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Modelling the viability of heat recovery from combined sewers

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ABSTRACT

Modelling of wastewater temperatures along a sewer pipe using energy balance equations and assuming steady-state conditions was achieved. Modelling error was calculated, by comparing the predicted temperature drop to measured ones in three combined sewers, and was found to have an overall root mean squared error of 0.37 K. Downstream measured wastewater temperature was plotted against modelled values; their line gradients were found to be within the range of 0.9995–1.0012. The ultimate aim of the modelling is to assess the viability of recovering heat from sewer pipes. This is done by evaluating an appropriate location for a heat exchanger within a sewer network that can recover heat without impacting negatively on the downstream wastewater treatment plant (WWTP). Long sewers may prove to be more viable for heat recovery, as heat lost can be reclaimed before wastewater reaching the WWTP.

Key words | heat pump, heat recovery, heat transfer, model, sewer

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NOMENCLATURE

b	Wastewater surface width (m)
B.C.	Boundary condition
COP	Coefficient of performance; ratio of outputted heat to electricity consumed in a heat pump
c_p	Specific heat capacity for water (J/g.K)
DS	Downstream
d_s	Soil depth (m) to which heat is transferred, as shown in Figure 1
dT	Temperature drop (K)
d_w	Depth of wastewater inside sewer pipe
h	Heat transfer coefficient (W/m^2.K)
k_s & k_p	Thermal conductivities of soil and pipe wall respectively
L	Pipe length (m)
M	Mass flow rate (g/s)
Q	Heat transfer rate along sewer pipe (W)
q_{wa}	Heat transfer rate between wastewater and in-sewer air (W)
q_{ws}	Heat transfer rate between wastewater and soil through pipe wall (W)
R_f	Fouling factor; thermal resistance caused by pipe surface biofilm (m^2.K/W)
RMSE	Root mean square error
R_{wa}	Thermal resistivity between wastewater and in-sewer air (K/W)
R_{ws}	Thermal resistivity between wastewater and soil surrounding sewer pipe (K/W)
T_{air} & T_s	In-sewer air and soil temperatures (K) respectively
T_j & T_{j+n}	Wastewater temperatures (K) at the upstream (inlet) and downstream respectively
T_{j+1}	Wastewater temperature (K) at the outlet of first pipe increment
u_{wa}	In-sewer air velocity relative to wastewater velocity
w, a, p & s	Wastewater, in-sewer air, pipe and soil respectively
wa	Denoting for heat exchange between wastewater and in-sewer air
wet.p	Pipe wetted perimeter (m)

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ws	Denoting for heat exchange between wastewater and soil through pipe wall
wt	Pipe wall thickness (m)
WWTP	Wastewater treatment plant
∇L	Mesh size in streamwise direction (m)
∇T	Temperature drop as a result of recovering heat from sewers (K)
∇T_{air}	Change in in-sewer air temperature (K)

