Assessment of the theoretical heat recovery potential from wastewater in sewer systems

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ABSTRACT
The present paper deals with the assessment of the theoretical potential of wastewater in the sewer system for heating of buildings. A classification scheme of the suitability of sewers for the installation of heat exchangers involving criteria like theoretically available heat, sewer diameter, number of the heat exchanger parallel modules in the sewer cross-section, and hydraulic conditions (hydraulic capacity of the sewer, pressurized flow) was developed. First, individual sewers in the pilot catchment were assessed based on monitoring the flow characteristics and wastewater temperatures and on pipe flow modelling. Second, connectivity of the suitable and partly suitable sewers was examined with respect to the length necessary for the installation of the heat exchanger with the minimum required power of 100 kW. For the continuous sewer sections, the maximum potential power was calculated. The presented approach is generally applicable, however, for other heat exchanger types and other climatic and economic conditions, values of the suitability criteria for the heat exchanger installation must be adapted.

KEYWORDS
Heat exchanger; heat recovery; sewer system; urban drainage masterplan

INTRODUCTION
Many countries take aim at strengthening the energetic self-sufficiency and increasing the exploitation of secondary sources of energy, including heat recovery. One of the alternative ways of exploitation of secondary energy sources is the installation of heat exchangers in the sewer system. Wastewater is an energy source exhibiting a stable temperature of 10–20°C all the year round, and thus the heat exchangers installed in the sewer system can be used for heating the buildings or for the combination of winter heating and summer cooling (DWA – M114, 2009). Over 500 wastewater heat pumps with thermal ratings ranging 10–20 MW are in operation world-wide, especially in Switzerland and Germany (Schmid, 2008).

In the Czech Republic, however, wastewater as an energy source for the heat pumps has so far been neglected. The main arguments are the long payback period due to the high acquisition costs and possible impacts of the decrease of wastewater temperature on the wastewater treatment efficiency (especially nitrification and thus nitrogen removal) and operation costs (Wanner et al., 2005).

Therefore the project which arose in the Czech Republic concentrated on the three aspects of the heat recovery from wastewater in the sewer system:

1. Development of a guidance for the conceptual planning of the heat recovery from wastewater in the sewer system at the level of the whole urban catchment,
2. Design of a cost-efficient type of an in-sewer heat exchanger,
3. Development of suitable maintenance techniques in order to reduce heat exchanger fouling and related decrease of the heat recovery (Characklis, 1981; Bott, 1995; Wanner, 2004).

The present paper deals with the assessment of the theoretical potential of the heat recovery from the sewer system for the designed heat exchanger in the pilot catchment. The goal was to develop a classification scheme, as much objective as possible, of sewers suitability for the installation of heat exchangers and to extend the assessment of the theoretical heat recovery potential so as to cover the whole urban catchment.

METHODS

The assessment of the theoretical potential of the heat recovery from the wastewater in the sewer system covered the following steps:

- pilot catchment monitoring,
- re-calibration of the simulation model of the pilot catchment (dry-weather flows),
- specification of the criteria of the sewers suitability for the installation of the heat exchangers,
- evaluation of the individual sewers (sewer reaches) in the pilot catchment based on the individual criteria as well as on their combination,
- evaluation of the whole sewer system.

Pilot catchment monitoring

The pilot catchment is the city of Hradec Kralove (90,000 inhabitants). It is drained by the combined sewer system composed of 8 trunk sewers (A, 1A, B, 1C, C, D, E, and F) running into the interceptor conveying the wastewater to the wastewater treatment plant (WWTP). The total length of sewers is 497 km.

In the pilot catchment one-year monitoring (02/2013–02/2014) of wastewater discharges, wastewater and air temperatures, and of rainfall was performed. The monitoring scheme is given in Figure 1. The monitoring time steps were 6 min for discharges and wastewater temperatures, 1 h for air temperatures, and 1 min for rainfall.

Model re-calibration

The existing sewer system simulation model created in 2005 within the Urban Drainage Masterplan in DHI software MIKE URBAN 2012 was originally calibrated focusing on wet weather flow. Re-calibration of the model for dry weather flow conditions was performed based on the data obtained from the monitoring.

