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Upstream heat recovery impacts on Käppala WWTP performance – Model-based analysis combining sewer tunnel and WWTP

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Contents

Background

Heat recovery from wastewater is increasingly gaining interest in Sweden. A significant portion of the heat energy used for heating tap water reaches the sewer system (Olsson, 2012). With increasing heat recovery installations at households and precincts, the effect of such upstream installations on temperature at wastewater treatment plant inlet and subsequently its impact on nitrogen removal, especially during winters becomes an important aspect to consider. This is an internal report in the research project Sustainability Analysis of Wastewater (WW) Heat Recovery (WWHR) – Hållbarhetsanalys av värmeåtervinning ur avloppsvatten (HÅVA), in Swedish

This report aims at understanding the impact of upstream heat recovery (households, in-sewer heat pump installations etc.) on the Käppala wastewater treatment plant (WWTP) performance. A unique aspect at Käppala and increasingly at other cities in Sweden is the relatively large sewer tunnels that connect the trunk sewers to WWTPs. This report also attempts to describe the heat transfer phenomena in these sewer tunnels. Finally, during the process of data collection and processing for modelling the sewer tunnel, several data measurement issues were noticed. These are discussed in this report. Despite the limited data, the model developed throws light on the temperature variations in the sewer tunnel and the potential impact of future heat recovery installations on nitrogen removal at the WWTP.

The report first describes the models used followed by the case study description for sewer tunnels and WWTP. Finally, the scenarios for WWTP evaluation are detailed. Results from the case studies are discussed and an overview of the data collection issues noticed is given.

Model description

Sewer tunnel model

The model describes temperature variations in sewer systems using energy balance equations for the major heat transfer processes in sewer systems - conduction, convection and biochemical heat generation) (Abdel-Aal et al., 2014, 2018; Saagi et al., 2019).

A mechanistic model that can estimate heat transfer phenomena based on energy balances for the different heat transfer processes as well as a detailed hydraulic model is available. Additionally, when limited data is available, a conceptual modelling approach that combines all the heat transfer processes into a single energy balance equation is also developed. In this approach, the flow rate is also modelled conceptually as a series of reservoirs (without the need for extensive sewer infrastructure data like diameters, slopes etc.). Both the approaches can be used to simulate gravity as well as pumped sewer systems.

Wastewater treatment plant model

Activated sludge models are used to describe the biological processes (ASM1) (Henze et al., 2015). The primary clarifier is modelled using Otterpohl & Freund (1992). Takacs's settler model approach (Takács et al., 1991) is used to describe the secondary settlers. A point settler is used to model the sand filters. The anaerobic digesters are modelled using ADM1 (Batstone et al., 2002). Other physicochemical processes (thickeners, dewatering units etc) are modelled using the BSM2 plant-wide model libraries (Gernaey et al., 2014). The model has been calibrated and validated from an earlier project (Arnell, 2016).

Since, the WWTP is located underground, no heat transfer processes like solar radiation, convection due to wind etc. that govern the temperature variations are included.