INTRODUCTION

The threat of global warming has driven the UK government to set a target of 80% carbon emission reduction with respect to 1990 levels by 2050. This has encouraged the examination of recovering thermal energy from wastewater within foul or combined sewer systems. A number of studies have provided limited information on the temperature of sewage and how it changes; for example, Schilperoort & Clemens (2009), Hoes *et al.* (2009) and Cipolla & Maglionico (2014) reported sewage temperatures of up to 293 K 300 K and 295 K respectively. Schilperoort & Clemens (2009) also reported a streamwise temperature drop of up to 5 K, over a 400 m sewer length. However, sewers are contained within soils and as well as heat transfer in the streamwise direction it is important to be able to understand the heat transfer rate that enters and leaves the soil via the buried sewer infrastructure. Thermal energy in sewers produced from wastewater with temperatures up to 298 K, has been recovered in some European countries such as Switzerland using heat pumps (Schmid 2008). The latter author referred to Hanspeter (2008) who predicted that the Swiss sewage system has the potential to provide up to 2 TWh of energy per annum. Extracting heat from sewer pipes, through heat pumps, can result in households reducing their thermal energy consumption by as much as 10% where conventional boilers are used and by 23% where oil-fired systems are used (Schmid 2008). Some authors have modelled heat transfer in sewers to predict the impact of temperature on water quality, e.g. Wanner *et al.* (2005), while others such as Brown & Enzminger (1991) developed a heat transfer model in a wastewater treatment plant (WWTP), in order to study the effect of operating temperature on the treatment process selection. Baek *et al.* (2004) studied the design of a heat pump that utilises hot spring wastewater discharged from both the sauna and 144 rooms of a Korean hotel and found that the wastewater heat pump annual mean coefficient of performance (COP) was 4.8, which is higher than that of a typical conventional air source heat pump. The latter authors concluded that both wastewater and black water can be utilised for meeting hot water thermal energy demands (2.8 GJ/d). Meggers & Leibundgut (2011) expanded the concept of recovering heat from residential wastewater by capturing it immediately after discharge through heat pumps and projected a high COP of 6. Establishing the potential of heat recovery from sewers depends on predicting heat transfer rates between wastewater and in-sewer air, and between the sewer pipe, wall material and the surrounding soil. Available literature in the field of heat transfer modelling in sewers is limited to only a small number of studies such as Durrenmatt (2006) and Durrenmatt & Wanner (2008a, b, 2014). The latter authors modelled the longitudinal spatial profile of the wastewater temperature in sewer pipes and developed a code named TEMPEST. Temperature of wastewater in sewer pipes is expected to drop along the pipeline axis due to the heat transfer (losses) from hot wastewater to the relatively cold in-sewer air, and adjacent soil through conduction with the pipe wall. Durrenmatt & Wanner (2008a) have incorporated the interaction between wastewater, in-sewer air and surrounding soil within TEMPEST by considering mass balance equations, rate expressions of heat transfer and a new empirical model of the heat transfer between the sewage and sewer airflow. Their model incorporated several heat transfer processes and divided the simulated sewers into conduits and nodes to include the effects of different soil types and pipe wall characteristics on temperature, flow velocity and depth along the sewer line. The TEMPEST model is a complex one due to the large number of input parameters, such as sewer slope, friction coefficient, chemical oxygen demand degradation rate and ambient temperature, that would result in insignificant effects (<0.2%) on the modelled sewer temperature (Durrenmatt 2006). Heat transfer in sewers is complicated as the hydraulics of the wastewater in sewer pipes change continuously depending on a number of factors such as stormwater, infiltration and the daily production pattern of wastewater from the catchment area. Furthermore, thermal transfer taking place between wastewater and in-sewer air and also between the former and pipe surface relies on heat transfer coefficients that require extensive laboratory work to be determined. Hence, limited literature has been published in the field of heat transfer between wastewater and its surrounding soil and in-sewer air. The literature reviewed here has clearly shown that apart from the TEMPEST model, no other published models incorporated air in partially filled sewer pipes to estimate the wastewater temperature profile along the pipe. Moreover, the wide range of variables incorporated within the TEMPEST model restricts its practicality as an assessment tool for identifying potential heat recovery from sewers at a network scale. This is due to both the difficulty of finding (or measuring) all the required input parameters and the computational load. Hence there is a gap in developing simple models that can estimate the temperature variation along the profile of a partially filled sewer pipe and thus asses the viability of installing heat exchangers into sewer networks. Therefore, this paper aims to develop a practical and simple modelling approach in order to assess the viability of recovering heat from sewer pipes by studying the impact of a heat exchanger on the downstream wastewater temperature.

METHODOLOGY

Key parameters to estimate the heat transfer rates in a sewer, such as wastewater and in-sewer air temperatures, flow rate, and velocity of wastewater, were measured at three sewers managed by Aquafin, near Antwerp. This was done in order to understand the processes within a real system and also to validate a computational model for the temperature change along the pipe length. Air temperature sensors with an accuracy of 0.2 K were installed 1 m below the manhole cover whilst wastewater temperature was measured just above the sewer pipe invert using thermocouples of the same accuracy. Other heat transfer related variables such as soil temperature and groundwater level were also measured at different locations within Antwerp. It was assumed that the soil surrounding the three sites was saturated, as the elevation profiles of the sewer pipes and groundwater levels located within 1 km of the sites were obtained. Pipe materials for sites 1 and 3 are concrete while site 2 pipe is made of masonry brick. Table 1 shows details of sites 1, 2 and 3 and their relevant measurements. While temperatures of wastewater and in-sewer air at both streams were measured for a year, other parameter data were monitored for 6 months.

Figure 1 shows a schematic drawing of the sewer pipe used for modelling heat transfer. Modelling starts by implementing energy balance along the pipe and then calculates thermal resistivity by estimating heat transfer coefficients. Equations for the heat transfer between different phases/materials were retrieved from literature and implemented to finally compute the wastewater downstream temperature. Drop of temperature along pipe profile is caused by thermal energy losses due to heat transfer from wastewater to both

Table 1 | Details of three sites where in-sewer air and wastewater temperatures as well as flow velocity and depth were measured. All sites were around 3 m below ground level

Site	Average dry weather flow (m^3/hour)	Pipe length (m)	Distance to soil temperature sensor at 3 m below ground level (km)	Pipe internal diameter (m)	Pipe level above datum (upstream–downstream) (m)	Groundwater level above datum (m)	Saturation condition
1	37	464	1.9	1.2	11.8–11.2	14.20	Saturated
2	48	175	2.2	1.3	5.5–4.3	9.2	Saturated
3	49	232	1.5	1.2	11.1–9.9	14	Saturated

