Modelling heat recovery potential from household wastewater

C. Wärff, M. Arnell, R. Sehlén and U. Jeppsson

ABSTRACT

There is a strongly growing interest for wastewater heat recovery (WWHR) in Sweden and elsewhere, but a lack of adequate tools to determine downstream impacts due to the associated temperature drop. The heat recovery potential and associated temperature drop after heat recovery on a building level is modelled for a case study in Linköping, Sweden. The maximum temperature drop reaches 4.2 °C, with an annual recovered heat of 0.65 kWh · person^{-1} · day^{-1}. Wastewater temperature out from the heat exchanger was 18.0 °C in winter at the lowest. The drinking water source type can be an important factor when considering wastewater heat recovery.

Key words | energy use, heat demand, heat exchanger, heat recovery, wastewater

C. Wärff
RISE Research Institutes of Sweden
Sven Hultins Plats 5, 412 58 Gothenburg,
Sweden

R. Sehlén
Tekniska Verken i Linköping AB,
Brogatan 1, 581 15 Linköping,
Sweden

M. Arnell (corresponding author)
U. Jeppsson
Division of Industrial Electrical Engineering and Automation,
Lund University,
Ole Römers väg 1, Lund,
Sweden
E-mail: *magnus.arnell@iea.lth.se*

INTRODUCTION

There is a strongly growing interest in wastewater heat recovery (WWHR) in Sweden and elsewhere, particularly on the property level to increase the energy efficiency of residential buildings. Regulations, however, often require written approval from the wastewater utility if WWHR is to be used since the biological nitrogen removal processes at the treatment plant can be severely affected if the temperature of the influent wastewater drops too far. Due to a lack of adequate decision-support tools in this regard, many utilities generally deny permits for WWHR because of the associated risks. Consequently, there is a need for a general tool for estimating the downstream impacts of WWHR and the resulting temperature drop (Arnell *et al.* 2017). As a first step towards a system-wide modelling tool, an existing stochastic model (Hillebrand 2014; Sitzenfrei *et al.* 2017) has been adapted and further refined to produce wastewater flow and temperature time series from households for Swedish conditions. The goal of the model development is to describe wastewater flow and temperature for multi-family buildings to allow estimation of heat recovery potential on the property level.

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This work is part of the project *Sustainability analysis from wastewater heat recovery* (HÅVA) in which impacts of large-scale implementation of heat recovery from wastewater is investigated on a system level. This includes (apart from this paper) model development for wastewater heat balance in the sewer network and wastewater treatment plant. Case studies will be performed for three Swedish cities where system-wide models will be used to predict heat recovery potential and impacts on the treatment plant (such as temperature loss in the system and effects on biological nitrogen removal).

MATERIAL AND METHODS

Wastewater generation model – general description

A stochastic wastewater generation model is developed based on the model presented by Hillebrand (2014) and Sitzenfrei *et al.* (2017). It is based on daily probability of use patterns and statistics for different water end usage types (shower, bath, WC, dishwasher, washing machine and taps) for a specified number of people. For each person and end usage type, a daily frequency of use is used to determine the probability of use each day. If a usage event occurs, a probability density function (PDF) is used to determine the time of use during the day. Water use statistics are then used to determine the generated water volume and temperature for each usage event. Inputs to the model include the number of people to generate wastewater for, cold tap water temperature, domestic hot water (DWH) temperature (temperature in the water heater) and day of the week. The model produces timeseries of wastewater flow and temperature as well as the DWH use over the desired number of days and distinguishes between workdays and weekends. The model terminology follows the one presented by Sitzenfrei *et al.* (2017) when possible. Aspects of the original model have been modified or extended: water for outside use is not included; daily use patterns are separated between workday and weekend use; probability of use during the day is described by four normal distributions instead of three (to account for nighttime use). Heat loss in the building is included according to Sitzenfrei *et al.* (2017). The model is implemented in Matlab R2017a (v 9.2, The MathWorks, Inc.).

The statistics for water use are assumed to be normally distributed, described by a mean value and standard deviation. These include: (i) frequency of use per person and day; (ii) flow (μ_Q, σ_Q); (iii) duration (μ_D, σ_D); and (iv) temperature (μ_T, σ_T). Statistics were collected for Swedish conditions and complemented with values from Sitzenfrei *et al.* (2017) and the model calibration phase. This data is presented in Table 1.