Case study details

Sewer tunnel

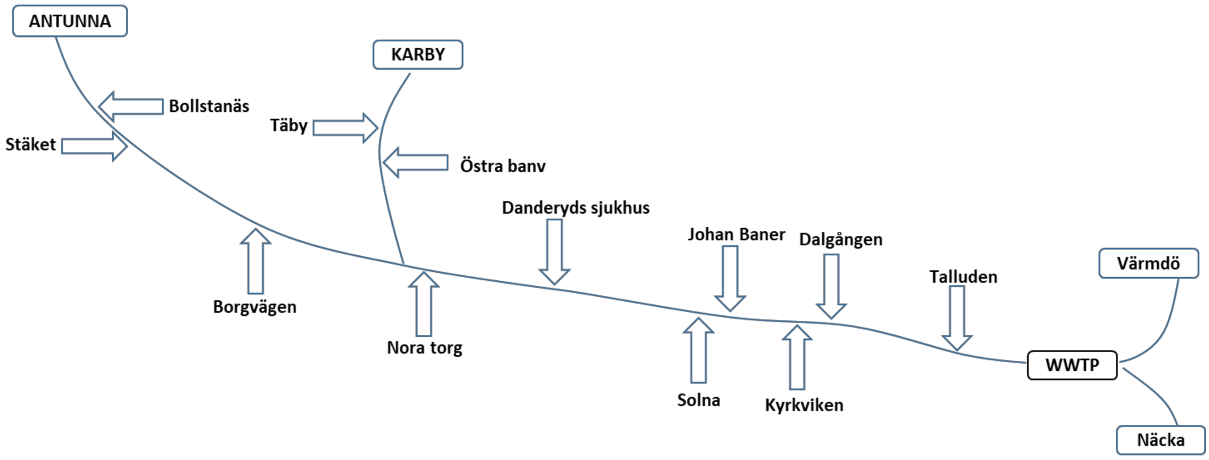

*Figure 1: Käppala sewer tunnel layout and the key inlet points (including sea links).*The drawing is representational and is not scaled. Only the locations included in the study are represented.

The tunnel system represented in Figure 1 connects the trunk sewers from different parts of the city to the wastewater treatment plant. Multiple inlet points exist for the tunnel system. Antuna pumping station is considered as the furthermost inlet. Major inlet points with high flow rates are included in the model while the smaller ones are excluded. List of all the inlet points considered in the model are mentioned in Table 1. The tunnel also has pumping stations along the way (Edsberg, L-STR). The location Verket in the figure is the Käppala WWTP. In addition, two sea links (Värmdö and Nacka) are also connected to the WWTP. The wastewater is pumped through two under-sea tunnels, each with two parallel pipes. In the case of Värmdö, only one pipe is operated at any given time while both the pipes are operated in parallel for the Nacka sea link.

Temperature and flow rate measurements are available at several locations in the tunnel and at the WWTP inlet. These measurements are used as inputs to the model. Out of the 17 inlets, Solna did not have flow rate data for the simulation period while a total of 14 inlets did not have temperature data for January 2019. For August 2019, 13 inlets did not have temperature data. Temperature data from Stäket, Täby and Nacka pipe 1 are used for several locations. For the sea links from Värmdö and Nacka, flow rate measurements are available at the downstream location near the WWTP. Hence, the downstream flow rate is used as upstream data for the model. Since, it is a pumped system, the upstream and downstream flow rates will be similar. However, temperature data is only available for one of the pipes in the sea link from Nacka to the WWTP. Hence, the same temperature is used as input for all the three sea link inlets. In total, the amount of flow rate with assumed temperature values is very high and can have an impact on the simulation results.

Table 1: Summary of the inlet points and data availability for the sewer tunnel.

No	Inlet location	Flow rate availability	Mean flow rate (l/s)		Temperature availability	Mean temperature °C)	
			Jan 2019	Aug 2019		Jan 2019	Aug 2019
1	Antuna	Yes	220	211	Yes (Aug 2019), Stäket (Jan 2019		16.7
2	Stäket	Yes	99	99	Yes	9.7	16.5
3	Bollstanäs	Yes	24	17	Stäket		
4	Borgvägen	Yes	18	18	Stäket		
5	Karby	Yes	92	79	Taby		
6	Täby	Yes	22	12	Yes	9.4	14.8
7	Östra banv.	Yes	115	111	Taby		
8	Nora torg	Yes	26	20	Taby		
9	Danderyds sjukhus	Yes	15	13	Taby		
10	Johan baner	Yes	65	52	Taby		
11	Solna	2017 data	293	231	Taby		
12	Dalgången	Yes	14	12	Taby		
13	Kyrkviken	Yes	56	44	Taby		
14	Talluden	Yes	4	3	Taby		
15	Nacka- Pipe1	No (downstream flow rate available)	67	53	Yes	8.8	15.5
16	Nacka Pipe 2	No (downstream flow rate available)	74	62	Nacka Pipe 1		
17	Värmdö	Yes	76	62	Nacka Pipe 1		
18	Verket (WWTP)	Yes	1485	1355	Yes	11.9	17.2

