 2014). During a relatively warm year (2006), 0.1% of the routine water quality samples exceeded this value (Versteegh & Dik 2007). With climate change, more samples may be expected to exceed the temperature limit. Monitoring the water temperature in the DWDS by random sampling is not enough because it only gives an indication of the occurrence. To better monitor and to prevent exceedance of the maximum allowed temperature, new decision support tools are required.

The temperature in the water distribution network can be assumed equal to the temperature of the surrounding soil, for pipes buried at *c.* 1 m depth (Blokker & Pieterse-Quirijns 2013). Soil temperature at shallow depths presents significant daily and annual fluctuations (Herb *et al.* 2008). Therefore, water temperature in the network also shows these fluctuations. Soil temperature fluctuations depend on meteorological conditions, soil properties, and land cover (Mihalakakou 2002; Herb *et al.* 2008; Blokker & Pieterse-Quirijns 2013). Therefore, measurements of soil temperature at the surface and at various depths are spatially and temporally limited (Mihalakakou 2002).

Blokker & Pieterse-Quirijns (2013) described a micrometeorology model to predict the soil temperature at various depths as a function of weather and environmental conditions, considering soil type and land surface cover. This model allows a continuous modelling of the soil temperature. For a Dutch city, the model had a mean error lower than 1%. In this article, we use soil temperature as a surrogate variable for temperature in the DWDS.

An early warning system based on weather conditions and local characteristics can support spatial analysis of climatic threats to drinking water quality (Agudelo-Vera *et al.* 2014). An early warning system is an integrated system for monitoring, collecting, analysing, interpreting, and communicating monitored data. Such a system can be used to make decisions early enough to protect public health and the environment to minimize unnecessary concern and inconvenience to the public (USEPA 2005). The objective of such systems is to provide important, timely information on specific phenomena to end-users and decision-makers, thereby enabling effective response.

The objective of this article is to evaluate the feasibility of using the micrometeorological model developed by Blokker & Pieterse-Quirijns (2013) to predict the maximum daily water temperature in the DWDS 2 days in advance. Two options were analysed: the first option was considering the records of the last day as forecast for the coming 2 days; the second one was using 2-day weather forecast data. Predicting the water temperature in the DWDS 2 days in advance could serve as an early warning system. This early warning system can predict the risk of exceeding the temperature limit. Furthermore, this system will allow water managers to prepare for the risk and act accordingly to prevent or mitigate exceedance of the maximum allowed temperature. This paper is an extension of that presented at the 12th International Conference on 'Computing and Control for the Water Industry – CCWI 2013' (Agudelo-Vera *et al.* 2014).

MATERIALS AND METHODS

Soil temperature model

The soil temperature model developed by Blokker & Pieterse-Quirijns (2013) considers four layers: the atmosphere, the roughness layer (RL), the soil surface (SS), and the soil (see Figure 1). The RL is the layer between atmosphere and SS, where air properties can be changed by, for example, vegetation or buildings. For built-up areas, the height of the RL depends on the spatial distribution and heights of buildings. The five heat transfer processes included in the model are as follows (Blokker & Pieterse-Quirijns 2013):

(1) Between atmosphere and SS: energy transfer by radiation from the sun to the earth's surface, through the RL. The radiation that reaches the SS is partitioned, one part is absorbed and the rest is reflected depending on the albedo of the SS.
(2) Between atmosphere and RL: energy transfer by convection, influenced by air temperature and wind.
(3) Between RL and SS: energy transfer by convection, influenced by air temperature, wind, reflection, and evaporation by vegetation.
(4) Between SS and soil: energy transfer by conduction through the soil to the outside wall of the water main.
(5) Between soil and pipe wall: energy transfer by conduction.

The heat transfer can be described by two energy balances: the energy balance in the RL and the heat balance in the SS, as described in Blokker & Pieterse-Quirijns (2013).

Available data and assumptions

The study area was the city of Eindhoven in the Netherlands. In the Netherlands, most water distribution pipes are located in urban areas at a depth of 1.00 m (Blokker & Pieterse-Quirijns 2013). The soil temperature at 1.00 m depth was modelled using the micrometeorological model developed by Blokker & Pieterse-Quirijns (2013). The model considers the soil type as well as the land cover material. For Eindhoven, sandy soil and an albedo of 0.16 for asphalt were used (Blokker & Pieterse-Quirijns 2013). For sandy soil, the heat conduction coefficient of 2.03 (W/m K), soil density 1.6×10^3 kg/m^3, and specific heat capacity of 1.06×10^3 (J/kg/K) were used (Blokker & Pieterse-Quirijns 2013).