Probability of use during the day

The Swedish Energy Agency (2008) measured water flow from individual water taps, including shower, WC, kitchen sink taps and wash basin taps, from ten different households. The households were chosen by the governmental agency Statistics Sweden to guarantee diverse types of households, but despite this the quantity is too low to be certain that the data is representative of the national average. The data can, however, be used to analyze user patterns and serve as a starting point for model calibration where the model parameters are changed to correct for the unrepresentative data. The original data (three weeks of measurements with a resolution of one minute) was accessed and analyzed for user patterns. The time of occurrence during the day was logged for each usage event and stored at 15-minute intervals. The data was then normalized to the number of inhabitants in the household, and finally averaged over all the households to obtain a PDF for that end usage type. This was done for shower, WC and tap water use (combining data for kitchen sink and wash basin for tap water use) for workdays and weekend days separately.

The probability of occurrence for a usage event during the day is described mathematically in the model by a PDF according to Equation (1) ($f(x)$, where x (and X, used to norm the PDF) is the time during the day [h]). The PDF is comprised of the sum of four normal distributions ($k=4$) with mean values ($\mu_{h,k}$) and standard deviations ($\sigma_{h,k}$), with the index h indicating the hour during the day. The values for each probability function are given in Table 2. For each k, a pair of one mean value and standard deviation describe each normal distribution. The mean values are therefore interpreted as time of day for the peak of each normal distribution, while the standard deviation describes the magnitude of the peak and spread of the normal distribution. Negative values mean that the peak occur outside of the 24 hours to obtain the correct nighttime probability. When the 4 normal distributions are combined, the PDF for the probability of use for each day is obtained.

$$f(x) = \frac{\sum_{n=1}^{k} \frac{1}{\sigma_{h,n}\sqrt{2\pi}} e^{-(x-\mu_{h,n})^2/(2\sigma_{h,n}^2)}}{\int_{X=0}^{24} \left(\sum_{n=1}^{k} \frac{1}{\sigma_{h,n}\sqrt{2\pi}} e^{-(X-\mu_{h,n})^2/(2\sigma_{h,n}^2)} \right)}; 0 \le x \le 24 \quad (1)$$

Table 1 | Water use statistics for the wastewater generation model

End use type	Frequency of use [person^{-1}.d^{-1}]	μ_T [°C]	σ_T [°C]	μ_Q [L/min]	σ_Q [L/min]	μ_D [min]	σ_D [min]
Shower	0.70	37	0.7	12	0.9	9.6	1.0
Bathtub	0.03	37	0.7	10.5	0.5	7.4	0.6
WC	6	T_{cw}^{a}	1.0	6.0	0.3	1.0	0.15
Washing machine	0.2	45	1.5	8.9	0.6	5.6	0.3
Dishwasher	0.29	40	5.0	9.0	0.7	1.6	0.15
Taps	25	20	5.0	3.0	0.15	0.7	0.14

[a]T_{cw}, cold tap water temperature.

Table 2 | Probability function values for the wastewater generation model (calibrated values)

	Workday		Weekend	
End use type	$\mu_{h,k}$, $k = 1/2/3/4$	$\sigma_{h,k}$, $k = 1/2/3/4$	$\mu_{h,k}$, $k = 1/2/3/4$	$\sigma_{h,k}$, $k = 1/2/3/4$
Shower	−3.3/8.6/14.0/20.5	2.5/2.4/4.0/2.7	−3.5/11.1/13.0/19.5	2.0/2.2/4.0/3.0
Bathtub	−/10.0/14.0/20.0	−/2.4/3/2.2	−/10.0/14.0/20.0	−/2.4/3/2.2
WC	−3.0/7.8/15.0/20.7	3.5/1.8/4.0/2.8	−3.0/10.6/17.0/20.3	3.2/2.0/3.5/3.6
Washing machine[a]	–	–	–	–
Dishwasher[a]	–	–	–	–
Taps	−4.0/8.5/14.0/20.5	3.2/1.7/3.5/2.4	−3.8/10.4/14.0/20.0	2.8/2.5/3.0/3.1

[a]Probability density function not described by normal distributions, instead calculated from Stamminger & Schmitz (2017).

Equation (1) was used to fit the function to the data collected for shower, WC and tap water use. This was then used as a starting point for model calibration. Data for the remaining end usage types was collected from other sources: the PDF for bathtub time of use was assumed identical to the one in Sitzenfrei *et al.* (2017); the PDFs for dishwasher and washing machine time of use were extracted from EU survey data (where Sweden was one of the countries included in the survey) by Stamminger & Schmitz (2017) (modified to exclude nighttime use). Due to lack of distinction between workday and weekend use in these other sources, the PDFs for bathtub, dishwasher and washing machine were assumed to be identical for workdays and weekends. Since the collected daily volume per person generated from these sources is low (<9 percent of the total volume produced), this assumption is deemed to have low impact on the final result. It should, however, be taken into consideration if trying to answer specific questions regarding the use of these appliances.

