Improving sediment monitoring strategies based on analysing heat transfer processes in sewer pipes

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Highlights

- A generally-applicable approach was developed to identify potential locations where sediment accumulation occur based on sewer network hydrodynamics.
- Sewer network thermodynamics were used to simulate sewer temperature patterns from which sediment accumulation could be estimated.
- The combination of thermal-hydraulic dynamic analyses led to an effective strategy for determining the deployment of sediment accumulation monitoring devices.

Keywords: sewer sediments, monitoring, heat transfer processes, temperature sensors

Introduction

Sediment accumulation in sewer systems remains a major problem, with significant costs associated with maintenance and cleaning. These processes are performed according to time-based intervals. However, monitoring approaches for predicting events and locations in a network where sediments accumulation occur will enable more effective cleaning strategies and improve the understanding of sediment transport dynamics. However, measuring sediment accumulation across an entire sewer system presents significant difficulties (Bertrand-Krajewski et al. 2021). Previous attempts to monitor volume of sediment deposits consisted mostly of single-pipe measurements that required a high cost of supervision and maintenance, e.g., Lepot et al. (2017).

This work aims to establish a strategy to identify points in a network where a potential risk of sediment accumulation exists and to implement a methodology based on temperature measurements to estimate its volume. For this purpose, the research question of this study is whether it is necessary to know the hydrodynamics and heat transfer processes of a whole pipeline network, or, if monitoring individual pipes is sufficient to establish a criterion for measuring bed deposits using temperature sensors. Sediment estimation from temperature sensor measurements is based on the idea of monitoring heat transfer processes between the wastewater and the sediment bed, resulting from oscillations in daily temperature patterns. This research is currently under development (Regueiro-Picallo et al., 2022).

Material and methods

This work is based on the analysis of hydrodynamic and heat transfer processes in two local sewer systems. The first system consisted in a single stretch section of 1.8 km in Rümlang (Switzerland), including 7 pipes with a diameter of 900 mm and an average slope of 0.09%. The second system represented the entire sewer pipeline network of an urban area of 6400 inhabitants located in Fehraltorf (Switzerland), including pipe diameters ranging from 150 to 1600 mm and minimum slopes of 0.04 %. Both systems were selected because data on wastewater temperature, flow velocity and water depth, and numerical models were available from previous studies (Blumensaat et al., 2021; Figueroa et. al., 2021; SWMM-HEAT, 2022).

SWMM-HEAT software was used to analyse both hydrodynamic and heat transfer processes in sewer systems. SWMM-HEAT is an open-source code that enhances the EPA-SWMM model with the necessary thermal components to simulate temperature evolution in drainage systems during dry and wet weather conditions (Figueroa et. al., 2021). Recent research efforts have been initiated to include heat transfer processes between wastewater and sediment bed. In this study, hydrodynamic and heat transfer processes were analysed for short dry weather flow (DWF) periods (< 4 days). Thus, we ensured no significant sediment thickness differences between the beginning and the end of the simulation, as accumulation rates in sewers are usually low (0.8-6.2 mm/day, Regueiro-Picallo et al. 2020). In addition, no erosion processes caused by rainfall events could be expected.

Regarding the hydrodynamic analysis, a simplified approach was introduced to determine the potential sediment accumulation in pipes. A critical bed shear stress value of 2 N/m^2 was selected and, thus, pipes with a maximum bed shear stress below this value presented a risk of sediment accumulation (Harpaz et al. 2022). For this purpose, bed shear stress patterns in the pipes were obtained from the hydrodynamic simulation by applying the following expression:

$$\tau = \rho_{water} * g * R_h * i_{water}$$

where τ is the bed shear stress (N/m^2), ρ_{water} is the water density (1000 kg/m^3), g is the gravity acceleration (9.8 m/s^2), R_h is the hydraulic radius (m), and i_{water} is the friction slope (m/m). For modelling simplification, we assumed that friction slope is relative similar to the pipe slope, and no sediment deposits were considered for this analysis. In addition, the hydrodynamic-based approach only considers hydraulic and geometric features of the sewer system, neglecting the influence of the suspended solid loads and the particle properties.

After identifying pipes with a potential risk of accumulation, spatio-temporal evolution of temperatures in the sewer systems were simulated by considering different scenarios of sediment accumulation:

- Scenario A: Sediments accumulated only in the analysis pipe of the sewer system.
- Scenario B: Same sediment thickness in pipes susceptible to accumulation.
- Scenario C: Random sediment thickness distribution in pipes susceptible to accumulation.