The roughness length, z_0, was estimated at 0.15 m. The height of the RL air column h_{RL} (m) was set to be 10 m (van der Molen 2002). The other variables not mentioned here are used as described in Blokker & Pieterse-Quirijns (2013).

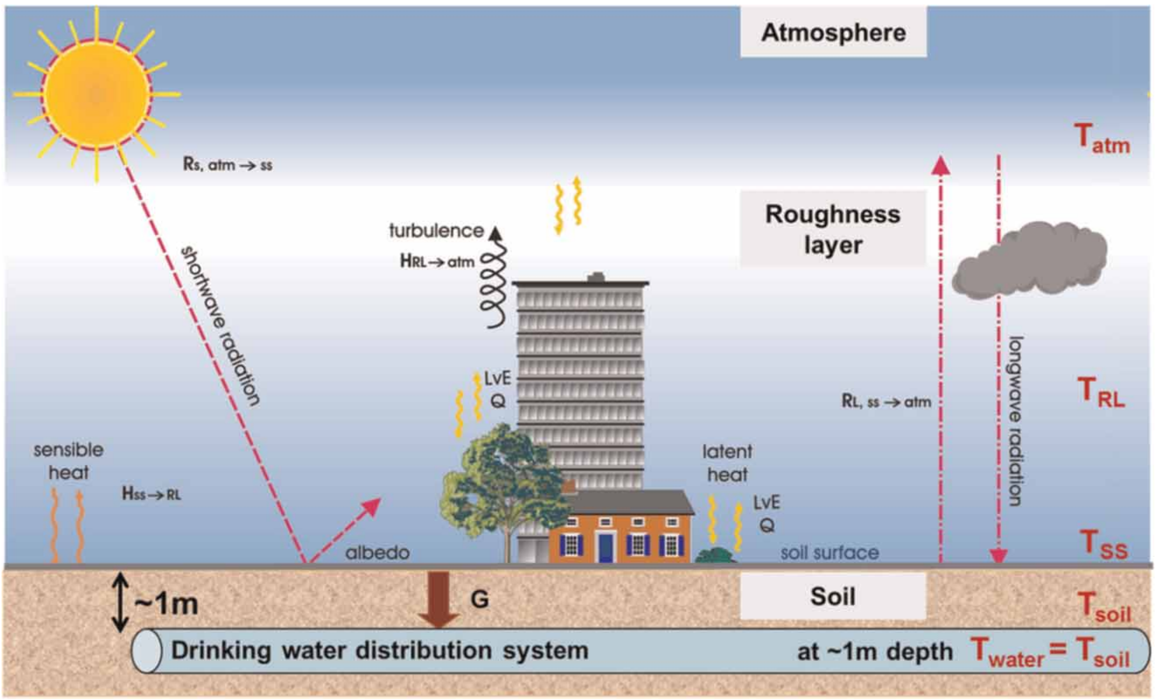

Figure 1 | Description of the model (adapted from Blokker & Pieterse-Quirijns 2013). atm: atmosphere, G: heat flux into the ground, H: sensible heat flux, LvE: latent heat of evaporation, Q: energy to heat vegetation, R: radiation flux, RL: roughness layer, SS: soil surface, T: temperature.

Soil temperature is used as a surrogate variable for temperature in the DWDS. The soil temperature was modelled for the year 2006, which was a warm year. Meteorological data used as input model are temperature (°C), relative humidity (%), wind speed (m/s) and global radiation (W/m^2). Two different meteorological data sets were used. First, the soil temperature at −1.00 m was simulated using actual meteorological records from Eindhoven from the Dutch meteorological institute – Koninklijk Nederlands Meteorologisch Instituut (KNMI 2013). These simulations were assumed as the actual soil temperature. Second, the soil temperature was modelled using the records of the last day as forecast for the coming 2 days. Third, the soil temperature was modelled for the warmest months of the year using the historical forecast records.

The historical weather forecasting used was generated by high resolution limited area model (HIRLAM) (HIRLAM 2013). HIRLAM is a 2-day numerical weather prediction. HIRLAM has a spatial precision of 11 × 11 km. A detailed description and validation of HIRLAM is reported by de Bruijn (1996). Subsequently, the simulated soil temperature was compared. For numerical stability of the model, the two data sets were interpolated to a suitable time step of 1 minute. An overview of the methodology is given in Figure 2(a).

