

A distributed heat transfer model for thermal-hydraulic considerations in sewer networks

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Abstract

Thermal-hydraulic considerations in urban drainage networks are essential to utilise available heat capacities from waste- and stormwater. However, available models are either too detailed or too coarse; fully coupled thermal-hydrodynamic modelling tools are lacking.

To accurately predict water-energy dynamics across an entire urban drainage network, we suggest the SWMM-HEAT model, which extends the EPA-StormWater Management Model with a heat-balance component. This enables conducting more advanced thermal-hydrodynamic simulation at full network scale than currently possible.

We demonstrate the usefulness of the model by predicting temperature dynamics in two independent real-world cases under dry weather conditions. We furthermore screen the sensitivity of the model parameters to guide the choice of suitable parameters in future studies. The results of our study shows that sewer temperatures are particularly sensitive to soil temperature, sewer headspace temperature and humidity under specific conditions. Comparison with measurements suggest that the model predicts temperature dynamics adequately, with RSR values between 0.71 and 1.1.

Simulation runs were generally fast; a five-day period simulation at high temporal resolution of a network with 415 nodes during dry weather was completed in a few minutes. Future work should assess the performance of the model for different applications and perform a more comprehensive sensitivity analysis under more scenarios. To facilitate the efficient estimation of available heat budgets in sewer networks and the integration in urban planning, the SWMM-HEAT code is made publicly available.

Keywords:

wastewater temperature; sewer networks; heat transfer; distributed modelling; thermal-hydraulic analysis; in-sewer measurements

1 INTRODUCTION (MOTIVATION, CONTEXT, SCOPE)

Understanding the evolution of storm- and wastewater temperature in urban drainage networks is highly important for optimal design and operation of different elements of the sewage system. Storm- and wastewater temperature in sewage networks affects the underground infrastructure and the operational condition of wastewater treatment plants in several aspects. For instance, Joseph et al. (2012) suggests that increased wastewater temperatures may contribute to the long-term corrosion of pipes, and Wanner et al. (2005) demonstrate that water temperature plays an important role in the efficiency of the nitrification processes at wastewater treatment plants. Furthermore, in recent decades, the available heat is being collected and used for the space heating and warm water production in buildings and households. This technology has been implemented in several urban settings around the globe, for example in Oslo, Norway (Schmid 2008), where an entire district is heated and cooled with this technique. In European wastewater systems numerous central heat recovery facilities are installed, predominantly at the outlets of Wastewater Resource Recovery Facilities (WRRF), e.g. in Zurich, Switzerland (Arpagaus and Bertsch 2020). Other examples have been reported from several cities in the North of China, namely Beijing, Hebei among others (Shen, et al. 2018).

Correct predictions of storm- and wastewater temperature dynamics during dry and wet weather in the underground pipe network will enable planning engineers to optimally place heat/energy recovery devices, improve the control of wastewater resource recovery facility (WRRF) to increase treatment efficiency, identify illicit infiltration points and accurately assess the available heat budget in storm- and wastewater that can be used for various other uses, such as city cooling. Moreover, knowing the temperature conditions at network-wide scale is important to predict biotransformation of wastewater constituents, e.g. with regard to H_2S formation or epidemiological analyses (McCall, et al. 2016).

Therefore, the estimation of the heat budget of wastewater in sewer networks has been studied in the past through various approaches: mathematical modelling (Durrenmatt and Wanner 2008, Durrenmatt and Wanner 2014), physically-based modelling (Abdel-Aal, et al. 2014, Abdel-Aal, et al. 2018, Schlagbauer 2018), or statistical modelling (Elías-Maxil, et al. 2017, Pelda and Holler 2019). Unfortunately, none of the methods is suitable to predict waste- and stormwater temperature dynamics at network scale, either due to the limitations of the modelling approach, lack of flexibility for use or high computational cost.

Our study aims to close this gap by developing a simulation tool that includes most objectively relevant processes and enables users to estimate temporal and spatial availability of heat budgets in sewer networks, solving the main limitations of the previous studies. The new modelling tool called “SWMM-HEAT” enhances EPA-SWMM with the necessary thermal components to simulate the evolution of temperature in drainage networks during dry and wet weather conditions, in addition to the hydrodynamic processes.

The novelty of this development lies in, i) the integration of an independent temperature state variable, ii) the direct coupling of heat exchange processes on top of a distributed hydrodynamic transport model, and iii) the demonstration of the model’s validity by two independent real-world cases of which one shows the applicability at full network scale using real world experimental data. Furthermore, we perform a screening-type sensitivity analysis to support the choice of suitable parameters in future modelling studies.

The remainder of the manuscript is structured as follows:

- Section 2 specifies the heat transfer processes that appear in sewer systems, includes a summary of the literature about storm- and wastewater temperature dynamics in drainage pipe networks is presented, and establishes evidence to present hereafter a new physical model that incorporates the knowledge acquired based on previous studies, field measurements and numerical experiments.
- Section 3 introduces a new heat transfer model for the estimation of temperature dynamics in sewers with a brief description of how it is integrated into the EPA-SWMM source code.
- Section 4 includes a description of the simulation models implemented for validating SWMM-HEAT and the performance indicators adopted in this manuscript.
- Section 5 encompasses a study of the main parameters affecting thermal dynamics in sewers and a comparison of simulation results with real-world field data.
- Section 6 discuss future work and potential uses of the SWMM-HEAT modelling tool.

2 FUNDAMENTALS AND PREVIOUS WORK

2.1 Heat transfer in sewer systems – Scope and Terminology

This section specifies processes related to heat transfer and wastewater temperature dynamics in sewer systems, whereas distinct knowledge from previous studies is incorporated in Section 2.2. In addition, we formally define the concept of *compartments* and *interfaces* to be unambiguous and consistent, and we designate the term *bulk liquid* to use it – in foresight – globally for storm- and wastewater indistinguishably.

Heat transfer mechanisms occur due to the interaction between the four following compartments: bulk liquid, pipe wall, sewer headspace and soil (see Figure 1 in the SI). Three interfaces can be defined among these elements:

- A. Bulk liquid – sewer pipe and the surrounding soil compartment (pipe/soil),
- B. Bulk liquid – sewer headspace, and,
- C. Sewer headspace – pipe/soil.

Heat transfer related processes that develop at each interface (SI-Figure 1) are:

- A.1: Convection between bulk liquid and pipe wall;
- A.2: Conduction between bulk liquid and pipe wall;
- A.3: Biofilm growth is hampering heat transfer at the pipe wall;
- B.1: Convection between bulk liquid and sewer headspace;
- B.2: Latent heat transfer between bulk liquid and sewer headspace;
- C.1: Convection between sewer headspace and pipe wall;
- C.2: Conduction between sewer headspace and pipe wall.