Calibration and validation

To calibrate and validate the model, several data sets were collected: (i) measurements were performed for wastewater flow and temperature outside a precinct in Linköping, Sweden, with approximately 279 inhabitants for seven days during May 2019; (ii) drinking water demand curves from Nikell (1994), including median values and confidence intervals based on ten measurement sites with 2,000–20,600 connected persons; (iii) diurnal hourly median tap water and DHW profiles from measurements in 1,006 apartments in Karlstad, Sweden, from the year 2012 (data not published, but described in Bagge *et al.* (2015) and Bagge *et al.* (2018)). The two latter were used as validation data sets.

Calibration procedure:

1. Uncertain statistics were identified and targeted as calibration parameters (here mainly shower use and tap water use).
2. The total water consumption per person and day was matched by varying the volume of water produced per person and day for shower and tap water use.
3. The flow profile over the day was matched to the measured flow profile in Linköping (actual flow values) by changing the probability function parameters for shower, WC and tap water use while simultaneously evaluating the normed simulated flow profile to the normed validation data sets.
4. The temperature profile diurnal shape was matched to the measured profile from Linköping by changing the probability function parameters for shower, WC and tap water use. Since the shower contributes the most to higher temperatures, the peaks in the shower use were the key variable for matching the observed times of the temperature peaks. Simultaneously the time of usage profiles for WC and taps were changed to match the points of low temperature and to maintain the flow profile established in step 3.
5. The temperature curve established in step 4 was matched to the measured temperature by adjusting the volume (mean flow and duration parameters) distribution between shower and tap water use, as well as the mean temperature for tap water use.

Scenarios

Two scenarios for evaluating heat recovery potential are defined, both based on a theoretical housing area with 1,000 inhabitants in Linköping. Heat recovery potential is investigated for the property level, where the recovered heat is used to pre-heat cold tap water before further heating for use as DHW. A simple heat exchanger model is used, described by Equations (2)–(5) (Geankoplis 1993).

$$q = \varepsilon_{hex} \cdot C_{\min}(T_{\mathrm{h,in}} - T_{\mathrm{c,in}}) \tag{2}$$

$$C_{\min} = \min_{i=c,h} (\dot{m} \cdot c_{\mathrm{p}})_i \tag{3}$$

$$T_{\mathrm{h,out}} = T_{\mathrm{h,in}} - \frac{q}{(\dot{m} \cdot c_{\mathrm{p}})_{\mathrm{h}}} \tag{4}$$

$$T_{\mathrm{c,out}} = T_{\mathrm{c,in}} + \frac{q}{(\dot{m} \cdot c_{\mathrm{p}})_{\mathrm{c}}} \tag{5}$$

where q is the actual heat transfer [kW]; ε_{hex} is the effectiveness of the heat exchanger [–]; $C_{\min}$ is the minimum heat capacity [$\mathrm{kW \cdot K^{-1}}$]; $T_{i,j}$ is the water temperature [°C]; $\dot{m}_i$ is the mass transfer rate [kg/s]; and c_{p} is the heat capacity [$\mathrm{kJ \cdot kg^{-1} \cdot K^{-1}}$]; index i indicates hot (h) or cold (c) media; index j indicate input (in) or output (out) to heat exchanger.

In Scenario 1, the tap water originates from a surface water source (as in Linköping), with seasonal fluctuations in tap water temperature. In Scenario 2, the tap water is assumed to instead originate from a groundwater source with small seasonal fluctuations. For Scenario 2, the groundwater temperature is assumed to be constant at 7.5 °C, corresponding to the mean air temperature in Linköping during 2017. The simulations are run for a period of one year, with daily data from January 2017 until January 2018 for the tap water temperature in Linköping as input to Scenario 1 (the temperature profile for the full year can be seen in Figure 1) and evaluated for energy demand, heat recovery and temperature loss in the wastewater. The demand and temperature of hot water at each time step is assumed equal to the hot water use calculated from the model.

Many types of heat exchangers are available for heat recovery from wastewater (Arnell *et al.* 2017), where two of the most cited types for use at the property level are vertical inline drain heat exchangers and horizontal counter-flow tube heat exchangers. A good estimate of the heat exchanger effectiveness ($\varepsilon_{\mathrm{hex}}$) is important for a correct estimate of heat

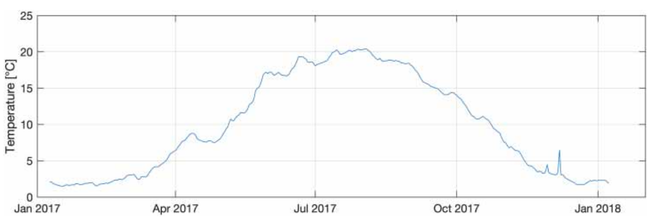

Figure 1 | Tap water temperature in Linköping from January 2017 until January 2018.