The actual meteorological records from the KNMI are logged every hour. For option 1, the soil temperature model is updated each hour (Figure 2(b)). The HIRLAM forecasted data are generated every 6 hours. HIRLAM forecasts the first 12 hours with a 3-hour interval, the subsequent 36 hours with a 6-hour interval. The HIRLAM data set is first interpolated to obtain an hourly data set. After that, the soil temperature is modelled with an update every 6 hours (Figure 2(b)).

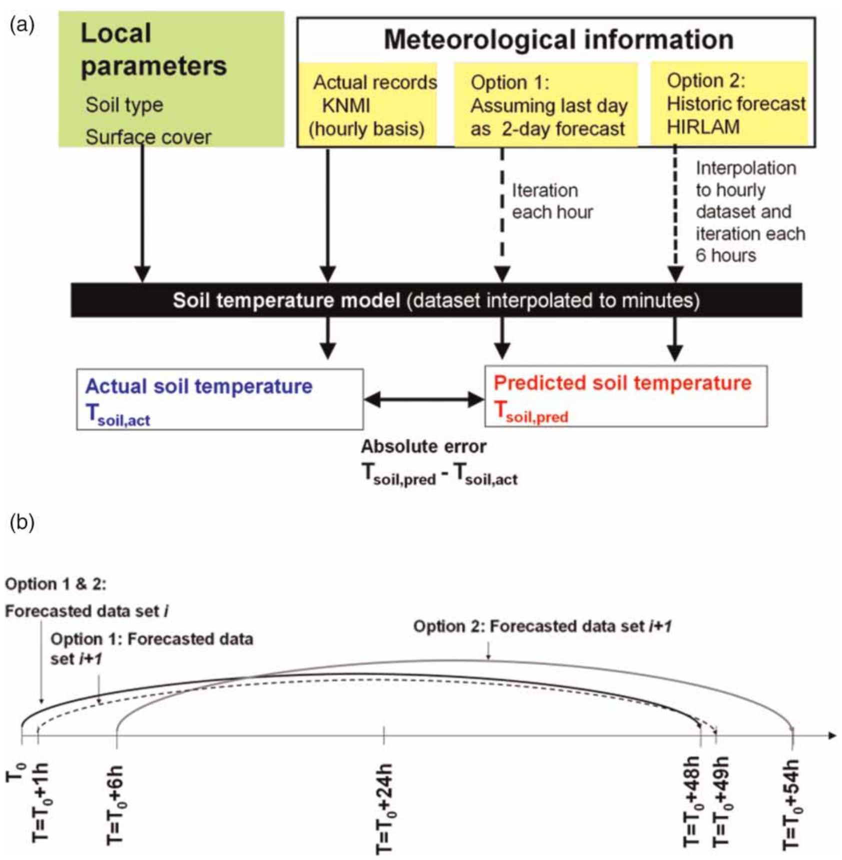

Figure 2 | (a) Description of the methodology, (b) detail of the iterations for the two options.

RESULTS

As a preliminary step, an analysis of the quality of the forecasted data was done, comparing the forecasted data against the actual data measured by the KNMI. For the year 2006, the air temperature forecasted showed an average error of 1.88 °C. Meanwhile, global radiation forecasted showed an average error of 18 W/m². Figure 3 shows the modelled soil temperature at −1.00 m depth for the city of Eindhoven for the year 2006 using actual meteorological records on an hourly basis. Figure 3 also shows the actual atmospheric temperature. The simulation clearly shows the soil temperature variations due to meteorological changes. For the year 2006, the soil temperature at −1.00 m depth varied from 3.8 to 27.4 °C, while the atmospheric temperature varied from −7.4 °C to 35.9 °C. June and July are the warmest months, with a possibility of exceeding the 25 °C temperature limit in the DWDS.

Figure 4 shows the simulated soil temperature during the warmest months of the year 2006. Three series are plotted. The KNMI records are the actual soil temperature. Two options are plotted as predictions. First, the HIRLAM predictions are the soil temperature based on forecasted data. Second, the KNMI records of the last day were used as a prediction for the coming 2 days. Note that the soil temperature from the actual record is given on an hourly basis, and the forecasted temperature is given

