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A distributed heat transfer model for thermal-hydraulic analyses 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 predict efficiently 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 approach 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. Comparison with measurements suggest that the model predicts temperature dynamics adequately, with RSR values ranging between 0.71 and 1.1. The results of our study show that modelled in-sewer wastewater temperatures are particularly sensitive to soil and headspace temperature, and headspace humidity. Simulation runs are 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 into urban planning, the SWMM-HEAT code is made publicly available.

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 amongst 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 engineers to take informed decisions about the placement of 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 (Millero et al.,

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1987; Sharma et al., 2008) 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., 2018; Schlagbauer 2018; Abdel-Aal et al., 2014), 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 develop 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. EPA-SWMM is a simulation tool used for engineers and governmental authorities throughout the world to perform hydrologic and hydraulic network simulations, and is used as the computational engine behind many commercial modelling packages. SWMM-HEAT provides EPA-SWMM users the ability to perform integrated thermal-hydraulic simulations after a small modification of their already developed input files.

The novelty of this development lies in, (i) the definition of an independent temperature state variable, (ii) the integration of this variable and modelled heat exchange processes with 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 Supplementary Information (SI)-Fig. 1). For reasons of simplicity, sewer pipe wall and the surrounding soil are considered as one compartment called pipe/soil. Three interfaces can be defined amongst these compartments:

A Bulk liquid-pipe/soil.
B Bulk liquid-sewer headspace, and,
C Sewer headspace-pipe/soil.

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

- A.1: Convection between bulk liquid and pipe wall.
- A.2: Conduction between bulk liquid and pipe wall/soil.
- 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 (Fig. 1) is defined by,

$$T_{wi} = T_{wi-1} - \frac{(A.1 + A.2 + A.3 + B.1 + B.2)}{c_p} \tag{1}$$

where T_{wi} and T_{wi-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 et al. 2014, Elías-Maxil et al. 2017) to simplify the approach by neglecting some of the above heat exchange processes. It is important to mention that there is no unique established quantitative measure for complexity available in the literature and comparison between models with this respect is not performed in the present article, but based on statements found in the literature (Abdel-Aal et al., 2014).

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

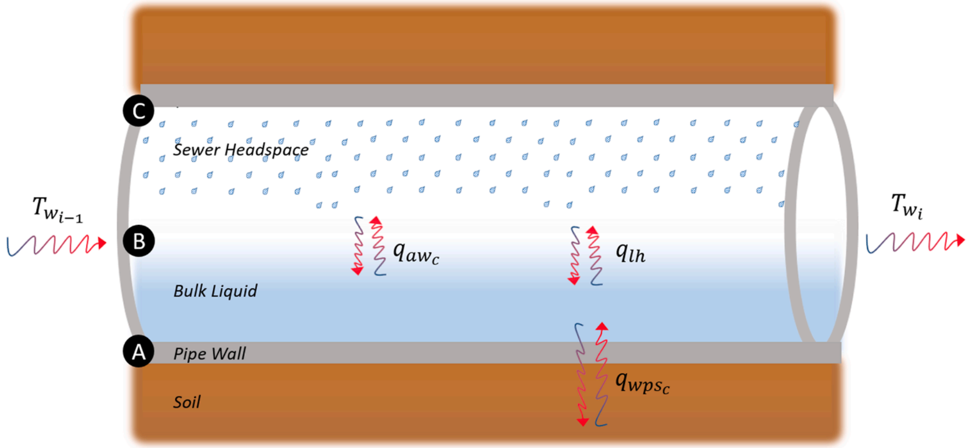

Fig. 1. Conceptual representation of the SWMM-HEAT modelling concept, including relevant thermodynamic processes. The nomination in the scheme follows the concept of compartments (sewer headspace, bulk liquid, pipe wall, surrounding soil) and interfaces A–C (see Section 2.1)

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, based on TEMPEST, that aims 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 (Rossman and Huber, 2016). 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 (cf. SI-Section B.2). Hence, convective heat transfer has little influence on the total heat exchange at interface A.
- Latent heat transfer is often disregarded based on the assumption of high relative humidity in the sewer headspace ($>$ 90%) (Elías-Maxil et al., 2017). Our measurements show that in summer periods the relative humidity can indeed fall below 70% (cf. SI-Fig. 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), with downstream temperature variations of up to 0.5 K in some scenarios.