Wastewater treatment plant

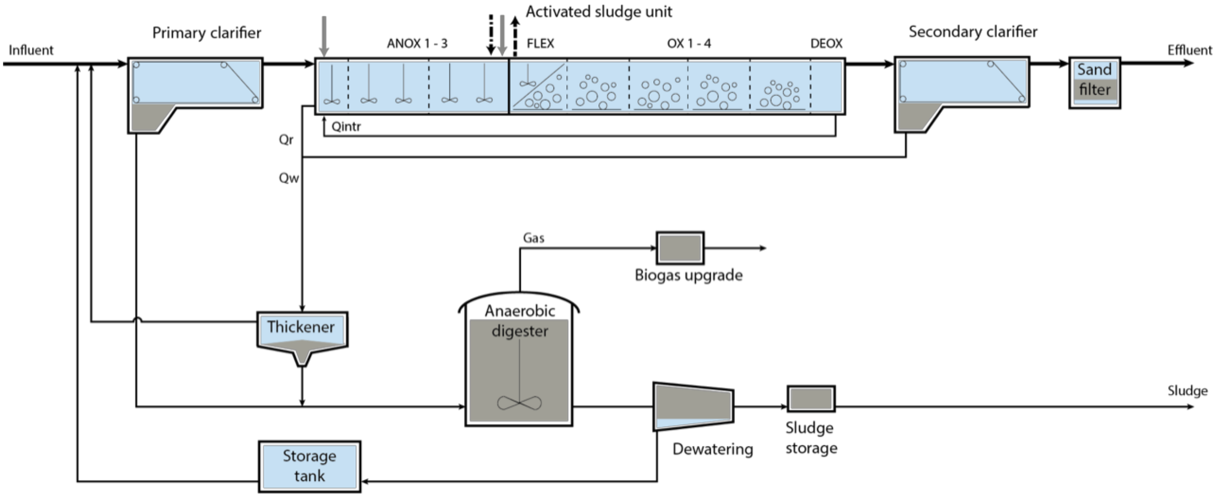

Figure 2: Käppala WWTP layout (Arnell, 2016) used for the scenario analysis representing the water line and sludge line.

The WWTP consists of a primary clarifier followed by biological reactors and secondary settler. Sand filters provide additional polishing after the secondary clarifiers. The sludge line includes thickeners that compress the sludge from both primary and secondary clarifiers before sending them to the digesters. 36% of the primary sludge is thickened using gravity thickeners and the rest doesn't need any thickening. The sludge from secondary clarifiers is thickened using centrifuges. The reject water from anaerobic digesters is fed back to the water line before the primary clarifier (Figure 2). It is important to note that the model used in the analysis only simulates the new section of the WWTP.

The mean pollutant loads used for the simulation are mentioned in Table 2. These are based on actual WWTP data from 2018. For the simulation study, only the lines 7 to 11 are considered.

Table 2: Average influent concentration used for the simulation study. Note that the data is from 2018.

Pollutant	Average concentration	
	Jan 2019	Aug 2019
Total COD (g/m^3)	394	539
NH_4-N (gN/m^3)	21	30
TN (gN/m^3)	34	50
NO_3-N (gN/m^3)	0.4 (assumed)	0.4 (assumed)

Scenarios

Three different scenarios are simulated for both summer (August 2019) and winter (January 2019) periods. The temperature inputs to the sewer tunnels are altered to model the scenarios. The basis for a maximum of 3 °C drop in temperature is from the other case studies where we noticed that upstream heat recovery (at showers, household level) has limited influence on the WWTP influent temperature compared to heat recovery at a precinct level or at sewer pumping stations. In that regard, a 3 °C drop is higher than the expected temperature drop noticed from the scenario analysis in Linköping and Malmö case studies.

1. SC1 – 1 °C drop in temperature at all sewer inlets

2. SC2 – 2 °C drop in temperature at all sewer inlets

3. SC3 – 3 °C drop in temperature at all sewer inlets

Results

The simulations and scenario analysis are carried out for both the periods (Jan 2019 and August 2019). The analysis of results for January 2019 is presented in the text here and similar graphs/tables for August 2019 are included in Appendix 1.

Data analysis for the sewer tunnel measurements

In order to verify the data quality for the flow rate measurements from Antuna, Stäket and Bollstanäs, the flow rate from the Edsberg pumping station is compared to the total flow from the three upstream points (Antuna, Stäket and Bollstanäs). Figure 3a indicates that the flow rate at Edsberg is several times higher than the total upstream flow. While there may be some other minor upstream inlets that are ignored, it is not possible to have such a huge discrepancy. Flow rate data from Edsberg is not recorded during the winter period and hence could not be used for the analysis. The flow rates of the upstream inlets are considered more reliable and used in the modelling study. The flow rate at the second pumping station L-STR also does not match with the total upstream flow (Figure 3b). Finally, a comparison was made between the total incoming flow rate (upstream tunnel inlets and the sea link inlets) with the measurements at WWTP inlet (Figure 3c). Results indicate a good match despite the missing flow rate at the Solna inlet (for which flow rate data from 2017 is assumed). Hence, flow rate data quality at the upstream inlets and the sea links is considered satisfactory for the simulation study.