The range of sediment thickness simulated was [0-20] cm for large diameter pipes (i.e., Rümlang sewer stretch), and [0-10] cm for secondary pipes with small diameters (i.e., major part of Fehraltorf pipeline network). The other required parameters to perform the simulation of heat transfer processes are the thermal properties of the sediments, water, pipes and soil, for which we considered reference values from different sources (Hamdhan and Clarke, 2010; Figueroa et al., 2021), and measured soil temperatures. The parameters that are likely to have the greatest variability are the thermal properties of the sediments, for which active heat systems are under development by the authors.

After simulating the heat transfer processes in the sewer systems, differences between wastewater and sediment-bed temperature time series were analysed in terms of amplitude ratio (A_r) and time-phase difference ($\Delta\phi$). These parameters were calculated by applying the Dynamic Harmonic Regression (DHR) method (Gordon et al., 2012).

$$A_r = \frac{A_{sed}}{A_{water}}$$

$$\Delta\phi = \phi_{sed} - \phi_{water}$$

where A_{sed} and A_{water} are the amplitudes (ºC), and ϕ_{sed} and ϕ_{water} are the time-phases (rad) of the temperature time series at the bottom of sediments and in the wastewater, respectively. Relationships between the parameters obtained from the harmonic analysis of the temperature series parameters (A_r and $\Delta\phi$), and sediment thicknesses were calculated for the simulations of scenario A. These relationships were applied to simulated temperature time series from scenarios B and C to assess the influence of the sediment accumulation in the whole pipeline network.

Results and discussion

Hydrodynamic analysis: risk of sediment accumulation

The shear stress analysis performed in the 1.8 km sewer stretch sector revealed that there is considerable risk of sediment accumulation in the sewer pipes, mainly due to the low slope of the network (< 0.1%). Figure 1a shows that maximum bed shear stress in all pipes was below 2 N/m^2. Similar bed shear stress patterns were obtained for all the pipes since there were no additional stretches connected in this sector. The daily average of bed shear stress ranges between 0.50 and 0.75 N/m^2, but a mild rainfall event at night increased the values without exceeding the threshold established. The impact of rainfall only meant that the minimum temperature at night was 0.5°C lower than the previous day (Figure 1b).

Regarding shear stress patterns in the sewer system of Fehraltorf, it was found that 30% of the sewer pipes (122 pipes) showed a maximum bed shear stress below the threshold since the average slope was of 0.9%. Most of diameters ranged between 300 and 600 mm, revealing that pipes prone to sediment accumulation are mainly located at the upstream secondary network, which is generally the largest contributor to solids production (Rammal et al., 2017). Figure 1c shows the spatial distribution of maximum bed shear stress in the sewer system. To simplify the analysis of heat transfer processes in the following section, a sewer stretch of 0.23 km and diameters of 300 mm was selected in Fehraltorf pipeline network.

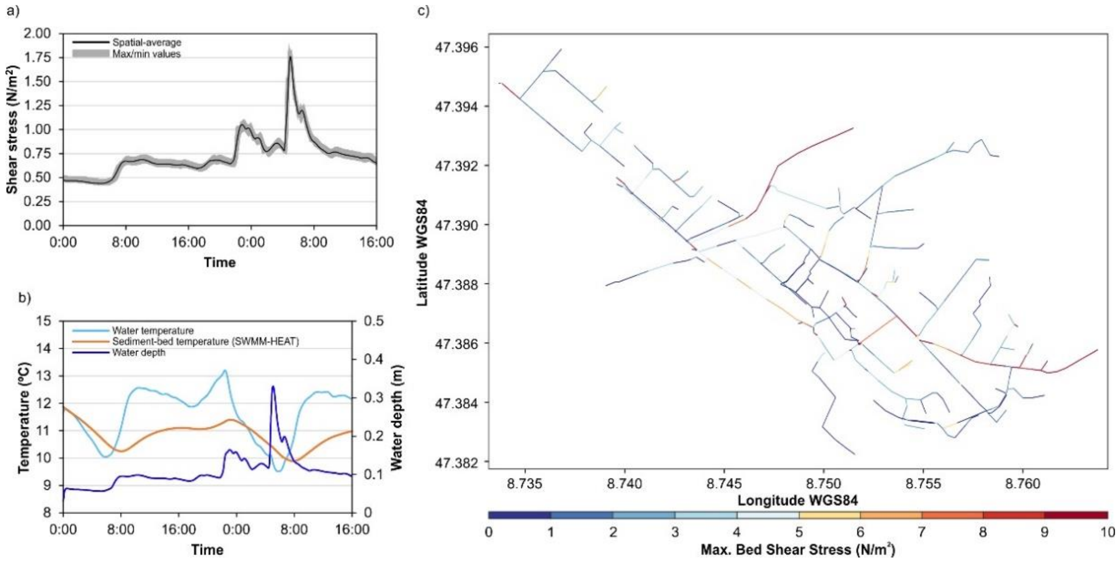

Figure 1. Shear stress distribution under no bed deposit conditions in the stretch pipeline of Rümlang (a). Time evolution of water depth, and wastewater and sediment bed temperatures in one pipe for a sediment height condition of 10 cm (b). Spatial distribution of the maximum bed shear stress in the pipeline sewer system of Fehraltorf (c).