Based on the previous heat related processes an overall energy balance equation of a sewer pipe section (Figure 1) is defined by,

$$T_{wi} = T_{wi-1} - \frac{(A.1 + A.2 + A.3 + B.1 + B.2 + C.1 + C.2)}{c_p}, \quad \text{Eq. 1}$$

where T_{w_i} and $T_{w_{i-1}}$ are the bulk liquid temperatures at the end and beginning of a time step, and c_p is the bulk liquid specific heat capacity. A detailed reflection on heat transfer related processes is given in the SI-Section A. Specific mechanisms that may affect the heat balance to a lesser extent and under special circumstances, e.g., heat generated by biological, exogenous degradation processes and/or biofilm generation, are also discussed there.

2.2 Review of existing modelling concepts

Dürrenmatt and Wanner (2014) developed TEMPEST, the most comprehensive approach to simulate thermal-hydraulic dynamics in an unbranched sewer section. The evaluation of the thermal-hydraulic dynamics is based on geometric considerations, thermal properties of the different compartments, and it covers the interaction between bulk liquid, sewer headspace, pipe wall and the surrounding soil. Unlike other approaches, TEMPEST combines the simulation of the hydraulics using the 1-D de Saint-Venant equations with heat transfer estimations based on mass and heat balancing. The obtained system of equations is numerically solved in time and space with an explicit second order Lax-Wendroff scheme. With this, TEMPEST is the most complete solver available for the study of thermodynamic mechanisms in sewers. However, owed to its complexity and high degree of detail the model requires precise information that might be difficult to obtain in most studies, and thus needs a large number of assumptions. Examples of quantities that might be challenging to estimate are the fouling coefficient and the biodegradation rate. The high complexity and the fact that it is computationally very expensive have served as motivation for several initiatives (e.g., (Abdel-Aal, Smits, et al. 2014, Elías-Maxil, et al. 2017)) to simplify the approach by neglecting some of the above heat exchange processes.

In a sequel of studies, Abdel-Aal et al. (2014, 2018, 2019, 2021) present the continuous development of a physically-based model that neglects processes such as the latent heat transfer, convection between pipe wall and bulk liquid, all heat transfer processes between sewer headspace-pipe wall and soil, the impact of biological fouling on the heat processes and biochemical heat production. Abdel-Aal et al. decouples heat transfer calculations from hydraulic transport; simulation results are achieved by applying the heat transfer model proposed in Abdel-Aal, et al. (2018) to the a-priori generated output of a commercially available hydrodynamic sewer model (Infoworks CS) which numerically solves the de Saint-Venant and Colebrook-White equations.

Elías-Maxil, et al. (2017) proposed a parsimonious model aiming to provide a very simple and fast approach. Their model completely excludes heat transfer mechanisms between the bulk liquid and sewer headspace. With this, it goes beyond the degree of simplification of approaches by Abdel-Aal, et al. (2014). The evaluation of the usefulness of this method appears challenging, since the case study used as a validation consists of adding hot water at 50 °C into an empty sewer system with literally no lateral inputs. In line with Abdel-Aal et al., we conclude here that, e.g. mixing processes and spatially distributed transport cannot be described adequately. The code was not available for testing.

More recently, Schlagbauer (2018) modified the EPA-SWMM source code (version 5.1.012 (2017)) by adding bulk liquid temperature as a concentration unit that is purely advected (i.e. the thermal diffusivity coefficient was set to zero) through the conduit section. The heat transfer model implemented in EPA-SWMM by Schlagbauer is similar to the one proposed by Abdel-Aal, et al. (2014). The temporal scales were solved adapting the simple and numerically robust EPA-SWMM formulation for water quality routing. Unfortunately, this approach introduced additional computational costs to the numerical experiments with the consequence of large simulation

runtimes. The concept of treating the bulk liquid temperature as dissolved pollutant, however, has some system-inherent limitations, namely: i) the temperature state can only be applied to the bulk liquid and not to other spatially discretized system compartments, such as the sewer headspace, and ii) implementing the temperature on the same hierarchy level as other pollutants limits the possibilities to implement individual heat transfer processes.

2.3 Didactical simulation experiments and field tests

Motivated by the tendency of relying on assumptions that lack rigorous validation in some previous studies, in particular with regard to the relevance of convection at the interface of bulk liquid and pipe/soil (A), and latent heat processes at the interface of bulk liquid and sewer headspace (B), we conducted didactical simulations that improve the understanding of individual thermodynamic mechanisms. We furthermore validate some assumptions regarding boundary conditions by dedicated field measurements in the soil compartment (temperature) and in the sewer headspace (humidity) - see detailed results in the SI-Section B. Our analyses clearly indicate that:

- A no-slip boundary condition is commonly imposed at interface A. Therefore, a velocity boundary layer and a thermal boundary layer are developed between the bulk liquid and the pipe wall. The existence of the thermal boundary layer causes convective heat exchange. Through an analysis of several didactical scenarios, we conclude that convective heat transfer between bulk liquid and the pipe wall is not as significant as conductive heat transfer, i.e. the convective heat transfer coefficient is lower than 1 % of the conductive heat transfer coefficient. Hence, convective heat transfer has little influence on the total heat exchange at interface A (cf. SI-Section B.2).
- Latent heat transfer is often disregarded based on the untested assumption of high relative humidity in the sewer headspace (>90 %). Our measurements show that in summer periods the relative humidity can indeed fall below 70% (cf. SI-Figure 2). Based on measurements and didactical experiment results (SI-Section B.2) we observe that latent heat processes are relevant (even when relative humidity values are large).

2.4 Summary of existing limitations

The review of previous research and existing model concepts (Section 2.2), the didactical simulation experiments supported by field measurements (Section 2.3 and SI-Section B), and the detailed discussion of individual processes (SI-Section A) lead to the following conclusions regarding the relevance of processes:

- Latent heat transfer at interface B is important and should be considered (cf. SI-Section B).
- Convective heat transfer at interface A can be considered as negligible.
- Convective heat transfer at interface B is usually recognized as a relevant process. Bischofsberger, et al. (1984) propose an adequate relation to represent this process.
- Fouling and biofilm formation may affect the heat transfer but depends on the wastewater composition and site-specific characteristics. Hence, it is difficult to predict and usually not considered in existing models. According to Dürrenmatt and Wanner (2014).it does not have a significant impact compared to other processes.
- There is limited knowledge about the importance of heat transfer mechanisms at interface (C). Due to the lack of experimental data for validation, this interface will be neglected and not considered for further investigation.