Suitability criteria of the individual sewers for the installation of heat exchangers

The criteria depend to a certain extent on the heat exchanger type and construction. In the framework of the project, a modular plate heat exchanger made of stainless steel was developed. The individual modules (250 × 1800 × 30 mm in size) can be connected in series and installed in parallel in the sewer. The construction of the heat exchanger facilitates also its installation in curved sections of the sewer system.

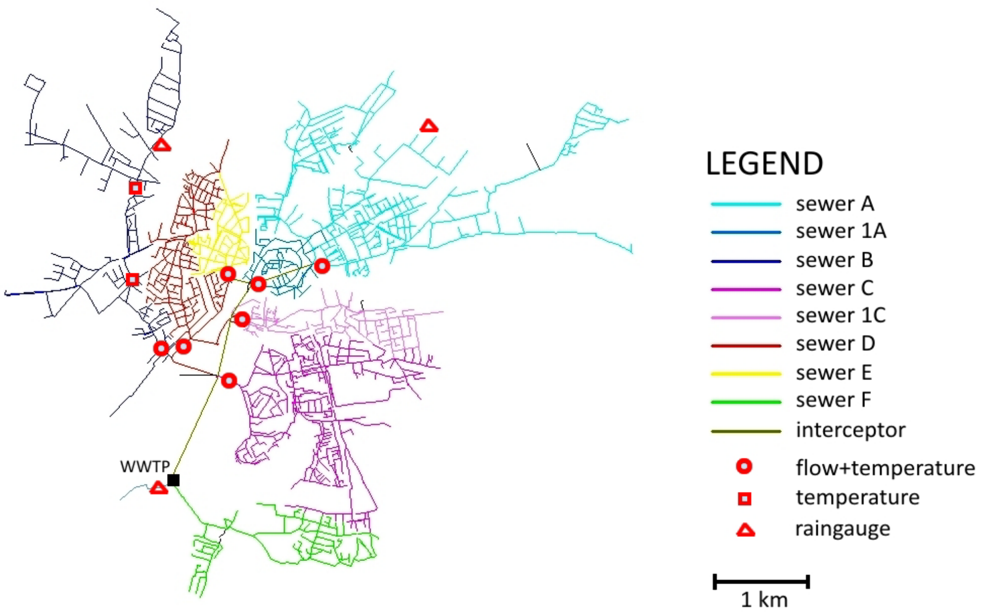

Figure 1. Situation map of monitoring in the pilot catchment

For the heat exchanger designed, the following main criteria influencing the possibility of its installation and of the amount of the heat recovered were specified:

- theoretically available heat,
- sewer diameter,
- number of the heat exchanger parallel modules in the sewer cross-section,
- hydraulic conditions (hydraulic capacity of the sewer, pressurized flow).

Theoretically available heat. Value of the theoretically available heat in the individual sewer reaches W_{WT} (kW) can be calculated as:

$$W_{WT} = c \,.\, \rho \,.\, Q \,.\, \Delta T \quad (1)$$

where c (kWs.kg^{-1}.°C^{-1}) is the specific heat capacity of wastewater (for 0–20°C temperatures a constant value of 4.19 kWs.kg^{-1}.°C^{-1} can be assumed), ρ (kg.l^{-1}) is the wastewater density (for 0–20°C temperatures constant value of 1 kg.l^{-1} can be used), Q (l.s^{-1}) is the wastewater discharge, and ΔT (°C) is the difference between wastewater temperatures upstream T_1 (°C) and downstream T_2 (°C) of the heat exchanger.

It is apparent from Eq. 1, that important factors influencing the available heat are the wastewater discharge Q and the exploitable temperature difference ΔT.

For Q, the average daily discharge during the heating season (period from September, 1st to May, 31st) was used. Its values in individual sewers were obtained from the simulation model calibrated for dry-weather flows.

The higher the wastewater temperature T_1 and the higher its admissible cooling, the more energy can be recovered. The values of T_1 adopted are the average daily temperatures of wastewater during the heating season expressed at a 95% lower confidence limit. The data were obtained by monitoring in closing profiles of the trunk sewers of the pilot catchment.