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 and Seyfried, (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 and is neglected for future consideration.

- There is limited knowledge about the importance of heat transfer mechanisms at interface C and their impact in the sewer headspace temperature. 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 and require the use of add-ons such as libraries, plugins or extra software tools.
- 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. preliminary hydraulic modelling exercises are required before allowing energy-related calculations for future infrastructure developments.
- 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 Fig. 1) are:

- q_{wps_c}, the heat transfer due to conduction at the bulk liquid - pipe/soil interface, $(Jm^{-1}kg^{-1})$;
- q_{lh}, the latent heat transfer, $(Jm^{-1}kg^{-1})$, and:
- q_{awc}, the convective heat transfer between bulk liquid and sewer headspace, $(Jm^{-1}kg^{-1})$.

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

$$T_{wi} = T_{wi-1} - \frac{\left(q_{aw_c} + q_{lh} + q_{wps_c}\right)\Delta x}{c_p}, \tag{2}$$

with T_{wi-1} (K) the mixed bulk liquid temperature obtained from the temperature of the bulk liquid that remain in the pipe from the previous time step and the pipe inflow temperature, and c_p the bulk liquid specific heat capacity $(J\ kg^{-1}K^{-1})$. Each of the previous heat transfer processes are expanded in the following equation that represents the bulk liquid temperature variation along a sewer pipe,

$$T_{w_i} = T_{w_{i-1}} - \frac{\Delta x\left(\alpha_{aw_c}^{-1}\left(T_{w_{i-1}} - T_a\right) + \alpha_{aw_t}^{-1}\left(P_{sat}(T_w) - P_a\right) + \frac{1}{R_{sw}}\left(T_{w_{i-1}} - T_s\right)\right)}{\rho Q c_p}. \tag{3}$$

Where α_{aw_c} is the convective thermal resistivity between bulk liquid and sewer headspace$(m\ K\ W^{-1})$, α_{aw_t} is the latent heat thermal resistivity$(m\ mbar\ W^{-1})$, P_{sat} is the saturated partial pressure$(mbar)$, P_a is the sewer headspace partial pressure $(mbar)$ ($P_a = \varphi_a P_{sat}(T_a)$, with φ_a the relative humidity and $P_{sat}(T_a)$ the saturated partial pressure at sewer headspace temperature $T_a(K)$, R_{sw} is the bulk liquid–pipe/soil thermal resistivity $(m\ K\ W^{-1})$, T_s is the soil temperature (K), ρ the bulk liquid density $(kg\ m^{-3})$ and Q the bulk liquid volumetric flow rate (m^3s^{-1}). The latent heat transfer resistivity coefficient is obtained from a mass-based transfer model, the Trabert equation($\alpha_{aw_t} = \left(8.75\sqrt{|u_a - u_w|\,b}\right)^{-1}$, with u_a the sewer headspace velocity$(ms^{(-1)})$,u_w the bulk liquid velocity $(m\ s^{-1})$ and b the surface width of the bulk liquid (m). 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. In order to reduce the complexity of the model and input information requirements, the proposed approach (Eq. (3)) does not include the variation of sewer headspace temperature and relative humidity along the longitude of the pipe. This supposition holds for large sewer systems with low exchange between the sewer headspace and the atmosphere.

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,

$$r_1 = r + t,$$

$$r_2 = r_1 + d_s,$$

$$R_{sw} = \frac{r}{w_p}\left(\frac{\ln\left(\frac{r_1}{r}\right)}{k_p} + \frac{\ln\left(\frac{r_2}{r_1}\right)}{k_s}\right) \tag{4}$$

Where r is the internal pipe radius (m), k_p the pipe wall thermal conductivity $(Wm^{-1}K^{-1})$, k_s the soil thermal conductivity $(Wm^{-1}K^{-1})$, w_p the wetted perimeter (m), t is the pipe thickness (m), and the penetration depth d_s (m), is defined as a function of the soil thermal diffusivity α_s (m^2s^{-1}), 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