Heat transfer processes analysis: influence of spatial scale on the sediment thickness prediction

Different sediment accumulation scenarios were simulated up to a sediment thickness of 10 cm in Rümlang sewer stretch (900 mm pipe diameter) and 20 cm in Fehraltorf sewer stretch (300 mm pipe diameter). In these simulations, a clear amplitude damping and time lag between the temperature series in the wastewater and at the bottom of the sediment bed was observed, e.g., Figure 1b shows simulation for a downstream pipe and 10 cm of sediment height in Rümlang.

The analysis of the harmonic-based features (A_r and $\Delta\phi$) between wastewater and sediment-bed temperature timeseries performed with the DHR method revealed that an increase in sediment thickness led to low amplitude ratios and large time lag differences. Figure 2a and 2b show the relationships between A_r and $\Delta\phi$ and sediment thicknesses in both pipe stretches. Straight lines correspond to the relationships obtain by simulating scenario A. For this purpose, synthetic sediment accumulation was only introduced in one pipe. Last downstream pipe of each stretch was selected for comparison.

Relationships between A_r and $\Delta\phi$ features and sediment thicknesses differ from each since thermal properties of the pipe and soil were different in each location (same sediment thermal properties were fixed). Therefore, the characterization of thermal properties plays a main role in the analysis of the heat transfer processes in the sediment-bed layer. Moreover, the duration of the dry weather period for the heat transfer analysis is also relevant to obtain smoother relationships between harmonic-based features and sediment thicknesses. Relationships in Figure 2a were obtained with an analysed period of 1.5 days while a period of 4 days was analysed in Figure 2b.

No differences were observed between A_r and $\Delta\phi$ features obtained in scenarios A, B and C for the last downstream pipes despite the combinations of simulated bed deposits. This means that heat transfer processes upstream did not have an impact and, therefore, the thermodynamic analysis can be performed independently in each pipe. On the other hand, main differences between A_r and $\Delta\phi$ were observed by comparing features obtained in the last downstream pipes (Scenario A) with those obtained in upstream pipes (Scenarios B and C). The deviation in these features (Figure 2a and 2b) occurs because the temperature patterns are not strictly the same in each pipe.

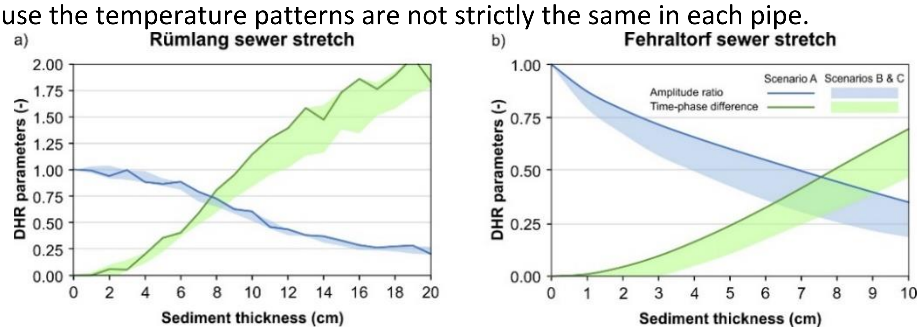

Figure 2. Relationships between sediment thicknesses and DHR features: A_r and $\Delta\phi$, obtained from the wastewater and sediment-bed temperature timeseries in Rümlang (a) and Fehraltorf (b) sewer stretches. *Straight lines: features obtained from scenario A simulations. Shaded areas: maximum and minimum features obtained from scenarios B and C simulations.*

Conclusions

This work presents a strategy to detect pipes susceptible to sediment accumulation based on a hydrodynamic study and a novel analysis to relate heat transfer processes to bed deposits. This analysis was performed by using SWMM-HEAT, which allows a holistic study of temperature distributions in sewer systems. Results show that monitoring heat transfer processes in a pipe during dry weather periods could be performed independently of the rest of the sewer network. Relationships between temperature pattern features and sediment bed deposits are influenced by i) the thermal properties of the sediment, pipe and soil, ii) the dry weather period analysed, and iii) the temperature daily pattern. Such studies would be useful to determine optimal placement of temperature sensors within a sewer system to observe differences in daily temperature patterns, and to develop data driven models that allow the measurement of sediment accumulation.

Acknowledgements

The work of Manuel Regueiro-Picallo is funded by the postdoctoral fellowship programme from the Xunta de Galicia. This work was partially founded by the EU under the Horizon 2020 program within a contract for Integrating Activities for Starting Communities (Co-UDlabs project. GA No.101008626).

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