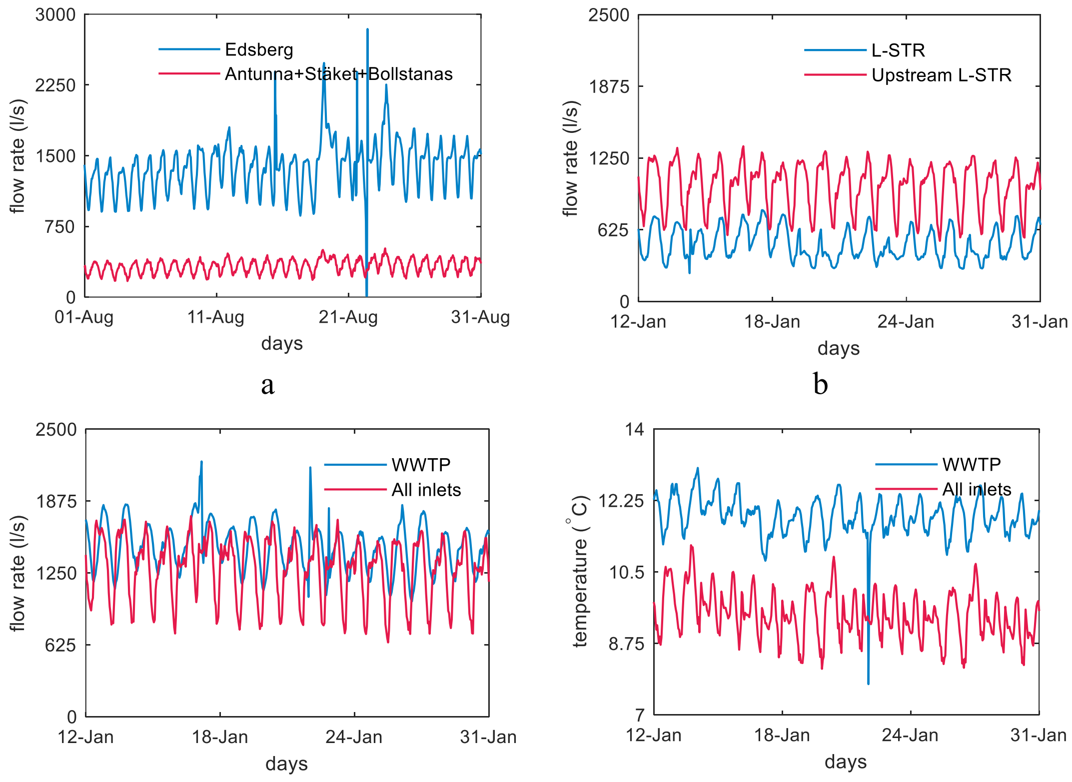

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Figure 3: Data analysis for the sewer tunnel.

Secondly, the temperature measurements at the WWTP are compared to the flow-weighted temperature from all the upstream points (Figure 3d). The temperature for all the upstream points together (assuming that they are all mixed at the same point) is lower than the WWTP temperature. This is difficult to explain as, in general, there is a drop in temperature as we move downstream in a sewer pipe. In exceptional cases, there can be an increase in temperature, but we did not have enough information to reach this conclusion. It should be noted temperature measurements are not available for all the upstream points. Only 3 of the 17 inlets (including the sea links) have temperature measurements and the same values are used for the rest of the inlets (from the closest available location). This weighs heavily on the uncertainty in the simulation results.

Model calibration – Sewer tunnel

The model calibration for the sewer model is carried out by first calibrating the conceptual flow rate model by identifying the number of reservoirs in series and the residence time constant for each reservoir. This is done using a trial-and-error approach to achieve a reasonable model fit for the influent flow rate at the WWTP (Figure 4a). The model reproduces the daily variations and the timing of the peaks, but the average flow rate prediction is lower than the actual data. Considering the uncertainties in the upstream flow rate data, this is regarded as a satisfactory fit.