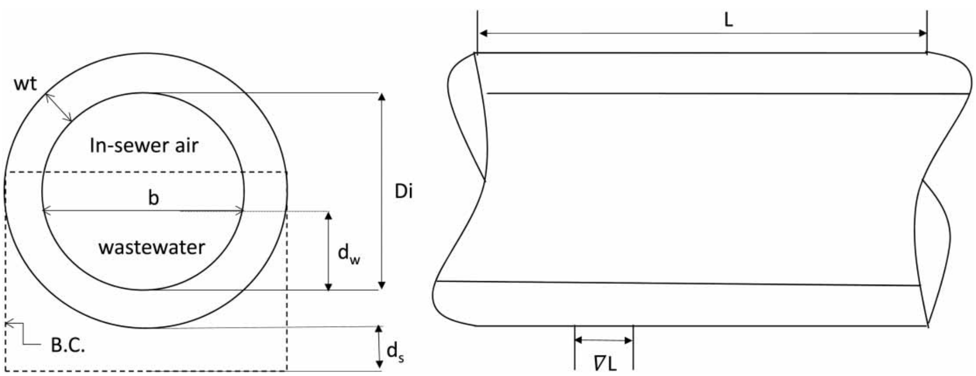

Figure 1 | Cross- and longitudinal sections of sewer pipe. B.C. is boundary condition.

in-sewer air and surrounding soil. These energy losses are expressed as heat transfer rates between wastewater and air (q_{wa}) and between wastewater and soil through pipe wall (q_{ws}). Equation (1) is based on energy balance laws to show the mathematics behind this phenomenon in a simple form

$$M \times c_p \times (T_j - T_{j+n}) = q_{wa} + q_{ws} \quad (1)$$

q_{wa} and q_{ws} are governed by the overall thermal resistivity between wastewater and in-sewer air (R_{wa}) and between wastewater and soil (R_{ws}). The latter accounts for the fouling factor caused by the biofilm growth on the pipe surface and the thickness of the soil surrounding the pipe. Accounting for R_{wa} and R_{ws} and dividing the pipe into a number of increments (n), where each increment length is equal to ∇L as shown in Figure 1, Equations (2)–(4) (Incropera *et al.* 2007) were obtained. Using measured wastewater temperature at upstream (T_j), temperature at the outlet of the first pipe increment (T_{j+1}) is computed. The latter is used as inlet temperature for the following increment and so on

$$q_{wa} = \frac{1}{R_{wa}} \times (T_{water} - T_{air}), \quad q_{ws} = \frac{1}{R_{ws}} \times (T_{water} - T_{soil}) \quad (2)$$

$$R_{wa} = \frac{1}{h_{wa} \times b \times n \times \nabla L} \quad (3)$$

$$R_{ws} = \frac{1}{h_{wp} \times wet.p \times n \times \nabla L} + \frac{R_f}{wet.p \times n \times \nabla L} + \frac{wt}{k_p \times wet.\,p \times n \times \nabla L} + \frac{d_s}{k_s \times wet.\,p \times n \times \nabla L} \quad (4)$$

R_f = thermal resistivity due to fouling on pipe surfaces (m^2.K/W), wt = pipe wall thickness (m), d_s = soil depth to which heat is transferred (boundary condition dependent). h_{wp} = heat transfer coefficient between wastewater and pipe (W/m^2.K), wet.p = wetted perimeter (m), n = increment number and ∇L = mesh size or increment length (m). k_p and k_s are pipe and soil thermal conductivities (W/m.K) respectively.

It was assumed that wastewater velocity gradually reduces to zero at the pipe surface (no-slip condition) and therefore heat is transferred to the soil through the pipe wall via conduction only. Resistance due fouling of the wall was assumed to be negligible. These assumptions were based on calculations using Equation (4) that showed R_{ws} being much larger than R_{wa} and hence most of the heat in sewers is transferred to air. This implies that large flow of in-sewer air (e.g. 1 m^3/s) is needed to accommodate this heat without excess temperature rises. This flow rate is much larger than in-sewer air flow rate in the three sites, described in Table 1, which was assumed to be around 0.15 m^3/s estimated by considering a typical in-sewer air velocity of 0.14 m/s, as found in Madsen *et al.* (2006), and pipe diameter of 1.2 m. For example, if the wastewater flowing at 45 m^3/hour (12.5 kg/s) and its temperature was to be dropped by 0.5 K, change in in-sewer air temperature (∇T_{air}) can be computed by applying Equation (1) and assuming the majority of heat is transferred to in-sewer air, as a result of the large R_{ws} value, as shown in Equation (5)

$$\begin{aligned} M \times c_p \times (T_j - T_{j+n}) &= q_{wa} \\ M \times c_p \times (T_j - T_{j+n}) &= M_{air} \times c_{pair} \times \nabla T_{air} \\ \nabla \boldsymbol{T}_{\mathbf{air}} &= \frac{12.5 \times 4.2 \times 0.5}{0.15 \times 1.22} = 143.4\ \mathrm{K} \end{aligned} \quad (5)$$