Regarding the usability of to date available tools, we identified the following limitations that restrict the application in a comprehensive fashion:

- Available tools do not allow coherent thermal-hydraulic simulations at network scale.
- Existent tools, such as TEMPEST, are complex and require a large number of input parameters, which are often/usually unknown.
- They are often computationally expensive and especially the detailed TEMPEST simulations have large runtimes.
- They are often not practical, e.g. as preliminary hydraulic modelling exercises are required before allowing energy-related calculations.
- With the exception of TEMPEST, implementations of the approaches are not readily accessible for users, i.e. code is not open source and are only available upon request.

3 SWMM-HEAT – MODEL DEVELOPMENT

3.1 The SWMM-HEAT modelling concept

Based on review outlined in Section 2 a new heat balance equation is defined. The thermodynamic processes contemplated in the heat balance equation (and shown in Figure 1) are:

- q_{wps_c} , the heat transfer due to conduction at the bulk liquid - pipe/soil interface;
- q_{lh} , the latent heat transfer, and
- q_{aw_c} , the convective heat transfer between bulk liquid and sewer headspace.

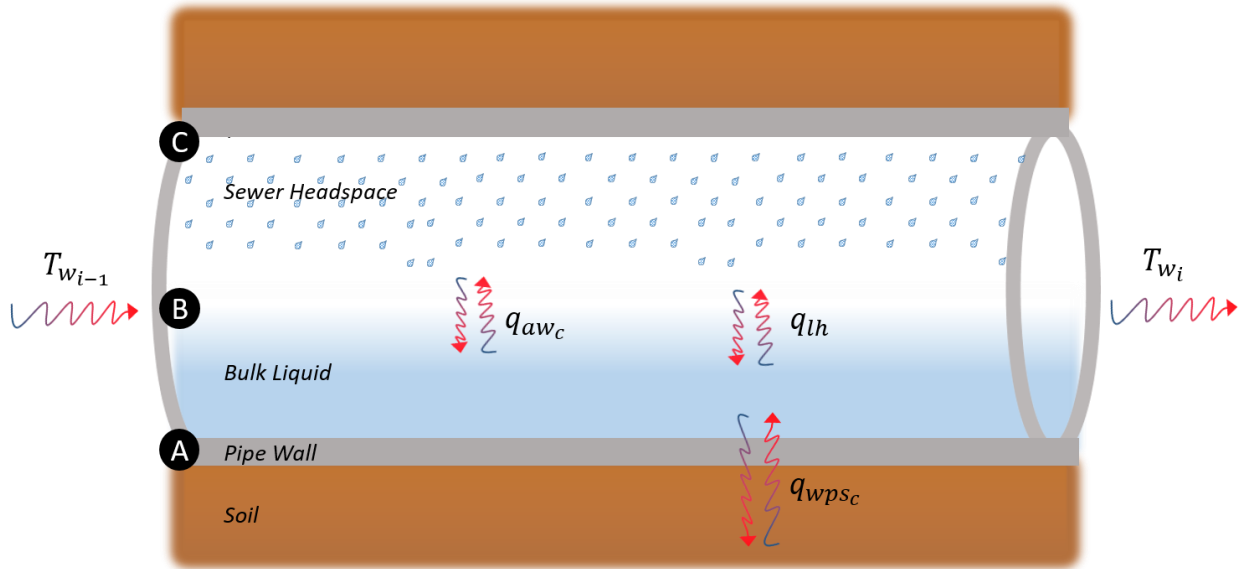


Figure 1: Conceptual representation of the SWMM-HEAT modelling concept, including relevant thermodynamic processes. The nomination in the scheme follows the concept of *compartments* (sewer headspace, bulk liquid, pipe wall, surrounding soil) and *interfaces* A, B, C (see Section 2.1)

The energy balance in a section pipe of length Δx (Figure 2) is characterized by the following equation,

$$T_{wi} = T_{wi-1} - \frac{(q_{awc} + q_{lh} + q_{wpsc})\Delta x}{c_p}, \quad \text{Eq. 2}$$

Each of the previous heat transfer processes are expanded in the following equation that represents the bulk liquid temperature variation along a sewer pipe,

$$T_{wi} = T_{wi-1} - \frac{\Delta x \left(\alpha_{awc}^{-1} (T_{wi-1} - T_a) + \alpha_{awt}^{-1} (P_{sat}(T_w) - P_a) + \frac{1}{R_{sw}} (T_{wi-1} - T_s) \right)}{\rho Q C_p}. \quad \text{Eq. 3}$$

Where α_{awc} is the convective thermal resistivity between bulk liquid and sewer headspace, α_{awt} is the latent heat thermal resistivity, P_{sat} is the saturated partial pressure, P_a is the sewer headspace partial pressure ($P_a = \varphi_a P_{sat}(T_a)$, with φ_a the relative humidity and $P_{sat}(T_a)$ the saturated partial pressure at sewer headspace temperature T_a), R_{sw} is the bulk liquid –pipe/soil thermal resistivity, T_s is the soil temperature, ρ the bulk liquid density, and Q the bulk liquid volumetric flow rate. Further details about the coefficients used in the previous equation are found in sections 3.1.1 and SI-Section A. In addition, certain considerations regarding air velocity modelling in sewers are discussed in Section 3.1.2.

3.1.1 Consideration of the pipe curvature

R_{sw} represents the conduction heat transfer between bulk liquid, pipe wall and the surrounding soil. Conduction in TEMPEST is modelled by a spatial discretization of the heat transfer processes in the radial direction while Abdel-Aal, et al. (2018) implemented a one dimensional steady-state conduction model of a multi-layer wall (more information in SI-Section A). The approach introduced in SWMM-HEAT is similar to the formulation of Abdel-Aal, et al. (2018), with a modification that incorporates the curvature of the pipe walls,

$$\begin{aligned} r_1 &= r + t, \\ r_2 &= r_1 + d_s, \\ R_{sw} &= \frac{r}{w_p} \left(\frac{\ln\left(\frac{r_1}{r}\right)}{k_p} + \frac{\ln\left(\frac{r_2}{r_1}\right)}{k_s} \right) m \, K \, W^{-1}, \end{aligned} \quad \text{Eq. 4}$$

Where r is the internal pipe radius, k_p the pipe wall thermal conductivity, k_s the soil thermal conductivity, w_p the wetted perimeter, t is the pipe thickness, and the penetration depth d_s is defined as a function of the soil thermal diffusivity α_s , by $d_s = \frac{\alpha_s}{2\pi/day}$ (Krarti and Kreider 1996).