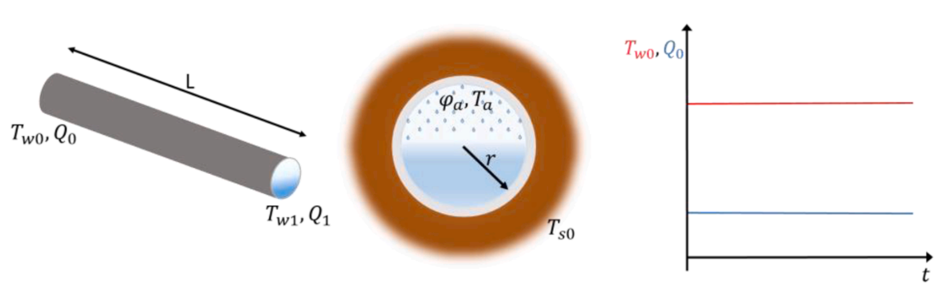

Fig. 2. Unbranched sewer section model including the relevant parameters.

critical importance for determining α_{awc} and α_{aw_t}. Based on experimental data from sewers in Denmark, Madsen et al. (2006) found that headspace velocities vary between 0.05 and 0.22 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 etal., 2009), three ventilation models were compared against measured sewer headspace velocity at different test sites in the United States: (i) an empirical model based on wind tunnel measurements 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 based on experimental data from Pescod and Price (1982) (fitted by Witherspoon et al. 2009) for implementation into SWMM-HEAT,

$$u_a = 0.397\left(\frac{u_w b}{P_a}\right)^{0.7234}, \tag{5}$$

with u_a the sewer headspace velocity (ms^{-1}), u_w the bulk liquid velocity (ms^{-1}), b the bulk liquid surface width (m), and P_a the conduit dry perimeter (m).

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 EPA-SWMM source code for the necessary thermodynamic information that allow users to model the temperature in the sewer system. Thermal-hydraulic simulations with SWMM-HEAT require the modification of a typical SWMM input file with the following information:

- Temperature time series at the node inflows;
- Patterns for sewer headspace and soil temperatures;
- Pipe thickness and pipe material, soil thermal properties;
- Relative humidity values.

A tutorial that provides information regarding setup SWMM-HEAT simulations with the Python libraries needed to read the output information is available in GitHub.[1]

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 GitHub.[2]

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 a numerical 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 a modified version of the case study considered 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 concrete pipe (Fig. 2) with length L, radius r, constant flow Q_0 and temperature T_{w0} at the inflow.

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 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. Reference model parameters represent the typical thermal properties of a concrete pipe and saturated sandy soil, while sewer headspace and soil temperatures values are associated to the month of May (SI-Figs. S9 and -S12). Pipe length, radius, slope and thickness dimensions in Table 1 are adjusted to describe a typical sewer section found in the underground infrastructure. Two distinct inflow scenarios are considered in the analysis, Scenario A relates to an extremely low inflow of 0.002 m^3s^{-1} that might occur during nighttime, while Scenario B relates to a typical dry weather load situation of 0.01 m^3s^{-1}.

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-Fig. S8). The network comprises 27.1 km of sewer pipes, in

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

Parameter name	Parameter value
Flow, Q_0	0.002 and 0.01 m^3s^{-1}
Water level, h	0.02 and 0.05m
Inflow Temperature, T_{w0}	20°C
Sewer Headspace Temperature, T_a	12°C
Soil Temperature, T_s	9°C
Length L	500m
Radius, r	0.35m
Slope, s	0.02 m/m
Pipe Thickness, t	0.085m
Pipe thermal conductivity, k_p	2.5 $W\ m^{-1}K^{-1}$
Soil thermal conductivity, k_s	3.5 $W\ m^{-1}K^{-1}$
Soil density, ρ_s	2200 $kg\ m^{-3}$
Soil specific heat capacity, C_{p_s}	1500 $J\ kg^{-1}K^{-1}$
Wastewater density, ρ_w	1000 $kg\ m^{-3}$
Wastewater specific heat capacity, C_{p_w}	4190 $J\ kg^{-1}K^{-1}$
Relative humidity, φ_a (SI-Fig. 2)	90%

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 min and the total dry weather inflow to the WRRF is $3370 m^3 d^{-1}$ for the period 2016/2017 (see SI-Fig. S14).