Obviously the high value of ∇T_{air} is unrealistic and therefore Equation (4) is reduced to only include conduction in THE pipe wall and surrounding soil. Thus, R_{ws} used in this paper is expressed in Equation (6)

$$R_{ws} = \frac{wt}{k_p \times wet.\,p \times n \times \nabla L} + \frac{d_s}{k_s \times wet.\,p \times n \times \nabla L} \quad (6)$$

The heat transfer coefficient between wastewater and in-sewer air (h_{wa}) can only be predicted and was found by Flinspach (1973) to be a function of wastewater velocity relative to that of in-sewer air (u_{wa}) as shown in Equation (7)

$$h_{wa} = 5.85 \times \sqrt{u_{wa}} \quad (7)$$

Combining Equations (1)–(3) and (6), so incorporating the assumptions described above, Equation (8) was developed for modelling wastewater temperature at each pipe increment. Equation (8) is then applied in sequence, starting from upstream wastewater temperature (T_j) to compute temperature variation along sewer pipe (T_{j+1}, T_{j+2}, ...) and finally calculates the downstream wastewater temperature (T_{j+n})

$$T_{j+1} = T_j - \left(\frac{\frac{1}{R_{wa}} \times (T_j - T_{air}) + \frac{1}{R_{ws}} \times (T_j - T_s)}{M \times c_p} \right) \quad (8)$$

RESULTS

To investigate the quality of the measured data and assess its reliability for model validation, wastewater temperature variation between upstream and downstream manholes at the three sites was plotted for a day in July 2012 as shown in Figure 2. It can be seen that the wastewater temperature varied between 293 and 295 K, which is consistent with measurements recorded by Schilperoort (2011). One can observe that the wastewater temperature starts dropping roughly at midnight and then increases again at around 7.00 a.m. and keeps rising until midday due to the larger, higher temperature wastewater inputs released into the sewer network, and then drops again at midnight as the warm wastewater inputs decrease.

Temperatures of wastewater, soil and in-sewer air increased from around 283 K in late February 2012 to reach 297 K in August 2012 as shown in Figure 3. The peaks shown in the flow pattern of Figure 3 reflect rainfall flow, which was occasional as expected. Hence, in this project only average dry weather flow is considered. The average annual difference between upstream and downstream wastewater temperatures were 0.7 or 4 K/km for site 2, which was the highest, compared to sites 1 and 3 (0.1 and 0.8 K/km respectively), as shown in Figure 4. Measured data, shown in Table 1, were logged on site every 20 min. Table 1 shows all of the parameters used for modelling wastewater temperature at the downstream end of each monitoring location. Of note, parameters presented are for the three sewer pipes between February and August

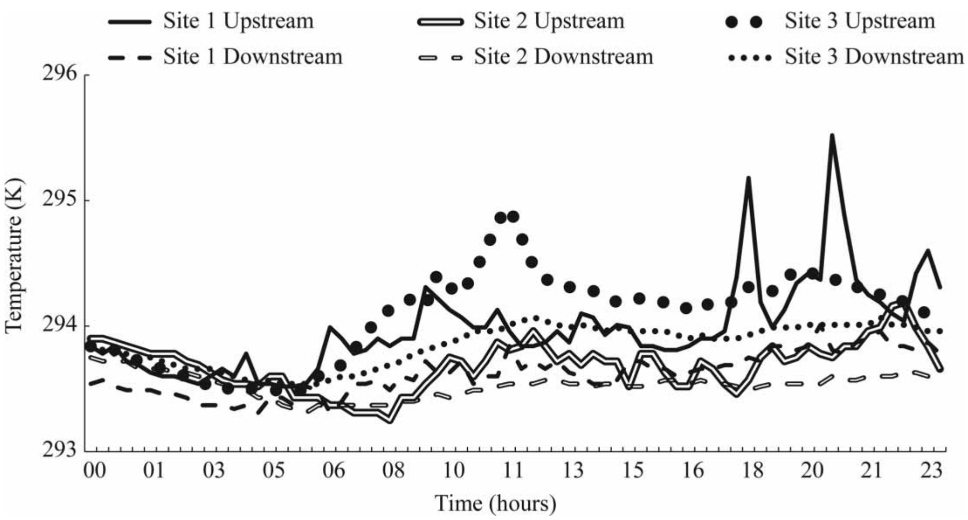

Figure 2 | Daily wastewater temperature variation between both streams for sites 1–3 on a day in July.