3.1.2 Air velocity in the sewer headspace matters for condensation

Sewer headspace velocity deserves a special mention because is of critical importance for determining α_{awc} and α_{awt} . Based on experimental data from sewers in Denmark, Madsen, et al. (2006) found that headspace velocities vary between $0.05 \, \text{ms}^{-1}$ and $0.22 \, \text{ms}^{-1}$. In TEMPEST, air velocity is modelled by a modification of the model proposed by Edwini-Bonsu and Steffler (2004) which is based on Computational Fluid Dynamics (CFD) simulations of turbulent flow in a sewer conduit. Moreover, Abdel-Aal, et al. (2018) implemented a theoretical formulation (Edwini-Bonsu and Steffler 2006) that depends on geometric considerations, bulk liquid flow velocity and pressure head loss. In a later study on odour problems in deep tunnel sewers (Witherspoon, Easter and Apgar 2009), three ventilation models were compared against measured sewer headspace velocity at different test sites in the United States: i) an empirical model by Pescod

and Price (1982), ii) the CFD model developed by Edwini-Bonsu and Steffler (2004), and iii) a thermodynamic model proposed by Olson, et al. (1997). Across the three tested models, the empirical model by Pescod and Prince most closely anticipated the measured values, although the average relative error was 103% and the resulting values usually overestimated the measurements. Based on the lack of experimental validation of some schemes, the previous analysis performed by Witherspoon, et al. (2009) and the simplicity of the implementation, we selected the empirical extrapolation model by Pescod and Price (1982) for implementation into SWMM-HEAT,

$$u_a = 0.397 \left(\frac{u_w b}{P_a} \right)^{0.7234} m s^{-1}, \quad \text{Eq. 5}$$

with u_a the sewer headspace velocity, u_w the bulk liquid velocity, b the bulk liquid surface width and P_a the conduit dry perimeter.

3.2 Model implementation in EPA-SWMM

We use EPA-SWMM as the hydrodynamic modelling platform, and numerical engine to i) implement the temperature as state variable fully independent from other constituents, ii) define a new heat exchange model including additional components such as air velocity in the sewer headspace, and iii) reorganize the code implementation to ensure full compatibility with EPA-SWMM and thus increase accessibility, efficiency and user-friendliness of the model.

The approach that we propose applies the heat transfer model established in Section 3.1 and it creates a new computing module for the treatment of the temperature variable leading to a new simulation code called SWMM-HEAT. Furthermore, SWMM-HEAT is based on the last available version of EPA-SWMM (version 5.1.015, (EPA 2020)).

The new implementation involved the creation of new data structures and computing subroutines inside the SWMM-HEAT code for the necessary thermodynamic information that allow users to model the temperature in the sewer system. In addition, during the implementation in EPA-SWMM, writing an efficient code was of great importance in order to avoid a negative impact of the new capabilities in the simulation runtime. The SWMM-HEAT source code as well as executable files are made publicly available in GitHub¹.

4 MODEL VALIDATION – APPROACH

4.1 Unbranched sewer section

The goal of this simulation exercise is twofold: i) to check the new approach's plausibility by reproducing the results of an experiment in a single-stretch sewer section, and ii) to learn about the most relevant heat transfer processes and associated parameters through a sensitivity analysis.

For comparative reasons, we apply our model to the case study used in Durrenmatt and Wanner (2014). Flow and temperature evolution are considered in a single-stretch sewer section with no lateral connections. Specifically, we modelled the single stretch pipe (Figure 2) with length L , radius r , constant flow F_0 and temperature T_{w0} at the inflow.

¹ <https://github.com/Eawag-SWW/EAWAG-SWMM-HEAT>

The sensitivity analysis of selected parameters of the new modelling approach consists on comparing results using reference model inputs and boundary conditions (shown in Table 1Table 1) with results obtained by modifying selected thermal and geometric properties by a factor of $\pm 10\%$ and $\pm 25\%$. The selected parameters for the sensitivity analysis are bulk liquid inflow temperature, soil temperature T_s , sewer headspace temperature T_a , pipe wall thermal conductivity k_p , pipe wall thickness t , relative humidity in the sewer headspace ϕ_a and soil thermal conductivity k_s . Two distinct inflow scenarios are considered in the analysis, Scenario A relates to an extremely low inflow of $0.002 \text{ m}^3 \text{ s}^{-1}$ that might occur during night-time, while Scenario B relates to a typical dry weather load situation of $0.01 \text{ m}^3 \text{ s}^{-1}$.

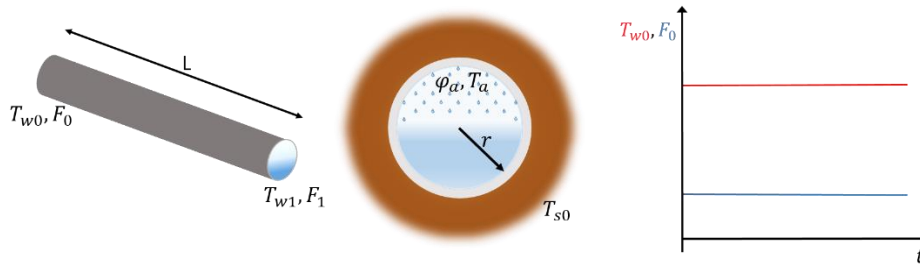


Figure 2: Unbranched sewer section model including the relevant parameters.

Parameter name	Parameter value
Flow, F_0	0.002 and $0.01 \text{ m}^3 \text{ s}^{-1}$
Water level, h	0.02 and 0.05 m
Inflow Temperature, T_{w0}	20° C
Sewer Headspace Temperature, T_a	12° C
Soil Temperature, T_s	9° C
Length, L	500 m
Radius, r	0.35 m
Slope, s	0.02
Pipe Thickness, t	0.085 m
Pipe thermal conductivity, k_p	$2.5 \text{ W m}^{-1} \text{ K}^{-1}$
Soil thermal conductivity, k_s	$3.5 \text{ W m}^{-1} \text{ K}^{-1}$
Soil density, ρ_s	2200 kg m^{-3}
Soil specific heat capacity, c_{ps}	$1500 \text{ J kg}^{-1} \text{ K}^{-1}$
Wastewater density, ρ_w	1000 kg m^{-3}
Wastewater specific heat capacity, c_{pw}	$4190 \text{ J kg}^{-1} \text{ K}^{-1}$
Relative humidity, ϕ_a	90%

Table 1: Reference model parameters for simulation of an unbranched sewer section.