recovery potential. Wallin & Claesson (2014) report a $\varepsilon_{\mathrm{hex}}$ value of 0.44–0.52 for vertical inline drain heat exchangers. Horizontal counter-flow heat exchangers reportedly have a $\varepsilon_{\mathrm{hex}}$ value of 0.335 (Soto 2015) to 0.381 (Wallin 2017), where the latter is based on long-time efficiency measurements at a property in Stockholm. For more detailed information about differences between the horizontal and vertical wastewater heat exchangers, see for example Arnell *et al.* (2017). For the scenarios in this paper, the heat recovery is calculated using $\varepsilon_{\mathrm{hex}} = 0.335$–$0.52$ to include a range of possible values. The total heat demand for domestic hot water (DHW) is also calculated from the simulation results and compared to literature values.

RESULTS AND DISCUSSION

Calibration and validation

The results from fitting of the model (Equation (1)) to the measured PDFs, as well as the PDFs after calibration, are shown in Figure 2. The model fits the measured data well, with mostly minor changes needed in the calibration phase to match the calibration and validation data sets. The PDF for shower use during workdays needed a more substantial change, resulting in an attenuated peak that occurs later in the morning (which is expected from a larger number of people with different habits).

Mean water use from the sewer measurements in Linköping and calibration is showed in Table 3. The measured mean water use (186 $\mathrm{L \cdot person^{-1} \cdot d^{-1}}$) is similar to values measured in multi-family buildings by the Swedish Energy Agency (2009) for 110 households with 148 residents. The calibrated simulated water use conforms well to the measured volume as well as the value from the Swedish Energy Agency (2009), including also the fraction of water that is hot water.

The model describes the daily variations in flow and temperature well, as can be seen in Figure 3. Large variations can be seen in the data as the number of days of successful monitoring is limited ($n = 5$ for workdays and $n = 2$ for weekend days). This was due to problems with the flow sensor (clogging). When compared to the validation data sets, the normed flows as seen in Figure 4(a)–4(d), the diurnal flow variation fits well. Although the suggested calibration procedure can be used for good model predictions of the total wastewater production as well as temperature, uncertainty will remain in the calibrated values for shower use and tap water use if those values are