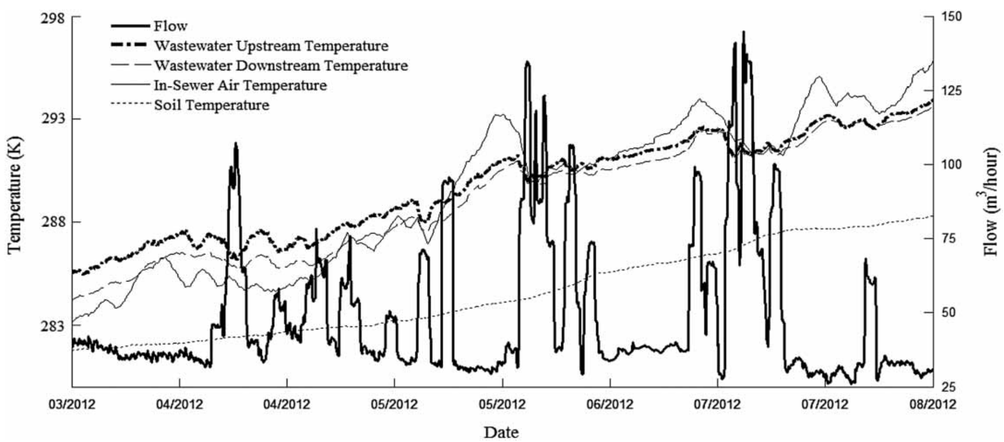

Figure 3 | Temperatures and flow variations at site 2.

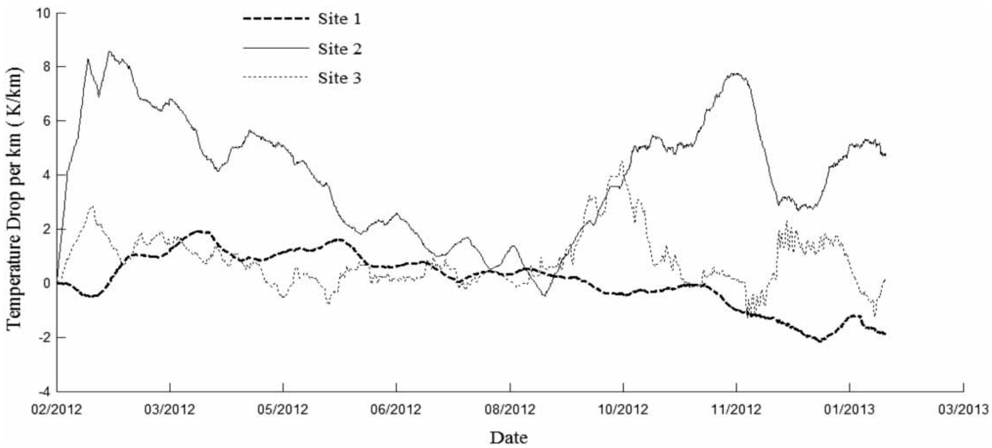

Figure 4 | Variation of wastewater temperature per km along pipe profile at sites 1–3 for a 12-month period.

2012 considering average data of 24th February and the 15th of the other months.

A comparison between modelled and measured results is shown in Figure 5. The latter figure shows trend line gradient (m) values, which varied from 0.9995 to 1.0012, corresponding to the relation between measured and modelled temperatures for the three sites between February and August 2012. Trend line intercepts were set to zero to compare the three gradients. Modelling error, which is the difference between modelled and measured temperature drops, varied from −1 K in February of site 2 to 0.76 K in April of site 1. Values of root mean square error (RMSE) varied: 0.9, 0.5 and 0.2 K for sites 1, 2 and 3 respectively, while the overall RMSE was found to be 0.37 K (Table 2).

Site 3 showed much higher modelled temperature drops than that of the measured one in June due to the insignificant measured temperature drop, which was 0.003 K (or 0.01 K/km). This value is unusual compared to average measured temperature drop among the three sites of 1.93 K/km or 1.1 K/km for site 3 alone. This overestimation by the model occurred at site 3 in July and August as well, yet at smaller scale than that of June. On the other hand, the model under-predicted temperature drops in a number of occasions and mostly at site 2. The latter site shows average temperature drop of 3.9 K/km, between February and August 2012, which is double the average drop in the three sites, and hence model estimations were relatively lower than measured temperature drops. Site 3 has shown temperature drops along pipe profiles of 0.01, 0.12 and 0.26 K/m in