4.2 Simulations at network scale

Network-scale case: The simulation of a real sewer network is included to validate the model's capability i) to simulate branched pipe networks, and ii) to reproduce results from distributed reference measurements in a real sewer environment. More concretely, we focus on the reproduction of wastewater temperature dynamics along the main collector in the sewer network of the small Swiss municipality of Fehraltorf, located 12 km Northeast of Zurich, Switzerland (see spatial representation in SI-Figure 8). The network comprises 27.1 km of sewer pipes, in which

the wastewater from Fehraltorf and two neighbouring municipalities is conveyed to the central Water Resource Recovery Facility (WRRF; design capacity: 12'000 PE). The mean travel time in the main collector during typical dry weather conditions is approximately 50 minutes.

Sewer model: We implemented sewer infrastructure data from the municipal cadastre, i.e. a link-node network of 415 manholes interconnected by 412 conduits into the Stormwater Management Model *EPA-SWMM* (v5.1.015; (EPA 2020)) to establish a consistent hydraulic model for dry weather conditions. This model is fed with four relevant inputs: i) two inflows from neighbouring municipalities represented as measured time series; ii) groundwater infiltration estimated from distributed long-term water level measurements; iii) simulated time series of residential wastewater production from households located within the municipality obtained from Hadengue, et al. (2021); and iv) industrial wastewater from one significant industry also represented as measured time series. Further details on input and reference data is given in the SI-Table 2; model construction is further outlined in Hadengue, et al. (2021).

Reference data was collected during a long-term monitoring campaign specifically initiated to advance this model development; details on the monitoring are described in Blumensaat, et al. (2021). Temperature is monitored with dual in-sewer sensors that simultaneously record the temperature of the wastewater stream and the sewer headspace at several locations across the catchment. The position of individual monitors is illustrated in Figure 3. The measurements themselves represent a uniquely consistent long-term data set, which enable validation at network scale, across different seasons and for different loading situations in the first place.

Due to the fact that SWMM-HEAT is a physically based model, it is important to remark that inform decisions regarding soil and sewer headspace temperature are utterly relevant in order to obtain accurate results. Due to the large temporal and spatial variability of the sewer headspace temperature (SI-Figure 12) and soil temperature (SI-Figure 9) it may be challenging to estimate some of these input parameters. For the sake of simplicity and lack of measurements from the period of April 2019 we assume these parameters to be constant during the whole simulation (for further discussion see Hadengue, et al. (2021)). Nevertheless, the SWMM-HEAT modelling tool allows the implementation of hourly, weekly or monthly patterns sewer headspace and soil temperature.

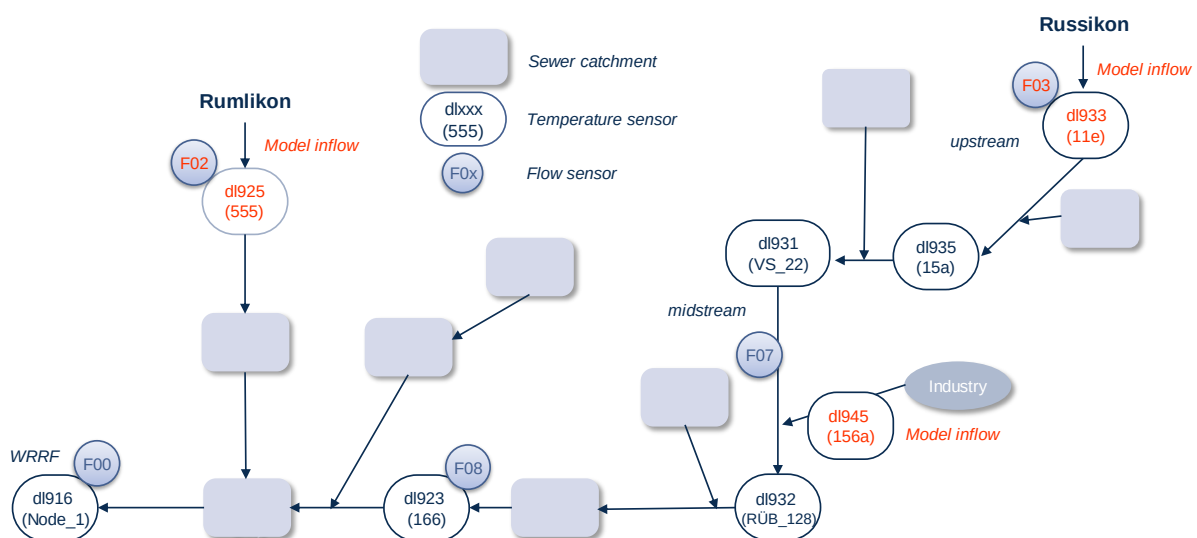


Figure 3: Simplified representation of the Fehrltorf sewer system. Positions of sensors are indicated: flow - circles; temperature - rounded boxes. Data from sensors highlighted in red are used as model inputs, resp. inflows, others are used as reference. IDs of data loggers (dl) correspond to the data shown in Figure 6.

Simulation scenarios: For the model validation, we focus on a period of four consecutive dry weather days in April 2019. The modelled scenarios refer to two loading situations during a typical working day, i.e. times of 8-9 am and 9-10 pm. This representation is chosen to reflect two main thermal loading situations in the system: A) one during working hours on workdays, at which a textile-processing industry discharges a significant amount of wastewater of elevated temperature into the main collector (see longitudinal reference thermograph in Figures 10, 11 in the SI), and B) one without the industry discharge solely representing municipal flows. A direct comparison of model results with stationary measurements at six different locations (see positions located in the map in Figure 3) is performed.

4.3 Performance indicators

The main variable selected for study and comparison with field measurements is the bulk liquid temperature. The metrics used for the assessment of the simulation results include the root mean square error (RMSE) and the *ratio of the RMSE to the standard deviation* of measured data, also named “RMSE-observations standard deviation ratio” (RSR). RSR is a recommended metric (Moriassi, et al. 2007) for hydrologic simulations that incorporates the benefits of RMSE error index statistics and includes a normalization factor. This eventually allows assessing the goodness of fit of this model with models from previous and/or future work applied to different datasets.

5 MODEL VALIDATION - RESULTS AND DISCUSSION

5.1 Unbranched sewer section

Figure 4 shows how bulk liquid downstream temperature evolves in a single-stretched pipe of length L , under two loading scenarios, due to a variation on selected parameters of the reference model.