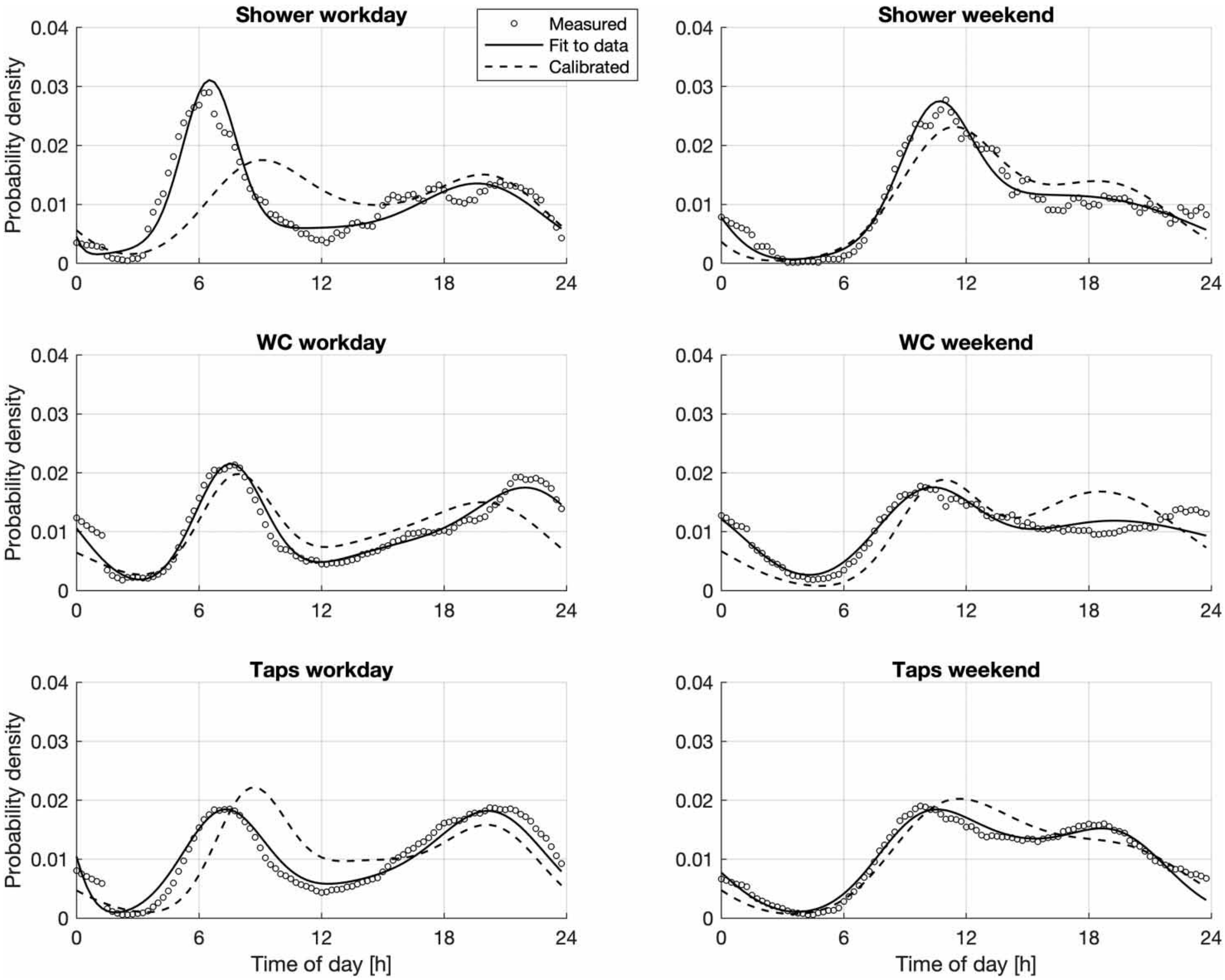

Figure 2 | PDF for time of use calculated from measured data and model fit to the data (before calibration) as well as calibrated values. The data includes shower, WC and tap use during workdays and weekends.

Table 3 | Mean water use during measurements and calibration of model

Target	Unit	Reference value	Calibrated value	Reference
Total water use	$L \cdot person^{-1} \cdot d^{-1}$	186; 184	184	Measured; Swedish Energy Agency (2009)
	$m^3 \cdot d^{-1}$	51.8	51.3	Measured
Hot water use	$L \cdot person^{-1} \cdot d^{-1}$	58	55.6	Swedish Energy Agency (2009)
Fraction of total water use	–	0.315	0.302	Swedish Energy Agency (2009)

not in a reasonable range as the calibrated values are no longer actual statistics or individual measurements. For this work, the calibrated values obtained are deemed in a reasonable range when compared to available statistics.

The simulated fraction of water use that is hot water does not fit well with the measurements from Karlstad (Figure 4(e) and 4(f)). The general shapes of the curves are similar but with an offset of 10–20 percent of the total water use, apart from the peak at noon for weekends. This offset can depend on several factors, mainly the cold tap water temperature and the hot water temperature in the heater, as well as a result of differences in water use. In