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) time series with one second resolution of residential wastewater production from households located within the municipality obtained from the detailed stochastic model developed by 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 S2; 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). Measurement errors were not explicitly considered in this study. 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 Fig. 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-Fig. S12) and soil temperature (SI-Fig. S9) 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.

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 Figs. S10, S11 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 Fig. 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).

$$RSR = \frac{\sqrt{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right)^2}}{\sqrt{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{mean}\right)^2}} \qquad (6)$$

RSR is a recommended metric (Moriasi 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. Due to the limited availability of software tools for thermal-hydraulic simulations and validation data, as well as constraints of other models, extensive comparison between models is not provided in the present article. Instead, a qualitative comparison (“higher or lower”) between RMSE values obtained by SWMM-HEAT and other models is performed.

5. Model validation-results and discussion

5.1. Unbranched sewer section

Fig. 4 shows how bulk liquid downstream temperature evolves in a

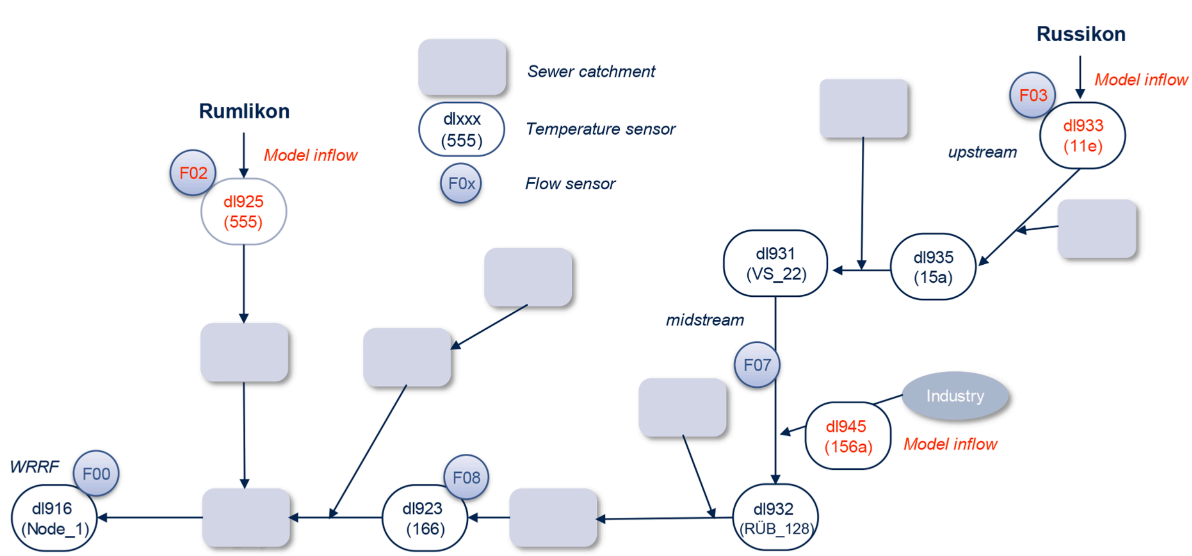

Fig. 3. Simplified representation of the Fehraltorf sewer system. Positions of sensors are indicated: flow - circles; temperature - rounded boxes. Data from sensors highlighted in red are used as model inputs, resp. inflows, others are used as reference. IDs of data loggers (dl) correspond to the data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