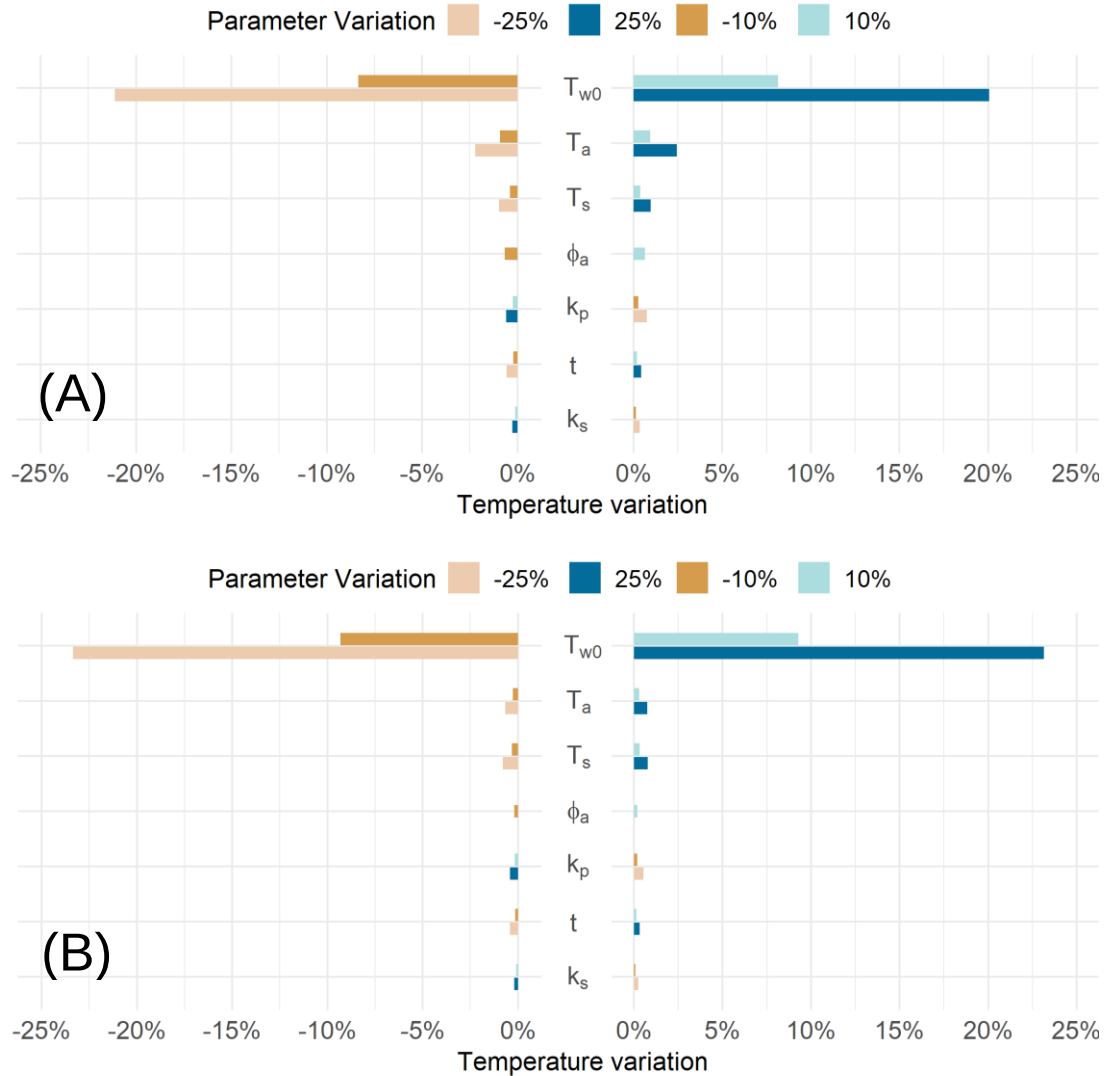


Figure 4: Relative change of the downstream temperature due to the change of parameter values (brown to blue in legend) and geometric/physical properties. Top: inflow $0.002 \text{ m}^3\text{s}^{-1}$; Bottom: inflow $0.01 \text{ m}^3\text{s}^{-1}$. The parameter description and the corresponding reference values (basis for the relative variation) are given in Table 1.

Based on results from Figure 4 we conclude that:

- A correct estimation of the upstream bulk liquid temperature is very important in order to obtain an accurate evolution of the temperature in the sewer system in both scenarios,
- The impact of soil temperature, sewer headspace temperature and humidity is relevant, but it is only obvious on the downstream temperature under specific circumstances, e.g. for very low flow (scenario (A)) or low relative humidity.
- Material properties and geometric considerations (pipe wall thickness) play a minor role on the evaluation of the bulk liquid temperature. Soil thermal conductivity is the least significant factor of all variables studied.

It is important to mention that conducting this *screening* sensitivity analysis is motivated through previous studies (Durrenmatt and Wanner 2014). We believe that a more comprehensive and

network scale sensitivity analysis should be performed, in order to better understand the impact of the different thermal-hydraulic processes on the wastewater temperature.

Additionally, we compare runtimes obtained with SWMM-HEAT and TEMPEST solvers of a single stretch pipe simulation. The comparison suggest that a twelve hour thermal-hydraulic simulation of a 500m pipe takes less than a second in SWMM-HEAT, while TEMPEST requires thirty second to complete the calculation. This is a noticeable difference in favour of SWMM-HEAT. Unfortunately, we have not had access to other codes to compare runtimes. Simulations were performed in an Intel Core i7-8565U with 16GB of RAM memory.

5.2 Simulations at network scale

Figure 5 shows the spatial distribution of the wastewater temperature in the *combined* sewer network of the municipality of *Fehrltorf* during two different loading situations. The first sub-figure (A) represents the average of the temperature in the morning period, where warm wastewater of industrial origin has a predominant influence on the wastewater temperature as soon as it arrives in the main collector. Thus, for loading (A) in this particular season of the year, the temperatures along the main collector vary in a range of 20 and 22 °C. Flows at the peripheral ends of secondary sewers generally appear hotter due to newly discharges from households. Some other flows in peripheral sewers are not equally hot because infiltration of (cold) groundwater is additionally accounted for; a few of the peripheral collectors carry groundwater only.

The second sub-figure (B) displays the hourly average of the temperatures between 9 and 10 pm, when industrial discharge is inactive and the only wastewater contribution to the flow in the network is municipal sewage from households. The temperature in the main collector is then stable at 20 °C along the longitudinal cross-section of the infrastructure.

Relevant for both scenarios, the wastewater transfer from residential neighbourhoods arriving at the North (F02 in Figure 3) and the West (F03 in Figure 3) is comparatively cold. These two flows reach the main network after an average travel time of about 45 minutes, and they carry a considerable amount of groundwater base flow, i.e. groundwater infiltration (~15 %). In the given case, the two transfer flows are represented as measured input (assuming low measurement uncertainty), but the example emphasizes that it is very important to correctly capture infiltration to reliably predict in-sewer temperature dynamics.