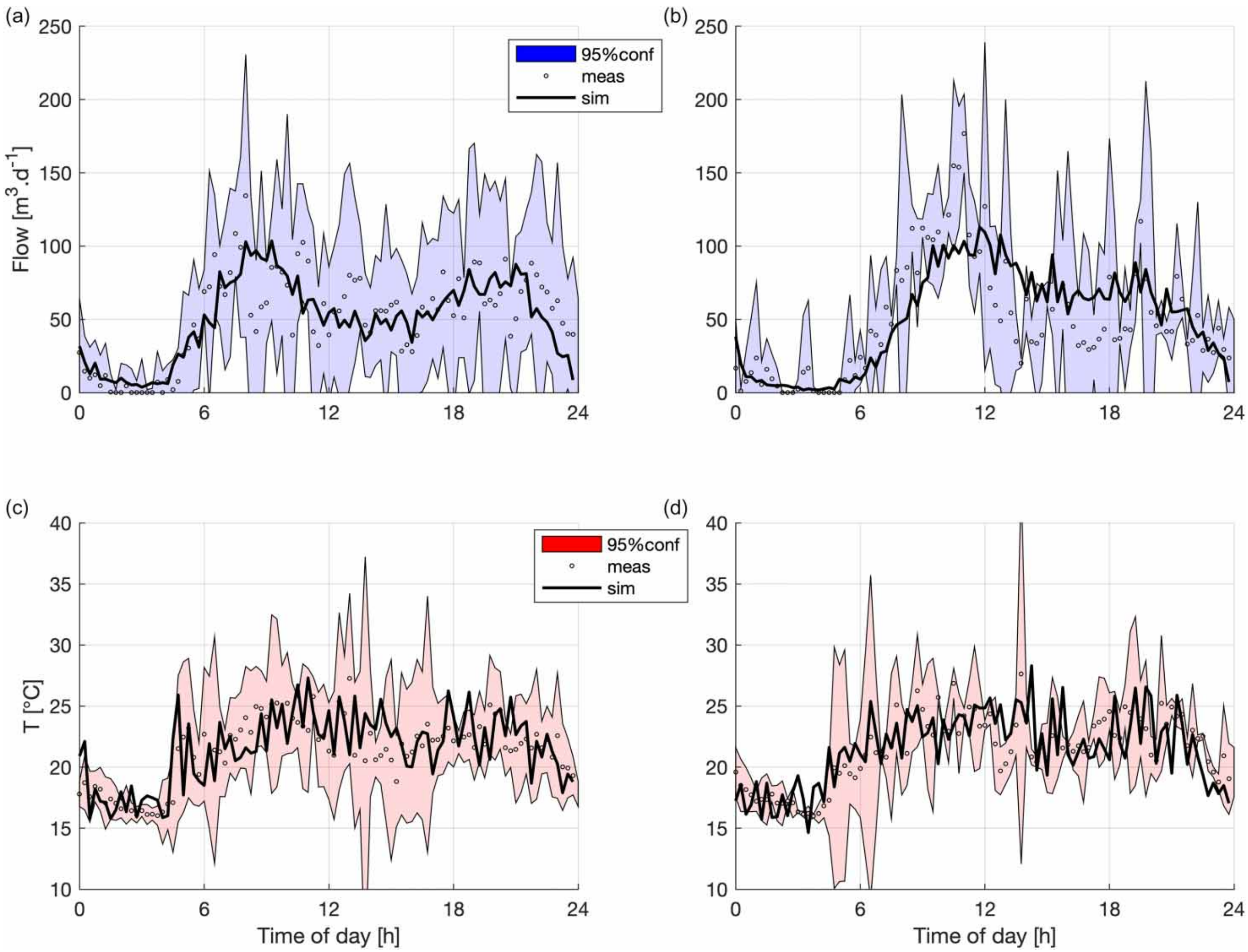

Figure 3 | Simulated median flow compared to measured median flow and 95 percent confidence intervals for measurements. Flow measurements performed in Linköping, Sweden.

the apartments in Karlstad the mean water use is roughly $100\,\mathrm{L}\cdot\mathrm{person}^{-1}\cdot\mathrm{d}^{-1}$, which is only around half of the measured consumption in Linköping. A possible explanation for this difference is that the apartments in Karlstad have individual water meters installed and are also billed individually for water that is consumed within the actual apartment. This can make the inhabitants more aware of their water use and impose lower consumption.

Scenarios

Relevant aggregated results from the two scenarios are presented in Table 4, while the monthly results are presented in Figure 5. Several results are presented as intervals according to the simulated intervals for $\varepsilon_{\mathrm{hex}}$.

The results from Scenario 1 are shown in Figure 5(a) and 5(c), with the temperature in and out from the heat exchanger as well as the temperature drop (a), the recovered heat and mean DHW heat demand (c). On a yearly basis, $3.2\,\mathrm{kWh}\cdot\mathrm{person}^{-1}\cdot\mathrm{d}^{-1}$ is needed for DHW heating of which 11.3–17.5 percent can be recovered from the wastewater in the simulated setup. As expected, the recovery potential is greatest during the winter when the cold-water temperature is at its lowest. The wastewater temperature drop over the heat exchanger is 2.7–4.2 °C as a monthly average during the coldest winter month, corresponding to an outgoing wastewater temperature of 18.0–19.5 °C after the heat exchanger. It should be noted that no differences in water consumption patterns over the year has been implemented.

The results from Scenario 2 are seen in Figure 5(b) and 5(d), with the temperature in and out from the heat exchanger as well as the temperature drop (b), the recovered heat and mean DHW heat demand (d). The monthly averages