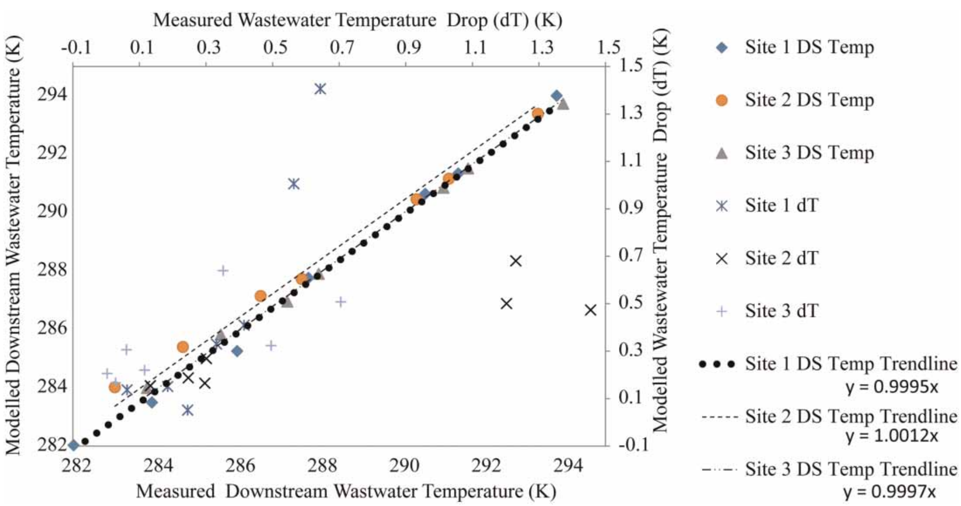

Figure 5 | Measured versus modelled downstream temperatures and temperature drops considering average daily values. Bottom horizontal and left vertical axes show the correlation between measured and modelled temperatures (DS (downstream) Temp), while top horizontal and right vertical axes show the relation between measured and modelled temperature drops.

Table 2 | Parameters and their values used for modelling downstream wastewater temperature

Parameter	Value/range	Unit	Notes/references
Wastewater temperature at upstream, T_j	282–294	K	Measured
Mesh size, ∇L	10	m	Assumed
Pipe length, L	175–464	m	Measured
Average in-sewer air temperature, T_a	280–298	K	
Pipe thermal conductivity, k_p	0.5 and 0.72	W/m.K	Concrete and masonry (Holman 1997)
Soil thermal conductivity, k_s	2.4	W/m.K	Saturated soil (Mitchell & Soga 1993)
Wetted perimeter, wet.p	0.46–1.4	m	Computed from measured wastewater depth (d_w) and known pipe diameters
Width of water surface, b	0.45–1.14	m	
Soil depth, d_s	0.4	m	Assumed, produced most accurate results
Soil temperature, T_s	282–289	K	Measured
Mass flow rate, M	5,333–32,541	g/s	Computed based on velocity measurements
Pipe wall thickness, wt	0.14	m	Measured
Wastewater depth, d_w	0.04–0.130	m	
Wastewater velocity, u_w	0.3–0.9	m/s	
Specific heat, c_p	4.2	J/g.K	Standard for water
Thermal resistivity between wastewater and in-sewer air (R_{wa})	0.001–0.09	K/W	Computed using Equation (3)
Thermal resistivity between wastewater and soil (R_{ws})	0.002–0.1		Computed using Equation (6)
Heat transfer coeff. between wastewater and in-sewer air, hwa	1.9–5.2	W/m^2.K	Equation (7), speed of in-sewer air = 0.14 m/s (Madsen et al. 2006)
Water thermal conductivity	0.59	W/m.K	Holman (1997)

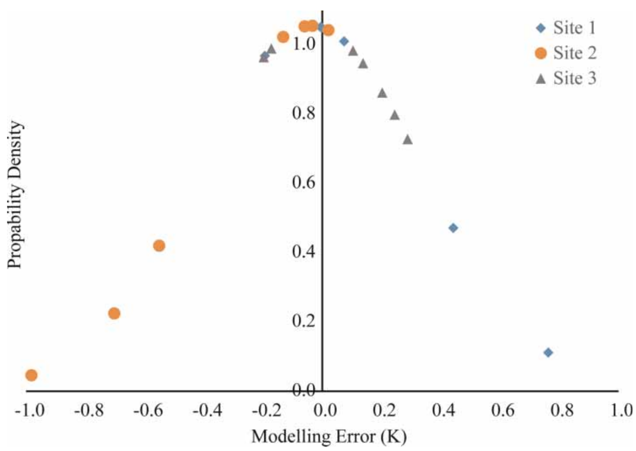

Figure 6 | Probability distribution of modelling error at the three sites in all months.

June, July and August respectively. This is considered to be insignificant when it is compared to the average of all other readings (2.2 K/m). Figure 6 shows the probability density (normal distribution) of modelling errors for the three sites. The probability density indicated that the mean error is close to zero and the shape of the distribution suggests normality; hence, the errors are random. Sensitivity analyses was performed, on all model parameters. This was done by testing the impact of multiplying the default parameters by 25%, 50%, 200% and 400%, on the default modelled downstream wastewater temperature value. The mode was most sensitive to wastewater temperature at upstream (T_j) as it showed 64% drop when T_j was 25% of default T_j and increased by 260% when T_j was 400% of the default value. Despite this expected high sensitivity to T_j, in-sewer air followed by soil temperatures are much more sensitive parameters than others as shown in Figure 7.