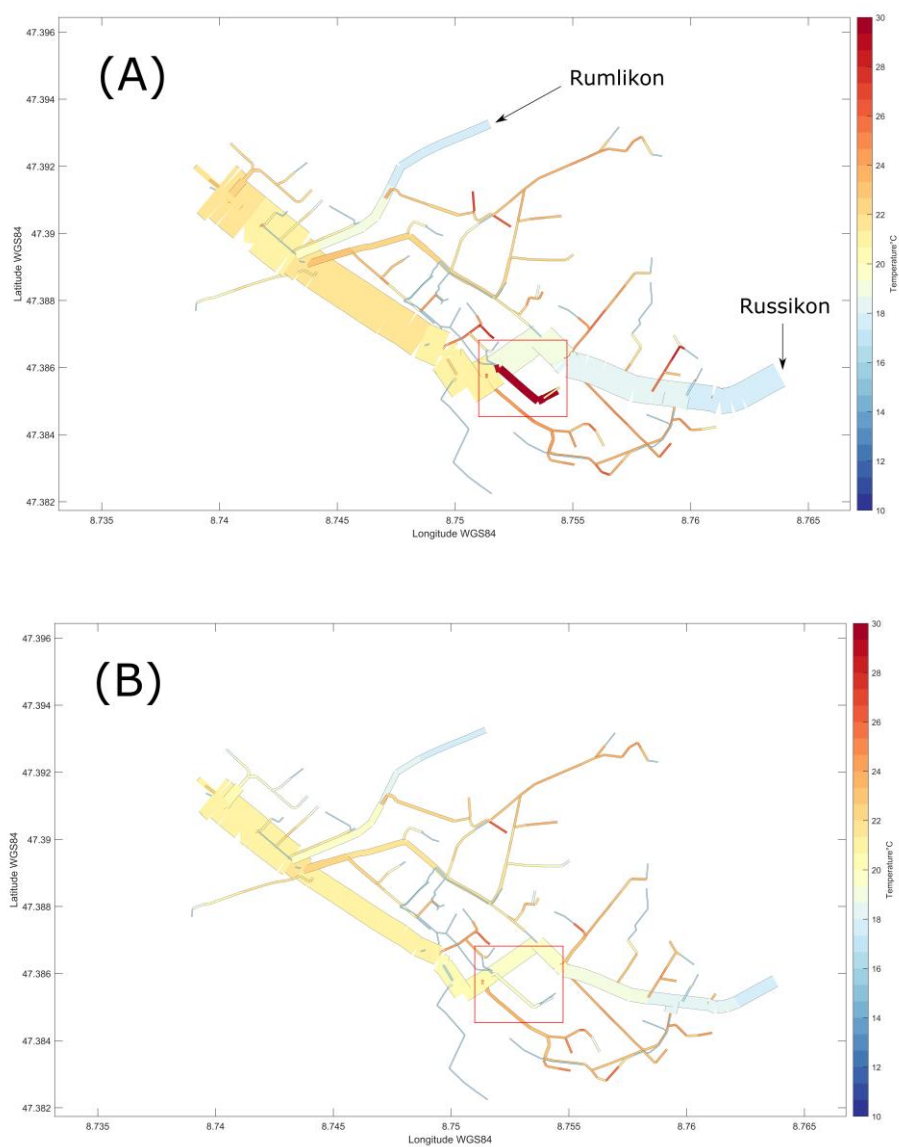


Figure 5: Hourly average wastewater temperature (°C). Top: 8 am; below: 9 pm. Line thickness is a visual representation of the flow rate carried in individual pipes. Red box: industrialized area.

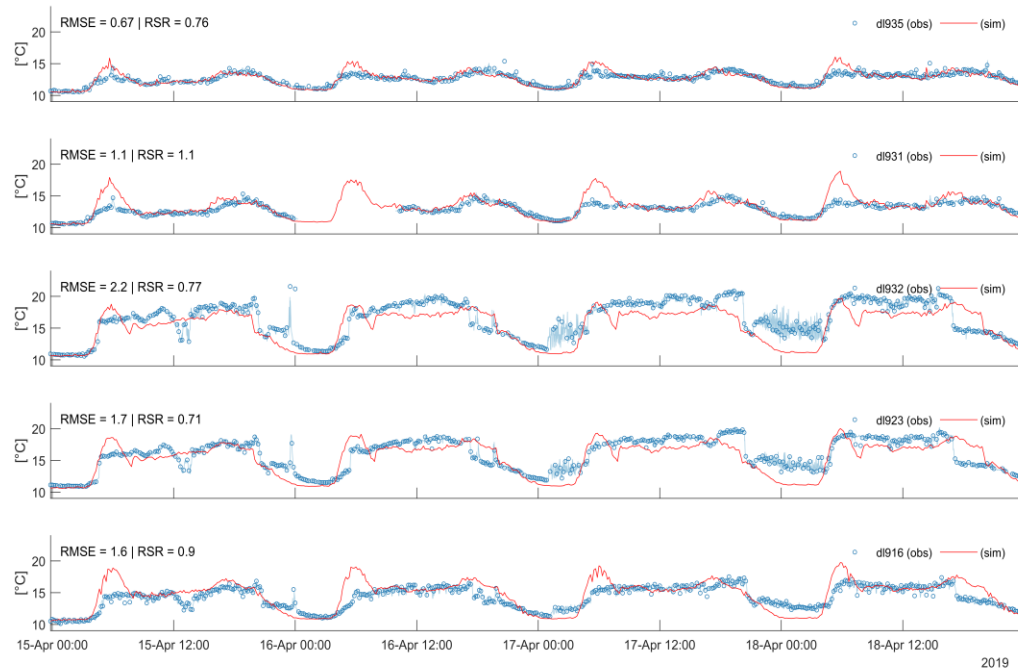


Figure 6: Observed vs. simulated wastewater temperatures at five different locations along the main collector in April 2019. RMSE and RSR indicate the goodness of fit. Signal IDs correspond to those shown in Figure 3.

The 1-to-1 cross-comparison of simulations with in-sewer measurements at several different locations (Figure 6) reveal that the model is capable of reproducing observed in-sewer temperature dynamics at several locations following the flow path along the main collector with consistent and sufficient accuracy. Generally, RMSE values (0.67 to 2.2) indicate a less good model fit as achieved in previous studies (e.g., (Abdel-Aal, et al. 2021)); RSR values (0.71 to 1.1) suggest a good model performance. It is notable to mention the higher thermal loading due to industry discharge (starting at dl932) leading to a higher temperature variation. Hence, RMSE values are inherently elevated.

A considerable deviation becomes apparent due to a consistent overestimation of the “household morning peak” arriving at 6 to 7 a.m. (UTC+0). This artefact “accumulates” along the flow path, and we found that its magnitude is clearly associated with the assumed inputs from household wastewater production (Hadengue, et al. 2021).