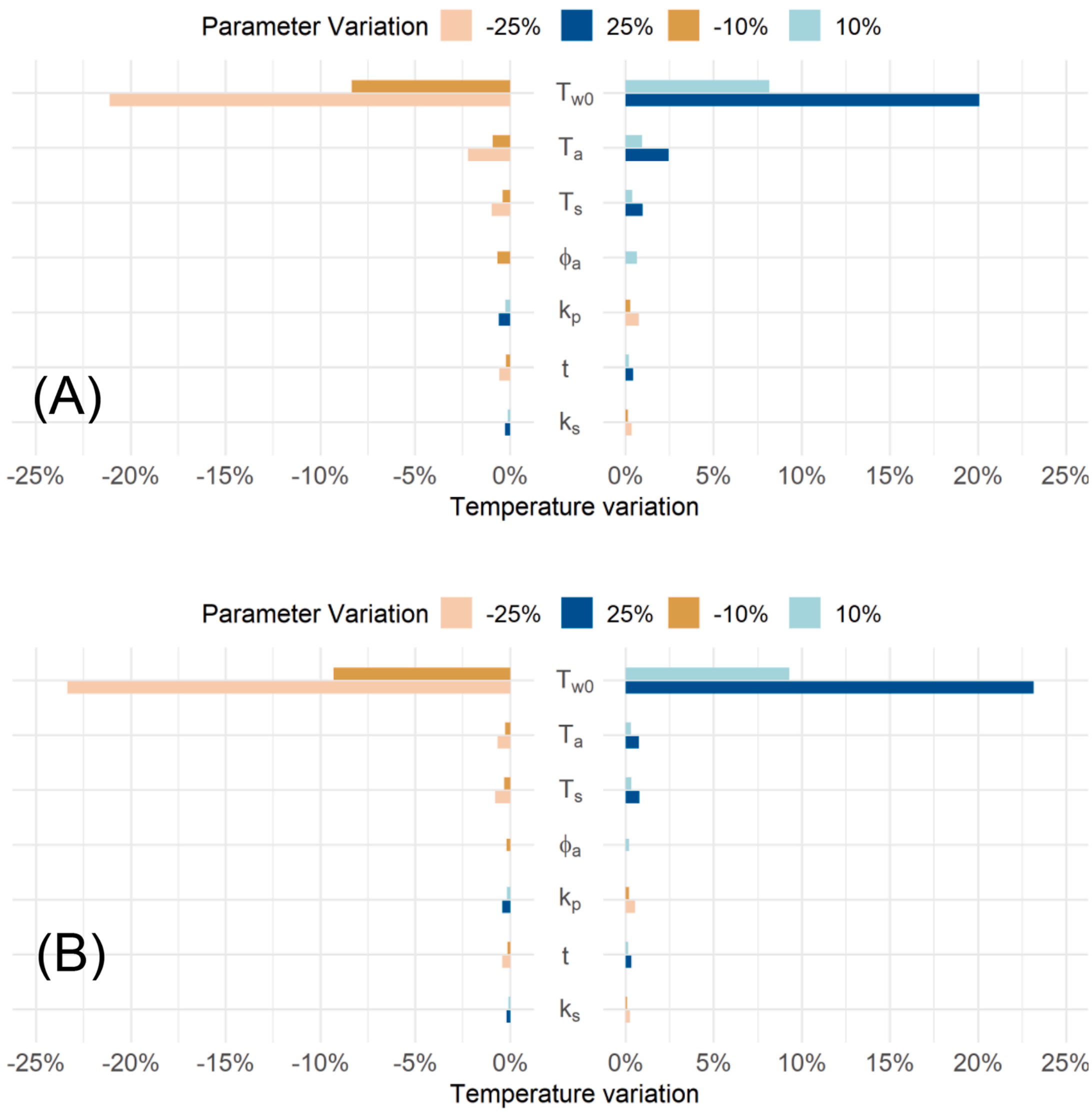

Fig. 4. Relative change of the downstream temperature due to the change of parameter values (brown to blue in legend) and geometric/physical properties. Top: inflow $0.002 m^3 s^{-1}$; Bottom: inflow $0.01\ m^3 s^{-1}$. The parameter description and the corresponding reference values (basis for the relative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

single-stretched pipe of length *L*, under two loading scenarios, due to a variation on selected parameters of the reference model.

Based on results from Fig. 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 measured runtimes of a single stretch pipe simulation using SWMM-HEAT and TEMPEST codes. The comparison suggests that a twelve hour thermal-hydraulic simulation of a 500 m 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 were not able to gain access to other codes to compare runtimes. Simulations were performed in an Intel Core I7-8565U with 16 GB of RAM memory.