To measure the impact of modelling error on estimating the potential of heat recovery, the ratio of modelled heat transfer rates along the sewers ($q_{wa} + q_{ws}$) to the available thermal energy at the downstream of each site ($Mc_p \nabla T$) was plotted against modelling errors as shown in Figure 8. It was assumed that heat recovered in the sewer pipes caused an overall temperature drop (∇T) of 5 K. It is clear, from Figure 8, that the impact of modelling error on the estimated heat transfer rates at downstream is minimal

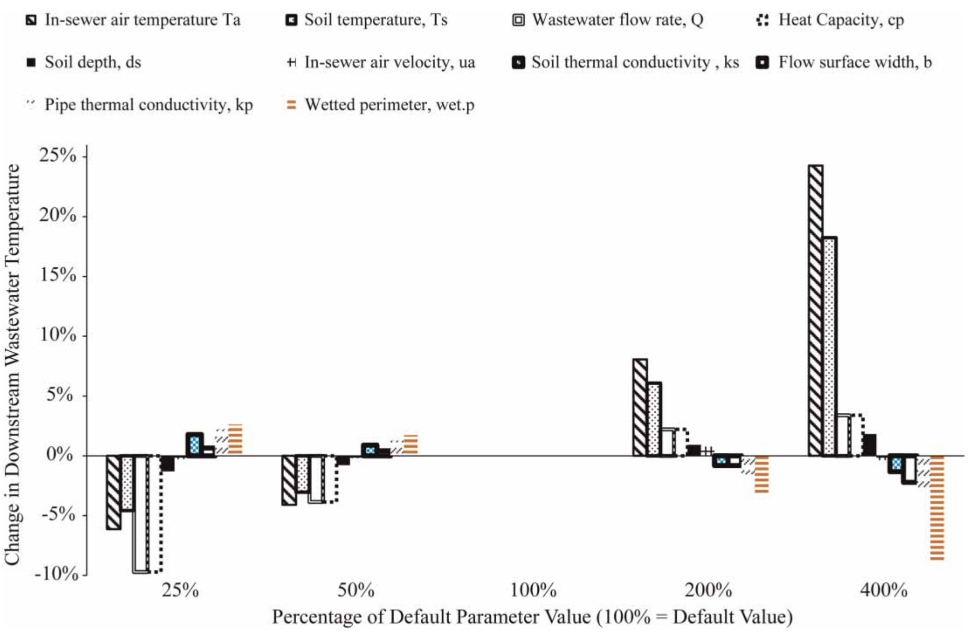

Figure 7 | Sensitivity analysis.

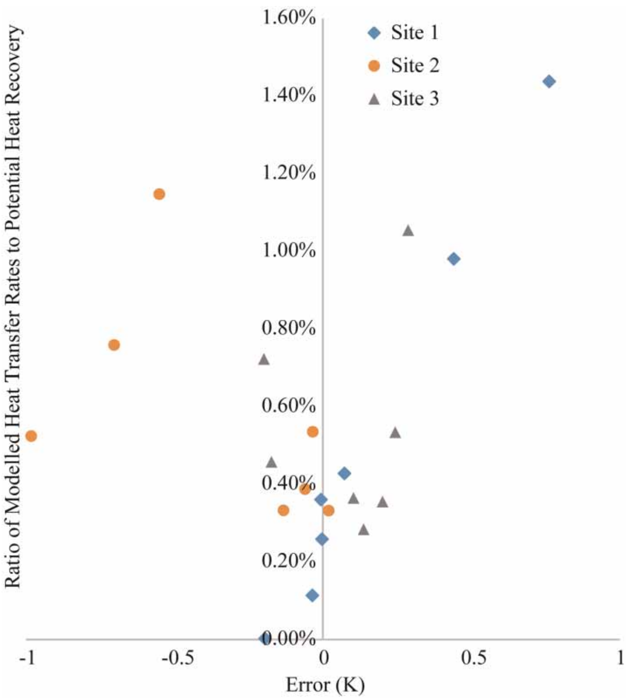

Figure 8 | Impact of modelling error on estimating potential heat recovery from sewers.

due to the low proportion of heat estimated (q_{wa} and q_{ws}) to that available in sewers.

An application example of the model is illustrated in Figure 9 in order to show the required sewer length for heat recovery at different scales. Site 1 was used, as it showed the closest value to the overall average modelling error, to represent assumed scenarios of heat recovery with imaginary sewer lengths. The 'business as usual' scenario represents the current condition of the sewer (i.e. no heat recovery system), whilst each of the other scenarios assumes heat is recovered upstream, using 100% efficient heat exchangers that are capable of recovering 20, 40, 50, 100, 150 and 500 kW. Each scenario is independent of the rest, yet they all share site 1 parameters, except that temperature variation was modelled along an imaginary sewer length with the same characteristics as site 1.