For the period in April, the continuous heat loss in the sewers is outweighed by thermal input loading through wastewater production in households. During non-working hours at night-time (scenario B, Figure 5), the temperature of the wastewater that travels along the main collector increases slightly from 17 °C at the catchment boundary at which the transfer flows arrive, to 19 °C at the inflow of the WRRF. Further simulations (see SI-Figure 13) suggest that this trend is even more pronounced during summer periods – wastewater temperature increase from 17 °C to 22 °C while traveling through the system.

Groundwater infiltration rates and soil temperature are found to be critical boundary conditions to be defined by the modeller. For the week in April 2019, the soil temperature is defined as 11 °C, an estimation based on soil temperature modelling, which is qualified by own soil temperature

measurements conducted in 2020-2021 (see details in the SI-Figure 9). Changing these boundary conditions, e.g. to a higher value of 20°C (which is a typical soil temperature in this soil compartment in summer, i.e. July) results in a significantly different temperature evolution (SI-Figure 13). Consequently, seasonal peculiarities cannot be reflected upon adequately in case soil temperature is not defined carefully, e.g. derived from simulations or nearby measurements. The estimation of groundwater infiltration is similarly decisive for the resulting temperature in the bulk sewer liquid.

A five days thermal-hydraulic simulation of the *Fehraltorf* network was completed in less than ten minutes with a routing step of five seconds. Despite a similar simulation cannot be performed using a different modelling tool (e.g. TEMPEST) we anticipate that calculations using such tools will require additional time to complete.

6 POTENTIAL USE AND FUTURE WORK

The proposed modelling approach enable new insights regarding the spatiotemporal distribution of heat losses in sewer systems at any scale, i.e. from single pipes to full networks.

Potential uses of the current model version include: i) analyse strategies to efficiently recover heat from wastewater and their corresponding impact on the biological wastewater treatment, ii) evaluate the potential of thermoelectric generators to power energy self-sufficient applications, iii) predict locations with critical biochemical activities in sewer networks, and iv) predict headspace velocities to support 3-phase modelling in order to evaluate H₂S formation or the risk of explosion in case of accidental dispersion of volatile flammable liquids. In the context of a *digital twin* concept, i.e. a virtual system that constantly mirrors the state of a real-world system, SWMM-HEAT may be applied to cross-compare simulated with observed temperature signatures allowing for immediate detection of critical operating states or process anomalies. Thus, illicit waste disposals, or (less dramatic) locations of increased infiltration of extraneous water may be identified.

The assumption that highest thermal gradients occur in peripheral collectors, and that heat recovery makes most sense at locations where harvested heat can actually be utilized, clearly favours decentralized, distributed heat recovery concepts. Feasibility studies for such strategies, so far only possible through punctual measurements, can now be accomplished more efficiently. A most recent study (Hadengue, et al. 2021), which utilizes a SWMM-HEAT prototype, quantitatively confirms this hypothesis. The detailed case study research, which is beyond the scope of this manuscript, clearly underlines the necessity of such thermal-hydraulic modelling tools.

Considering the aspect of heat budgets in stormwater fluxes, the SWMM-HEAT development is an important contribution towards a model-based assessment of strategies to regulate urban microclimate using rain- or temporarily stored stormwater. This becomes increasingly relevant not just against the background of more frequent weather extremes (heat, storms). An ever-growing urbanization with higher building density does not only lead to increased heat stress but also to substantial space constraints in urban areas. This in turn, limits the possibilities to implement distributed stormwater infrastructures, which potentially mitigate adverse heat island effects.

Limitations: The current version of the SWMM-HEAT model is developed and validated for dry weather conditions only. Heat transfer phenomena related to rainfall-driven surface-runoff processes are currently not included. While some of the future research should aim at further model validation, e.g. for different sewer networks, other activities should focus on the

incorporation of stormwater-related processes during wet weather. This may include thermal enrichment of stormwater while travelling across impervious surfaces, as well as expanding the scope to estimate the impact of stormwater discharges on the temperature of the bulk liquid that requires biological treatment at the WRRF. While continuous heat loss e.g., due to central heat recovery applications had been researched in the past, the integrated consideration of the dynamic impact of “shock-loads” due to cold storm- and meltwater on biological wastewater treatment processes has so far been an unresolved issue.

The above-proposed developments require a thorough understanding of the model’s functioning, including its most influential factors. The preliminary sensitivity analysis presented in this study helps to pinpoint some of these factors. In future work, this analysis will be extended to include: i) the identification of non-linear relations between parameter changes and model outputs, ii) the assessment of interdependencies between individual parameters, and iii) the estimation of the impact of the network topography in the model outputs. Unfortunately, to explore these relations is beyond the scope of this manuscript.

7 SUMMARY AND CONCLUSIONS

The main findings can be summarized as follows:

- The detailed analysis and prediction of temperature dynamics in sewers is important for numerous applications from biological activities to heat recovery, which will be particularly important for decarbonization and decentralized wastewater systems. Current models are either too simple or too complex, and less straightforward to apply.
- SWMM-HEAT closes this knowledge gap and allows analysts to predict the heat exchange of the bulk liquid within its operational environment in sewers at very high spatiotemporal scale. Short-term dynamics are consistently reproduced and validated by two independent real-world cases. Simulation results confirm the model is capable of reproducing the evolution of wastewater temperature under varying thermal loading conditions and at full network scale.
- For our sensitivity analysis study, upstream bulk liquid temperature is the most important variable for an accurate prediction of thermal dynamics in sewers. However, other boundary conditions such as humidity, headspace temperature and soil temperature might become increasingly relevant under specific circumstances. A network-wide application suggests that a careful estimation of groundwater infiltration and soil temperature are critical to capture seasonal peculiarities.
- To be readily applicable to practitioners, SWMM-HEAT has been implemented in the established open-source hydrodynamic “Stormwater management model” (EPA-SWMM) to estimate heat transfer processes across an entire network. With this ready-to-use application, it is just a small step for practitioners and researchers alike to make use of or further develop the model.
- The model is expected to produce similar results also for other cases. Future work includes further model application to confirm the model’s performance for different cases and the development of the required modulus for wet weather simulations.
- The straightforward modelling approach exhibits potential for the integration in urban planning in order to optimize heat/energy recovery strategies, maintenance cycles and for fast detection of critical operating states.

8 ACKNOWLEDGMENTS

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9 SUPPLEMENTAL INFORMATION

Supplementary data can be found online at <https://doi.xxxxx.xxxxx>. Moreover, a study case of a 1.8km sewer line in the area near Rümlang, Switzerland that includes inflow/outflow measurements and scripts for visualization are available at <https://doi.xxxxx.xxxxx>.

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