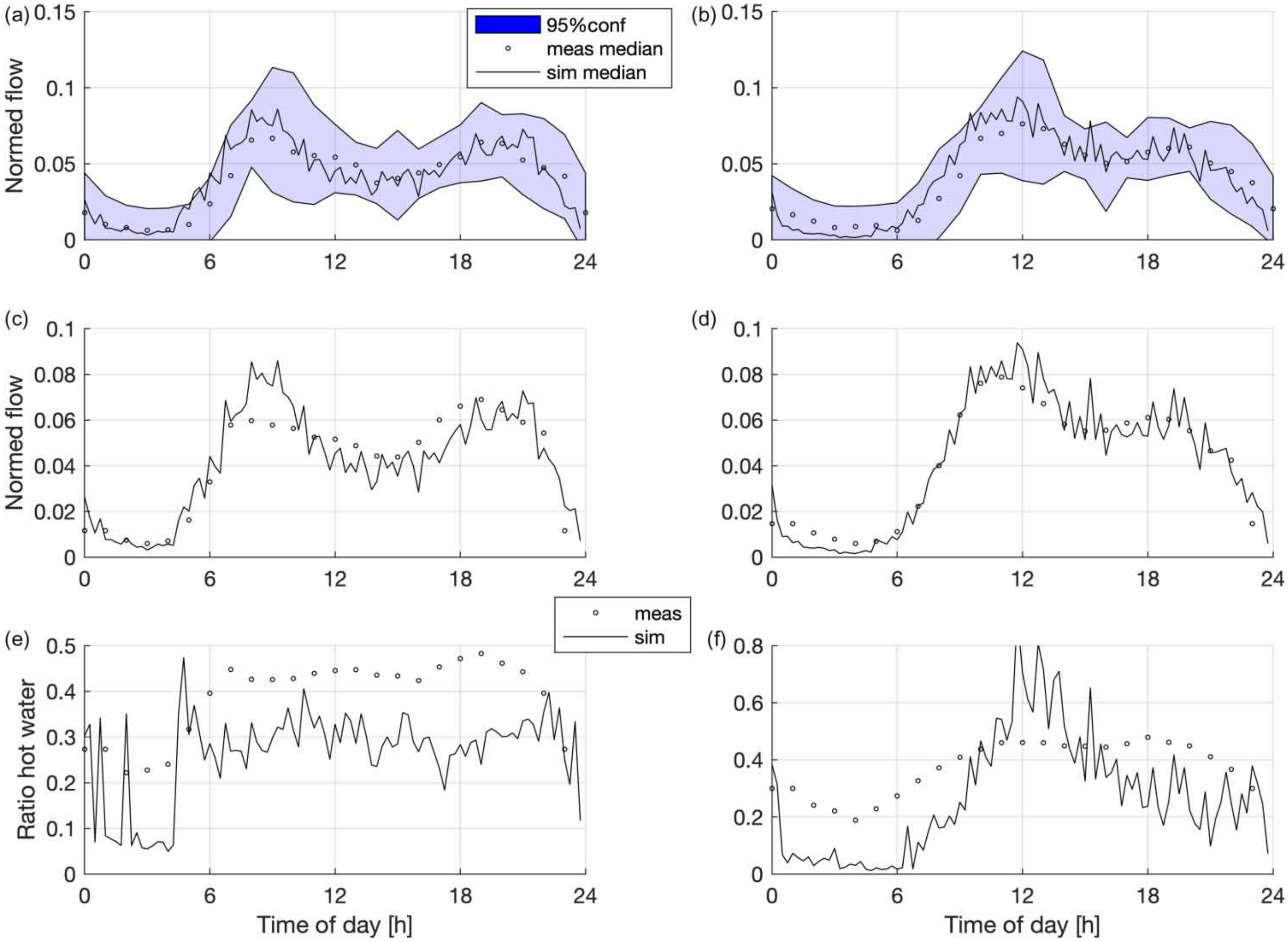

Figure 4 | Normed simulated median flow compared to median values and measured 95 percent confidence intervals for water demand curves from Nikell (1994) for workday (a) and weekend (b), as well as normed simulated median flow compared to normed measured median flow of tap water (workday (c) and weekend (d)) as well as the fraction of water use that is hot water (workday (e), weekend (f)) from measurements in Karlstad, Sweden.

Table 4 | Heat demand, recovered heat, temperature loss over the heat exchanger and outgoing wastewater temperature after the heat exchanger for Scenarios 1 and 2

	Annual DHW heat demand	Annual recovered heat	Ratio of heat demand recovered	$\Delta T_{hex,winter}$ (monthly mean)	$T_{out,hex,winter}$ (monthly mean)
Unit	$kWh \cdot person^{-1} \cdot d^{-1}$	$kWh \cdot person^{-1} \cdot d^{-1}$	%	°C	°C
Scenario 1	3.2	0.37–0.57	11.3–17.5	2.7–4.2	18.0–19.5
Scenario 2	3.6	0.42–0.65	11.6–18.0	1.9–3.0	20.6–21.6

The recovered heat and temperature are given in intervals depending on the assumed effectiveness of the heat exchanger.

are close to constant due to the constant cold tap water temperature, with small differences noticeable due to the stochastic temperature variations in the model. The average domestic hot water energy demand was $3.6\, kWh \cdot person^{-1} \cdot day^{-1}$, with 11.6–18.0 percent recovered. The wastewater temperature drop over the heat exchanger is 1.9–3.0 °C as a monthly average throughout the year, corresponding to an outgoing wastewater temperature of 20.6–21.6 °C after the heat exchanger.

The results are consistent with previous studies in Sweden regarding DHW energy demand ($3.15\, kWh \cdot person^{-1} \cdot day^{-1}$ according to the Swedish Energy Agency (2009)).