For the temperature model, the heat transfer parameters for the conceptual sewer model for the gravity system are calibrated to achieve a reasonable temperature prediction at the WWTP inlet. For the pumped sewer stretches, the default parameters from (Saagi et al., 2019) are used. As noticed in the earlier analysis (Figure 4b), the temperature measurement at WWTP is higher than the upstream temperature, which is not feasible. Hence, a temperature bias in introduced to increase the temperature at all inlet points (Jan 2019: 2.2 °C; Aug 2019: 1.5 °C). The temperature corrected model prediction gives a very good model fit. The sewer model predictions without the temperature correction are also mentioned in Figure 4b. The WWTP model calibration is done in an earlier project (Arnell, 2016). The current model uses pollutant load data from 2018 as model inputs. Since, our goal is to evaluate the influence of upstream heat recovery on WWTP performance, this assumption is reasonable.

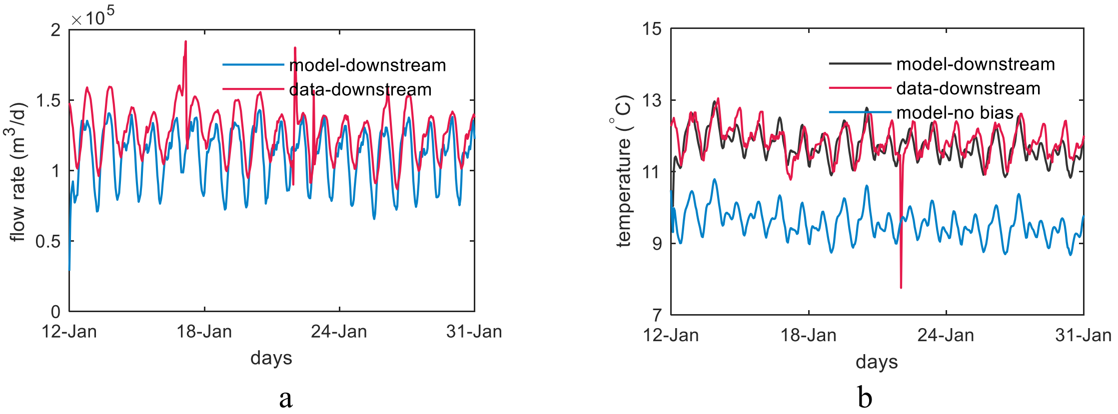

Figure 4: Model calibration for the WWTP inlet

Analysis – Sea links

The sea links from Nacka and Värmdö to the WWTP are modelled as pumped sewer systems with a mechanistic heat transfer model. Figure 5 shows the temperature and flow rate predictions for one of the sea link pipes from Nacka. It should be noted that upstream flow rate information is not available. However, since it is a very short pumped sewer pipe (length around 2 km), the upstream flow rate can be expected to be very similar to the downstream measurements. The model results also indicate the same (Figure 5b). An interesting aspect that is observed from the temperature data is that there is a significant delay (around 2 hrs) in the temperature dynamics between the upstream and downstream locations (Figure 5a), although the flow rate measurements do not have any delay. This delay is also well reflected in the model, which predicts the downstream temperature as well as the time delay accurately. This can be attributed to the residence time and the heat transfer dynamics in the sewer pipe.

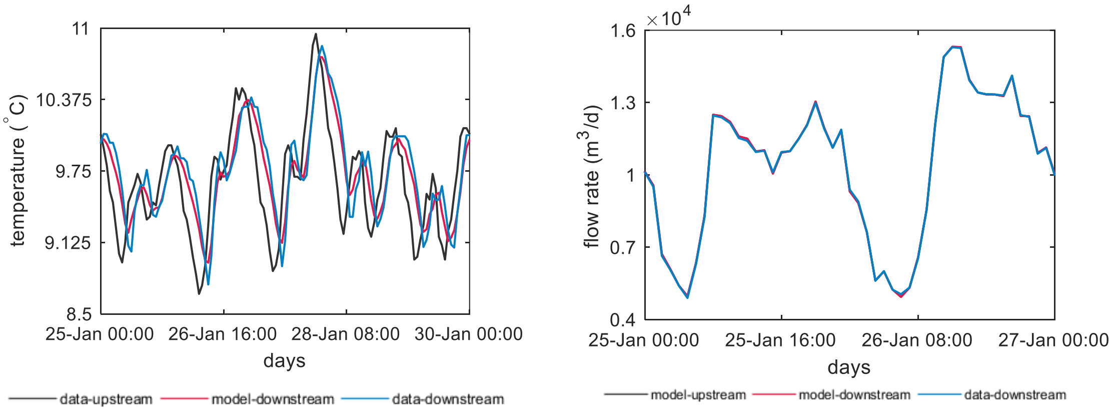

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Figure 5: Temperature and flow rate analysis for the Nacka sea link