For the evaluation, the temperatures were assumed to be constant along the trunk sewer. This assumption is on the safe side (Wanner, 2004; Monsalve, 2011). The value of the minimum admissible wastewater temperature after cooling by the heat exchanger T_2 is 8^{o}C. It corresponds to the average daily temperatures of about 12°C in the pilot catchment (Table 1).

Table 1. Statistically evaluated data from monitoring of trunk sewers closing profiles

Flow and temperature characteristics			A	1A	B	C	1C	D	E
Q	mean value	($l.s^{-1}$)	60	26	58	61	27	65	31
T_1	mean value	(^{o}C)	12.9	13.4	12.1	14.8	13.7	14.1	13.8
	95% lower confidence limit	(^{o}C)	7.6	9.9	8.6	10.3	8.9	10.9	9.6

Sewer diameter. This criterion takes into account the possibility of an installation of the heat exchanger and its accessibility for the maintenance and biofilm removal. The data for the pilot catchment were obtained from the GIS of the sewer system.

Number of parallel modules of the heat exchanger. The number of the parallel modules, which can be installed in a sewer cross-section, depends on the minimum daily water depth of wastewater H_{min} and on the sewer diameter (Table 2). When more parallel modules are installed, minimally a 400 mm walk-through space must be ensured (Figure 2). Necessary information was gained from the simulation model calibrated on dry-weather flows.

Table 2. Number of parallel modules of the heat exchanger for different ranges of minimum daily water depths in circular pipes

Diameter of circular pipe (mm)	No. of parallel modules of the heat exchanger 0	1	2	4
	range of minimum daily water depths (mm)			
800	< 50	50–266	267–511	> 51
1000	< 45	45–223	224–451	> 451
1200	< 43	43–193	194–397	> 397
1500	< 40	40–162	163–335	> 335
2000	< 37	37–129	130–265	> 265

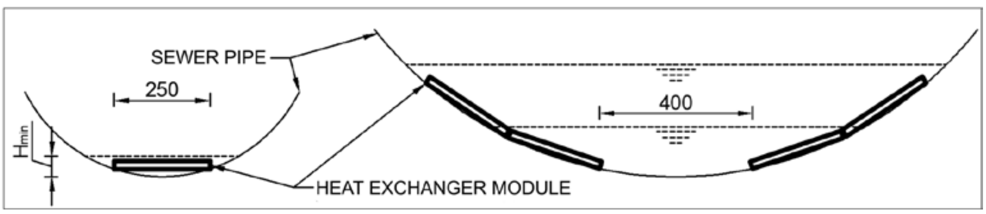

Figure 2. Scheme of the heat exchanger installation (left: 1 module, right: 4 parallel modules)

Hydraulic conditions. Heat exchangers should not substantially decrease the hydraulic capacity of the sewer and should not be installed in overloaded sewers. The analysis of the sewer system in the pilot catchment was performed using the original simulation model calibrated for wet weather discharges for a 10-year rainfall series.

Classification. Numerical values of the criteria and classification of the sewers suitability for the installation of heat exchangers are presented in Table 3. The limiting value of the available heat of 100 kW is based on the economic efficiency (Müller and Butz, 2010). The final classification is determined by the worst value of the individual criteria.

Table 3. Suitability criteria of sewers for the installation of heat exchangers

Criterion		Suitability classification		
		unsuitable	partly suitable	suitable
Theoretically available heat	(kW)	< 100	---	≥ 100
Sewer diameter	(mm)	< 800	800–1200	> 1200
Parallel modules	(number)	0	1	> 1
Hydraulic capacity decrease	(%)	> 5%	---	≤ 5%
Pressurized flow	(frequency)	> 1 per 2 years	---	≤ 1 per 2 years