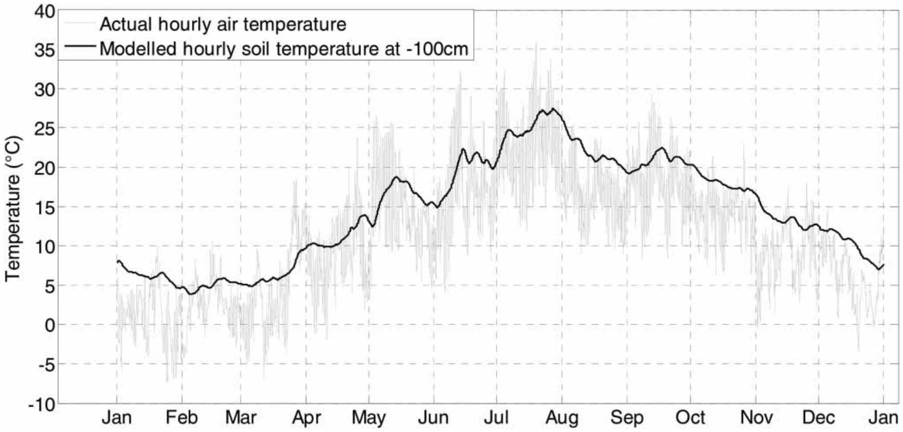

Figure 3 | Comparison of atmospheric (measured) and soil temperature (modelled with the KNMI data set) for the year 2006 for the city of Eindhoven on an hourly basis.

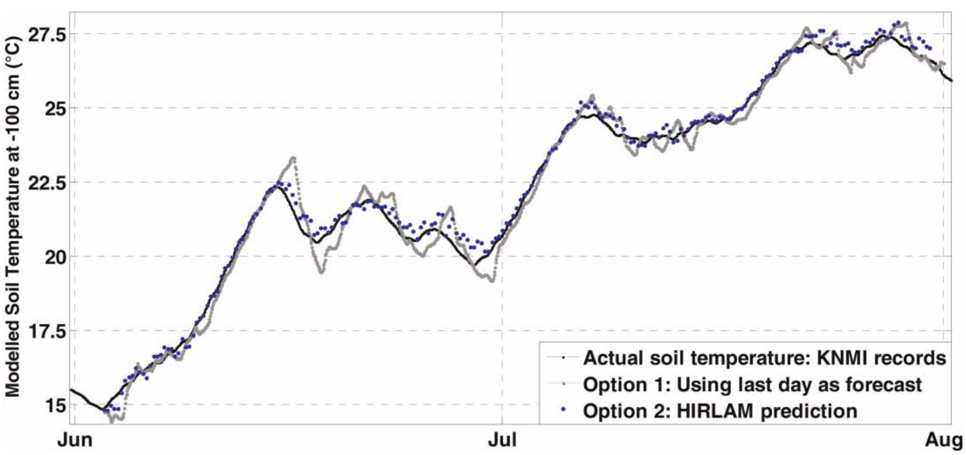

Figure 4 | Comparison of modelled hourly soil temperature at −1.0 m for the two meteorological data sets, during June and July 2006.

every 6 hours, due to the characteristics of the forecasted data set. Results show a good correlation between the soil temperature calculated with the historical weather forecast data and the soil temperature calculated using the meteorological records. For the daily maximum temperature in June and July 2006, the HIRLAM predictions showed a 0.09 °C average mean error and a maximum error of 0.3 °C, while using the last day record as forecasted showed a mean error of 1.09 °C and a maximum error of 2.5 °C. The HIRLAM forecast was shown to be able to predict maximum daily temperatures well. Using the last day records as a forecast for the following 2 days showed larger errors, which can result in false positives. However, this approach was shown to demand little data while providing an insight into the risk of exceeding a given temperature. The maximum actual change in the soil temperature at −1.0 m in 2 days was 1.6 °C. These results demonstrate that it is possible to use weather forecast information to predict soil temperature and therefore to estimate water temperature in the drinking water distribution network 2 days in advance.

Figure 5 shows the number of days during the months of June and July in 2006 exceeding 20, 22.5 and 25 °C for the three simulations. Based on the KNMI records, during June and July 2006 soil temperatures at 1.00 m depth above 25 °C were recorded on 14 days. Using the HIRLAM forecast, 16 days with exceeding temperature were expected, and using the last day as forecast resulted in 17. This information can complement the data collected on site and support the development of new measurement schemes and contingency plans.