DISCUSSION

The annual average temperature drop along the pipe profile was shown to be up to 4 K/km at site 2, which proves that there are heat losses (to soil and in-sewer air) along sewers. Daily wastewater temperature variation along sewers in July showed some peaks at the upstream location as shown in Figure 2. This is expected as the sewers for these sites (1–3) are close to residential areas, and personal usage of hot water by residents can directly have an impact on the daily wastewater temperature pattern. Peak sizes in Figures 2 and 4 would also vary depending on the size and practice of residents. Wastewater temperature at the three sites in the

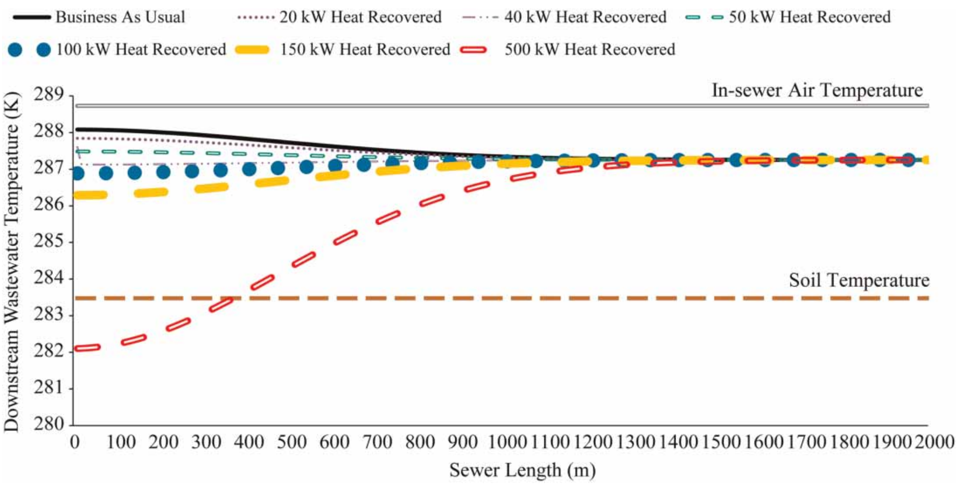

Figure 9 | Heat recovery application on a 2 km sewer line with similar characteristics to site 1 in May 2012.

7 months (February to August) was dropping along sewer pipes due to the lower in-sewer air and soil temperatures. Although on occasions in-sewer air temperature was higher, by up to 2.8 K, than that of wastewater at upstream, soil temperature was always lower than that of wastewater during both winter and summer except in February of site 1. Therefore, there was a drop in wastewater temperature in all sites at all times. This also confirms that temperature variation in sewer pipes is sensitive to both soil and in-sewer air temperatures. Implementing Equation (6) instead of (4) supports this argument and reduced modelling error significantly. Thus, the sensitivity analysis presented in Figure 7 shows soil and in-sewer air temperatures to be the most sensitive parameters, following wastewater temperature at upstream. Modelling error, which is defined as the difference between modelled and measured temperature drops along sewer pipes, had an average RMSE of 0.37 K. This is reasonable considering the temperature sensor accuracy of 0.2 K and the conditions surrounding the sensor.

In Figure 5 gradients of 0.9995–1.0012 showed good agreement between measured and modelled values. Although individual predicted values of the difference in upstream and downstream temperature differences showed a wider scatter, Figure 8 showed that the impact of such errors on estimating the amount of heat available at the downstream end of the pipe was minimal. This simplified, but computationally efficient, model was therefore useful for delivering fairly accurate estimation of the distance required to reclaim heat recovered at upstream as shown in Figure 9. This figure shows that heat recovery of 500 kW causes a large upstream temperature drop, yet heat is reclaimed again with the attempt to reach in-sewer air and soil temperatures. However, recovering heat at such a large scale requires long sewer pipes for the wastewater to regain the original wastewater temperature.

CONCLUSIONS

Measured wastewater temperatures at both streams show an average annual temperature drop along sewer pipes of up to 4 K/km. Wastewater temperature drop along sewer pipes was modelled, assuming steady-state conditions, using a computationally efficient model and it showed a reasonable match between measured and modelled temperatures. An overall RMSE of 0.37 K was obtained on the basis of modelling error, which is the difference between measured and modelled temperature drops. Heat recovery of large capacities (>100 kW) were modelled and the results presented a potential for heat recovery in sewers providing that the location was many hundreds of metres upstream of a WWTP.

The model is to be further developed to be more sensitive to other parameters such as soil thermal conductivity and will be tested against data from more sites. Incorporating the effects of lateral flows on the downstream temperature will also be considered in future work.

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