5.2. Simulations at network scale

Fig. 5 shows the spatial distribution of the wastewater temperature in the *combined* sewer network of the municipality of *Fehraltorf* 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 20–22 °C. Flows at the peripheral ends of secondary sewers generally appear hotter due to newly

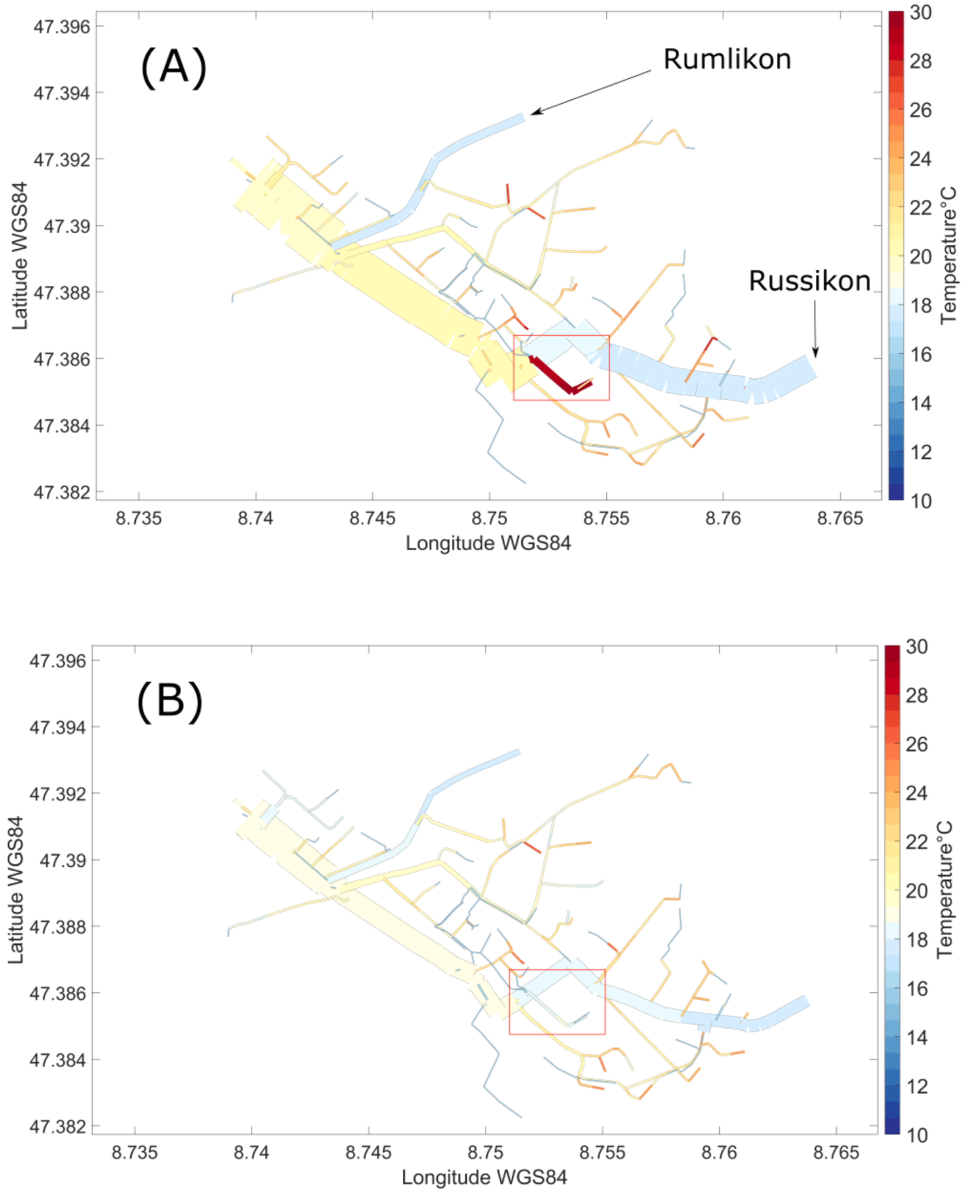

Fig. 5. Hourly average wastewater temperature (°C). Top: 8 am; below: 9 pm. Line thickness is a visual representation of the flow rate carried in individual pipes. Red box: industrialized area.

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 Fig. 3) and the West (F03 in Fig. 3) is comparatively cold. These two flows reach the main network after an average travel time of about 45 min, and they carry a considerable amount of groundwater base flow, i.e. groundwater infiltration (~15%). In addition, it is assumed that groundwater temperature is equal to soil temperature. In the given case, the two transfer flows are represented as measured input (assuming low measurement uncertainty), but the example emphasises that it is very important to correctly capture infiltration to reliably predict in-sewer temperature dynamics.