Evaluation of the whole sewer system

For the whole sewer system it is decisive if the suitable and partly suitable sewers are connected so that their length is sufficient for the installation of the heat exchanger with the minimum required power of 100 kW. If not, these sewer reaches are further classified as unsuitable. The power of the heat exchanger P_{WT} (kW) can be estimated by the following equation where literature values (DWA – M114, 2009) for the unknown coefficients are used:

$$P_{WT} = k \, . \, f \, . \, A_{WT} \, . \, \Delta T^{*} \qquad (2)$$

where k (kW.m^{-2}.°C^{-1}) is heat transfer coefficient and its value is assumed to be 0.75, f (-) regards the decrease of the heat transfer due to the surface fouling and its value is assumed to be 0.80, A_{WT} (m^2) is the heat exchanger surface area calculated as the multiple of the number of parallel modules, exchanger width b (m) and length L (m). ΔT^{*} (^{o}C) can be calculated as:

$$\Delta T^{*} = T_1 - (T_{sec}^{out} - T_{sec}^{in}) \qquad (3)$$

where T_{sec}^{in} (^{o}C) and T_{sec}^{out} (^{o}C) are temperatures of the secondary medium at the heat exchanger inlet and outlet, respectively. In order to ensure effective functioning of the heat exchanger, ΔT^{*} should be in the range of 3–4^{o}C (the value of 3.5^{o}C was used in calculations).

RESULTS AND DISCUSSION

Theoretical heat recovery potential of individual sewers

Individual criteria. Evaluation of the sewers in the pilot catchment based on individual criteria of the heat recovery potential is summarized in Table 4. Hydraulic conditions were assessed only for sewers with the theoretically available heat ≥ 100 kW and were not limiting in any case. The most stringent criterion was the theoretically available heat, the least stringent one was the sewer diameter. Thus, for practical reasons, it can be recommended to start the evaluation either from the most stringent or from the most easily evaluatable criterion and further progress to other criteria.

Table 4. Classification of the suitability of sewers for the installation of heat exchangers in the pilot catchments according to the individual criteria

Suitability classification	theoretically available heat		sewer diameter		parallel modules	
	No. of sewers	length (m)	No. of sewers	length (m)	No. of sewers	length (m)
Suitable	182	10,742	293	17,920	25	1,851
Partially suitable	---	---	611	37,597	460	24,597

Criteria combination. The evaluation of the sewers in the pilot catchment for the combination of all criteria is visualized in Figure 3. Total length of the reaches suitable for installation of the heat exchangers is 642 m, of the partly suitable reaches 8,645 m. The highest potential was identified in the downstream parts of the trunk sewers B, C, and D.

Figure 3. Suitable and partly suitable sewers for the heat recovery in the pilot catchment

Theoretical heat recovery potential of the whole sewer system

Assessment of connectivity of the individual sewers identified as suitable or partly suitable revealed that they are connected at the trunk sewers B, C, and D whereas other trunk sewers (1A and 1C) are interrupted by short reaches of either small diameter or insufficient water depth where the heat exchangers cannot be installed. Evaluation of suitability of all continuous trunk sewers sections for the heat recovery enhanced for the estimated potential power of heat exchangers according to Eq.2 and Eq. 3 is summarized in Table 5. The final total length of the reaches suitable for installation of the heat exchangers remained 642 m, that of the partly suitable reaches decreased by 215 m – to 8,430 m. Trunk sewers sections where the heat exchangers can be installed can be seen in Figure 4.

Table 5. Classification of suitability of continuous sewer sections of the trunk sewers in the pilot catchment for the installation of heat exchangers and estimation of their potential power

SEWER		Total length *L* (m) suitable	Total length *L* (m) partly suitable	P_{WT} (kW)	Installation potential
1A		0	7	4	no
B		0	1073	563	yes
C	C1	0	393	206	yes
	C2	70	814	501	yes
	C3	0	499	262	yes
	C4	0	725	381	yes
	C5	0	1167	613	yes
1C	1C1	0	361	190	yes
	1C2	0	967	508	yes
	1C3	0	129	68	no
	1C4	0	45	24	no
	1C5	0	34	18	no
D		484	2117	1620	yes
D + B		22	23	35	yes
E		66	291	222	yes[1]