Scenarios analysis – Wastewater treatment plant

During the evaluation period, the default WWTP inlet temperature has a mean value of 11.7 °C. With the different scenarios (SC1, SC2, SC3), the mean values are 10.7 °C, 9.8 °C and 8.8 °C, respectively (Figure 6a; Table 3). Hence, there is a 1 °C loss in temperature observed due to the sewer tunnel considering all the sewer inlet locations. It is important to consider that some of the inlets are closer to the WWTP than others. For the maximum WWTP inlet temperature, a similar trend (with a 1 °C drop between each scenario) can be observed for SC1 and SC2 while the reduction in temperature from SC2 to SC3 is only 0.5 °C. This is interesting to note and can be due to the drop in temperature gradient (between wastewater and the surrounding environment in the sewer pipe) as we approach lower temperatures. It can also be noticed that the mean WWTP outlet temperature does not vary much in comparison to the inlet temperature. However, the values are significantly smoothened, mainly due to the large reactor volumes (Figures 6a & 6b).

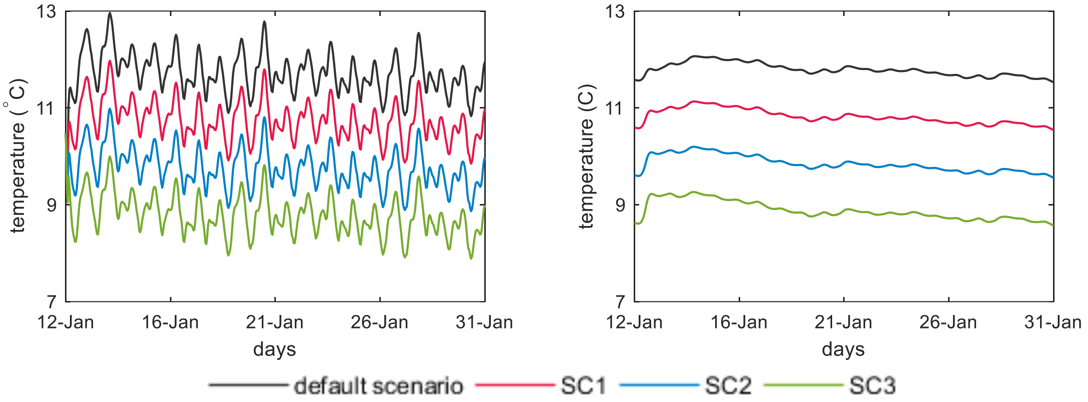

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Figure 6: Scenario analysis results for the WWTP inlet and outlet temperatures

The effluent quality in terms of ammonia (NH_4-N) and total nitrogen (TN) concentrations is evaluated as nitrogen removal is of main concern when reducing inlet wastewater temperature. It is clear that nitrification performance degrades with temperature, which is also expected (Figure 7a; Table 3). However, the loss in performance for the simulated scenarios is not significant. The increase in the mean NH_4-N concentration for each 1 °C drop in temperature is less than 0.1 g/m^3. This is still within the yearly average limit of 3 g/m^3 even for the dynamic data. Similar trend is observed for the TN concentration (Figure 7b). The mean TN increases by around 0.1 g/m^3 while the max TN concentration increases by approximately 0.2 g/m^3. This increase is also within the yearly average TN limit of 10 g/m^3. Hence, the nitrogen performance is not severely affected due to the existing capacity in terms of aeration and reactor volumes to handle the nitrogen removal during winter. However, it should be noted that heat recovery can impact the overall capacity and the maximum capacity that can be handled by the WWTP can be reached earlier than expected. This would mean that future plant upgrades will be needed earlier than planned.

Table 3: Key evaluation metrics for the WWTP inlet temperature, effluent NH_4-N and TN for the different scenarios.

		Default	SC1	SC2	SC3
WWTP inlet temperature (°C)	Mean	11.7	10.7	9.8	8.8
	Max	13.0	12.0	11.0	10.5
WWTP effluent NH_4-N conc (gN/m^3)	Mean	0.29	.0.34	0.41	0.51
	Max	0.53	0.61	0.71	0.90
WWTP effluent TN conc (gN/m^3)	Mean	6.40	6.48	6.59	6.71
	Max	7.53	7.67	7.84	8.05

Sudden changes in the effluent quality are noticed in the plots (e.g. Jan 21 – Jan 24 in Figures 7a & 7b)). This is due to the variation in the influent quality. The influent pollutant loads for the model consist of daily average values that are multiplied by a standard diurnal variation curve to generate dynamic data.