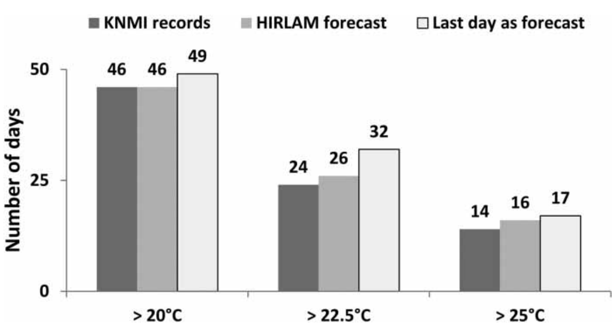

Figure 5 | Number of days exceeding certain temperatures for the months June and July 2006 based on soil simulations.

DISCUSSION AND CONCLUSION

Hot extreme events are expected to substantially increase in intensity, duration, and frequency. Therefore, global warming, combined with the urban heat island effect, will pose new challenges to control physical, chemical, and biological processes in the DWDS. Moreover, heterogeneity of land cover and urban morphology results in spatial variability in soil temperatures across urban areas meaning that exposure to extreme heat events is variable at the sub-city scale. Such variability must be quantified in order to better understand urban temperature interactions and to identify areas with the greatest potential exposure to extreme heat events.

We studied a city in the Netherlands, with a moderate maritime climate with cool summers and mild winters. For (mega)-cities with warmer climates, this type of early warning system is an inexpensive option to monitor and predict water temperature in the distribution network using available information.

Further research could focus on testing the model with a longer time span prediction and in other locations. Attention should be given to the trade-off between temporal and spatial resolution. Longer forecast data sets are available, but on larger spatial scale or with less detail. Longer-term forecasted temperatures can provide a larger time window for action; however, trade-offs regarding accuracy of the prediction have to be analysed to avoid false positives.

Quantifying soil temperature is of significance to engineering design, for instance to determine and monitor the thermal interaction of the soil with pipelines (Blokker & Pieterse-Quirijns 2013), ground heat storage, and heat pump ground heat exchangers. Further research is being conducted to include additional heat sources present in urban areas.

Results indicate that it is possible to use weather forecast information as an early warning system to predict temperature in the DWDS. Table 1 shows an overview of the results, including the assumption that the soil temperature is constant during the coming 2 days. Although assuming that the soil temperature will be constant over the coming 2 days has a lower error than option 1, assuming a constant soil temperature leads to a delay in the detection of soil

Table 1 | Overview of the results

	Number of days ($T_{max} > 25\,^{\circ}C$)	Average error (°C)	Max error (°C)
Assuming soil temperature constant in the coming 2 days	14	0.73	1.85
Option 1: using today's meteorological data as 2-day forecast	17	1.09	2.50
Option 2: 2-day HIRLAM forecast	16	0.09	0.30
Actual soil temperature	14		

temperature above 25 °C, which implies that there is not enough time to react. Therefore, using a prediction based on records provides a better estimation which can be used as an early warning system. Moreover, using the HIRLAM forecast improves the prediction of the soil temperature at −1.0 m. For a forecast of 2 days in advance the maximum absolute error was 0.3 °C. Therefore, the consequences of climate change for drinking water temperature can be assessed by using the micrometeorological model in combination with weather forecast data or actual meteorological records. Advantages of this approach are the possibility it presents to study different soil and land covers and different soil depths. Modelling offers the flexibility to simulate a range of urban configurations, although generally relying on simplified expressions of the energetic processes. In this way, hot-spots can be identified. Moreover, with this type of analysis, different risk levels can be identified in an urban area, resulting in specific measures according to the risk. A 2-day forecast will allow a timely response, for instance, to warn the population with 'boil water advice'. Moreover, modelling soil temperature can also support or give valuable information about where and when to take samples on site and to better monitor the DWDS. This approach couples spatial (land cover and soil type) with non-spatial information (meteorological information) in a very systematic and reliable way. Better understanding of soil thermal dynamics and their effect on DWDS can support the improvement of current action plans.

Although setting an early warning system can be expensive, a strength of this approach is that the model uses existing forecasting data. When the model is calibrated for a location, the costs of modelling are much lower than measurement campaigns. Measurements on site will only allow reactive measures to be taken. We believe that these types of analysis and tools are needed for a proactive response.

In the Netherlands, pipes are typically located at 1 m, based on the experience that frozen soils generally occur above this level. With climate change predicting less frost, and with the focus on lowering cost it may be attractive to install pipes at a shallower depth. However, higher temperatures may then occur and may produce negative effects. Also, the largest part of the drinking water network will still be in place in 2050, at the same depth, and will then experience higher temperatures than today. As a monitoring system is feasible, this will help the operation of the drinking water supply.

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