[1]section connected to upstream trunk sewers B and D with identified potential

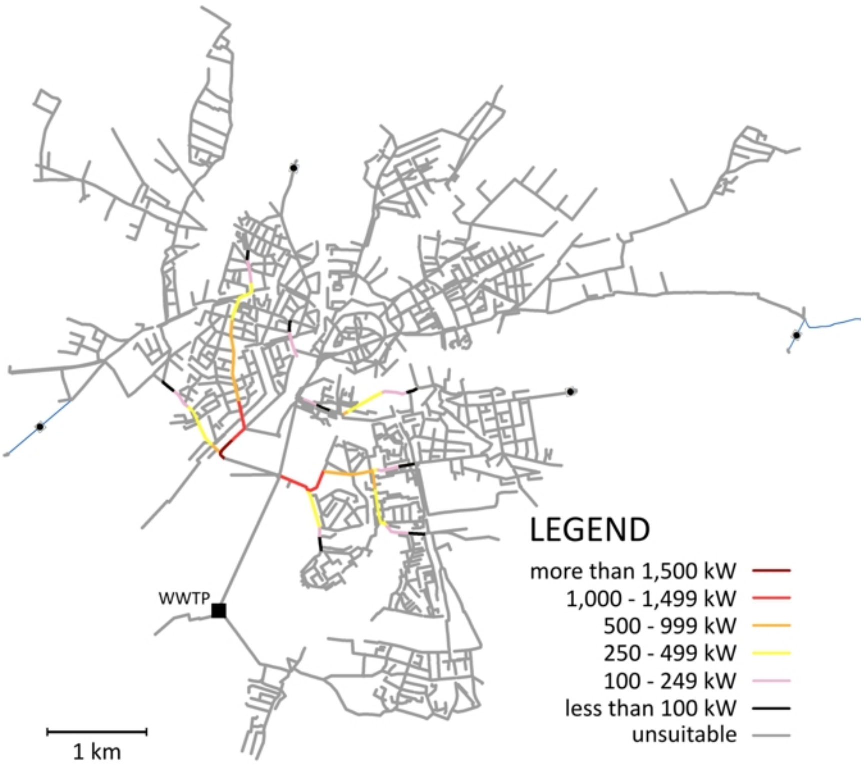

Figure 4. Available power of the heat exchangers in the pilot catchment. The colour scale distinguishes the maximum potential power of the heat exchanger supposing it is installed in the upstream direction along the whole section. Reaches where the heat exchangers installation can be performed only on condition it starts at the reach exhibiting the potential power of at least 100 kW are indicated in black.

Maximum amount of heat recoverable from the whole sewer system depends on the admissible decrease of temperature at the WWTP inflow. A value of 0.5°C is considered the admissible drop of wastewater temperature still not affecting the WWTP efficiency (Wanner et al., 2005; DWA – M114, 2009). This corresponds to the maximum possible installed power of the heat exchangers (about 700 kW) providing heat of 16.3 TJ per heating season, representing thus 2.2% of the total heat consumption in the pilot catchment. In the Czech Republic, the current price for this amount of heat if produced by a central heating plant, would be ca. 360,000 EUR.

CONCLUSIONS

The presented approach to the assessment of the theoretical heat recovery potential from wastewater in the sewer system is generally applicable, however, for other heat exchanger types and other climatic and economic conditions, values of the suitability criteria for the heat exchanger installation must be adapted.

Temperature and discharge characteristics in the individual sewers used for the identification of the theoretical heat recovery potential are biased by uncertainties as the monitoring and dry weather flow model calibration were performed only for the closing profiles of the trunk sewers. Thus, every heat exchanger project should be preceded by a seasonal monitoring of temperatures and discharges at the installation site and their statistical evaluation.

Further steps of the project will include determination of the realizable potential of the heat recovery from wastewater combining information on suitable users (based on the distance from the sewer system and on energy demand), on the economic efficiency and on boundary conditions given primarily by the admissible decrease of wastewater temperature regarding the wastewater treatment efficiency and costs (different levels of temperature decrease and relationship to the wastewater treatment will be investigated).

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