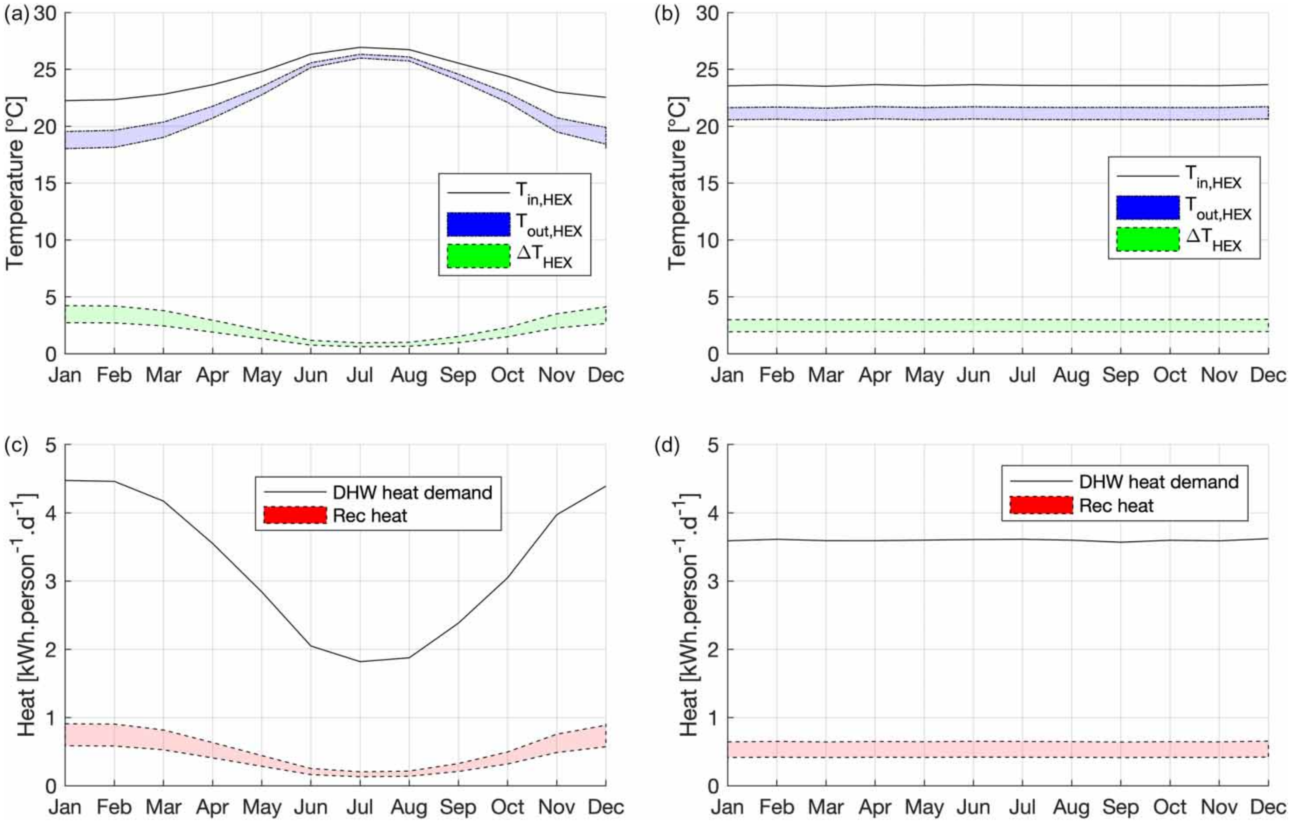

Figure 5 | Wastewater temperature before and after heat exchanger as well as temperature drop for Scenarios 1 (a) and 2 (b), monthly mean recovered heat energy and mean monthly domestic hot water heat energy demand for Scenarios 1 (c) and 2 (d). Intervals represent results for the specified interval for ε_{hex} (0.335–0.52).

CONCLUSIONS

The calibrated model can be used to describe wastewater production, including flow and temperature, from areas with multi-family buildings. The simulated values correspond well to literature values and measurements for cold and hot water use as well as wastewater flow hydrograph and temperature.

As expected, heating demand for domestic hot water, the amount of recovered heat and temperature loss over the heat exchanger are lowest in the summer when a surface water drinking water source is used. Consequently, the opposite situation is found during winter, which is also the time when the wastewater temperature is the most critical and the need for heat recovery the greatest. With the constant tap water temperature, the wastewater temperature loss during winter is not as large, highlighting the impact on the type of water source since a few degrees difference in temperature may have a large impact on the nitrification in a treatment plant. It remains to investigate the subsequent heat losses in the sewer system and the difference in temperature for the same scenarios, but the type of drinking water source and the yearly temperature profile are important factors for utilities when considering allowing wastewater heat recovery.

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