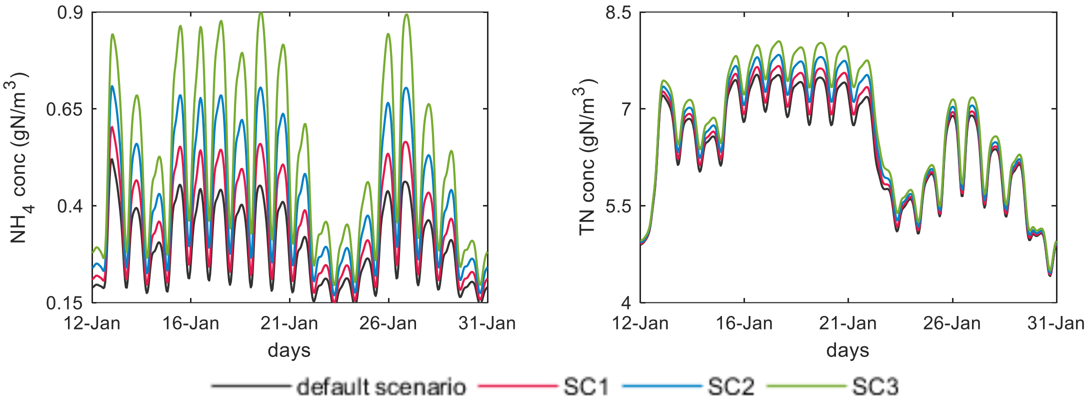

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Figure 7: Dynamic results for the WWTP effluent NH_4-N and TN concentrations for the different scenarios.

Conclusions

In conclusion, it can be said that for the predicted temperature drop at WWTP inlet, the nitrogen removal performance will still be within the limits considering upstream heat recovery at households.. Another aspect to take into consideration is that, while the heat recovery does not have an impact on the current operation due to existing over capacity, it can have an impact in the future as loads increase. This can also mean that future upgradations might have to take place earlier than planned when significantly high (more than 50% heat recovery) is allowed at household level. The data analysis has thrown light on sevreal data reconciliation challenges in the sewer tunnel measurements and that should be an area to focus on to get more accurate insights into the process performance and heat transfer processes in the sewer system.

Acknowledgements

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Appendix 1 – Simulation results for the summer period (August 2019)