The 1-to-1 cross-comparison of simulations with in-sewer measurements at several different locations (Fig. 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, due to the high variance of the temperature.

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, for further discussion about this topic see 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

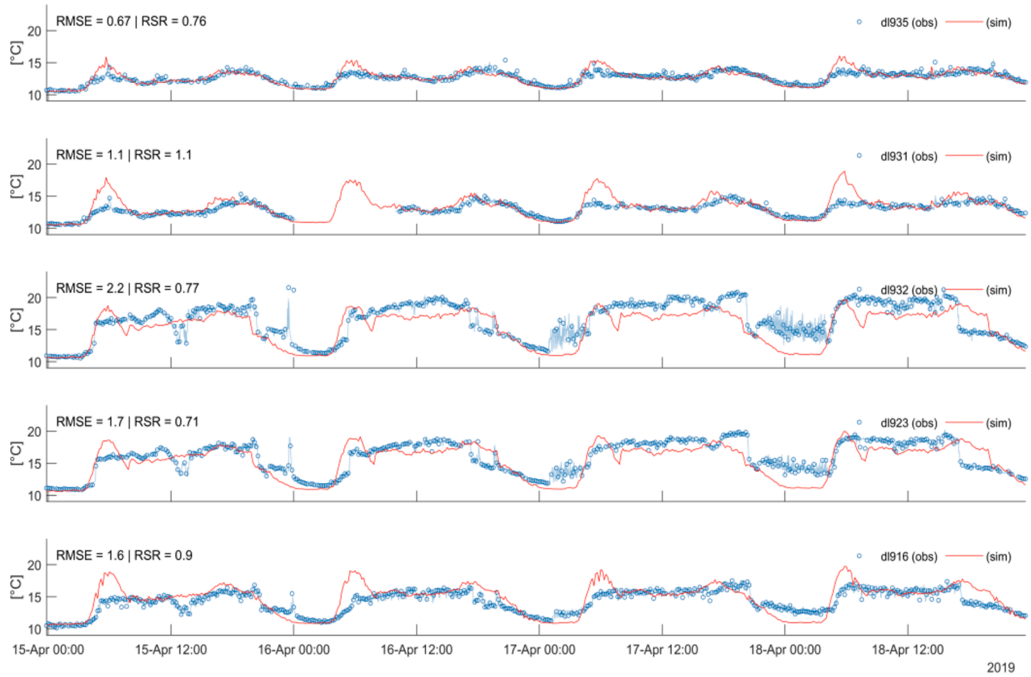

Fig. 6. Observed *vs.* simulated wastewater temperatures at five different locations along the main collector in April 2019. RMSE and RSR indicate the goodness of fit. Signal IDs correspond to those shown in Fig. 3.

households. During non-working hours at night-time (Scenario B, Fig. 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-Fig. S13) suggest that this trend is even more pronounced during summer periods-wastewater temperature increase from 17 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 and 2021 (see details in the SI-Fig. S9). 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-Fig. S13). 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 H_2S 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 utilises 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.

Further limitations of SWMM-HEAT include the use of sewer headspace humidity and temperature as input variables. Enhancements considered for future integration into the SWMM-HEAT model are the prediction of humidity in the sewer headspace, and pipe wall and headspace temperatures.

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, (iii) the estimation of the impact of the network topography in the model outputs, and (iv) the necessity of lateral heat inputs for accurate simulation results. 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 ranging 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 addresses this deficit, allows analysts to predict the heat exchange of the bulk liquid within its operational environment in sewers at very high spatiotemporal scale with a balanced complexity in terms of model structure. By two independent real-world cases, we show that short-term dynamics are consistently reproduced. Simulation results further confirm that 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 headspace temperature and humidity, and soil temperature 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 a modest modification of their already developed EPA-SWMM input files and this ready-to-use application, it is just a small step for practitioners and researchers alike to make use of 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.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.watres.2021.117649. Moreover, a study case of a 1.8km sewer line in the area near Rumlang, Switzerland, including inflow/outflow measurements and scripts for visualization, is available at https://github.com/Eawag-SWW/EAWAG-SWMM-HEAT/tree/main/Tutorial.

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