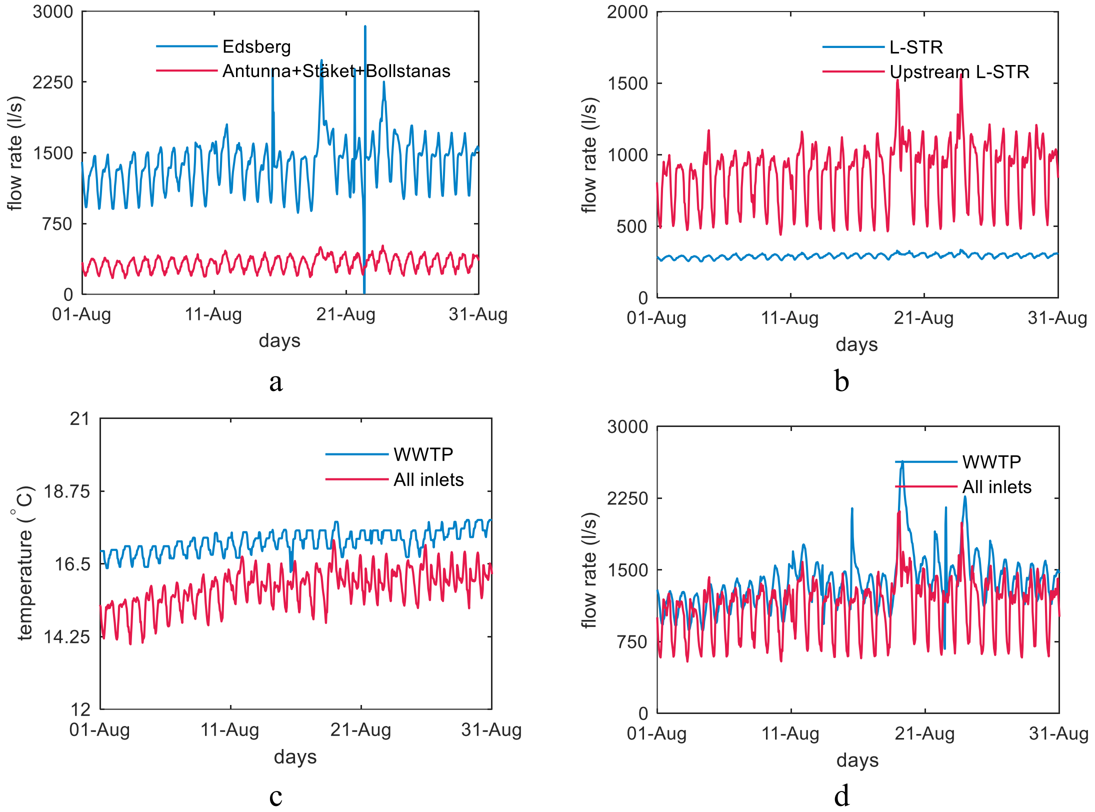

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Figure A1.1: Data analysis for the sewer tunnel (Aug 2019).

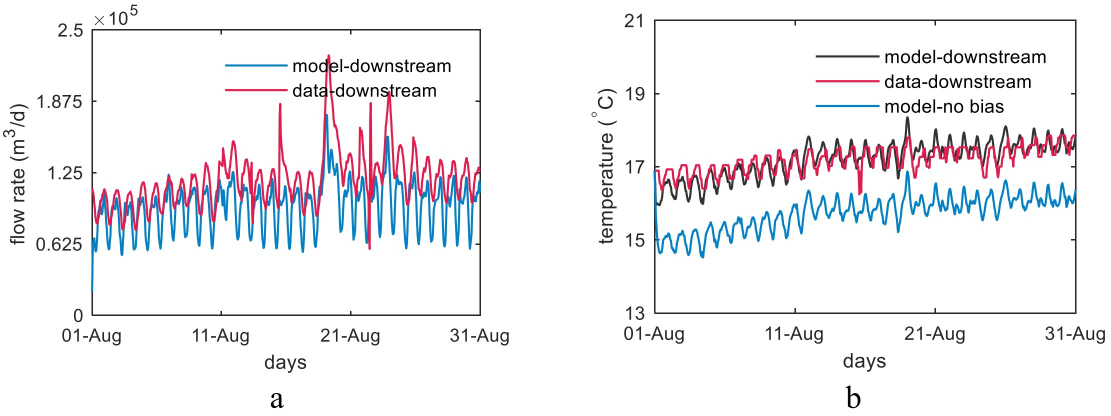

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Figure A1.2: Model calibration for the WWTP inlet (Aug 2019).

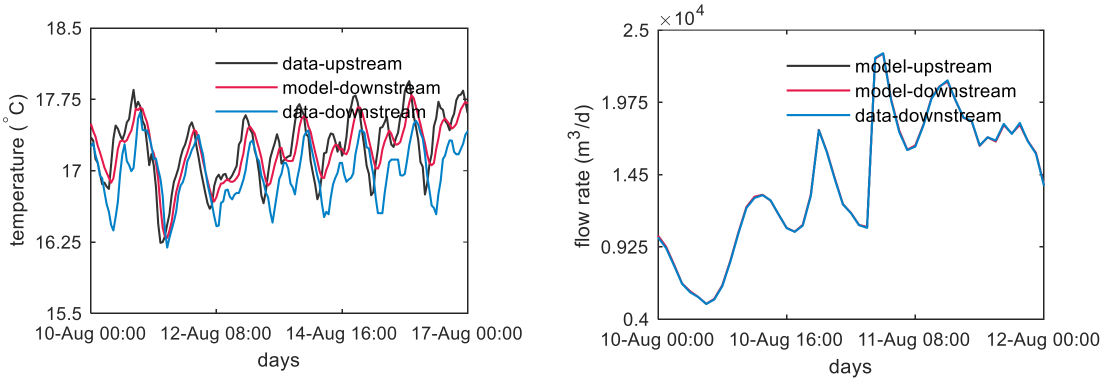

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Figure A1.3: Temperature and flow rate analysis for the Nacka sea link (Aug 2019).

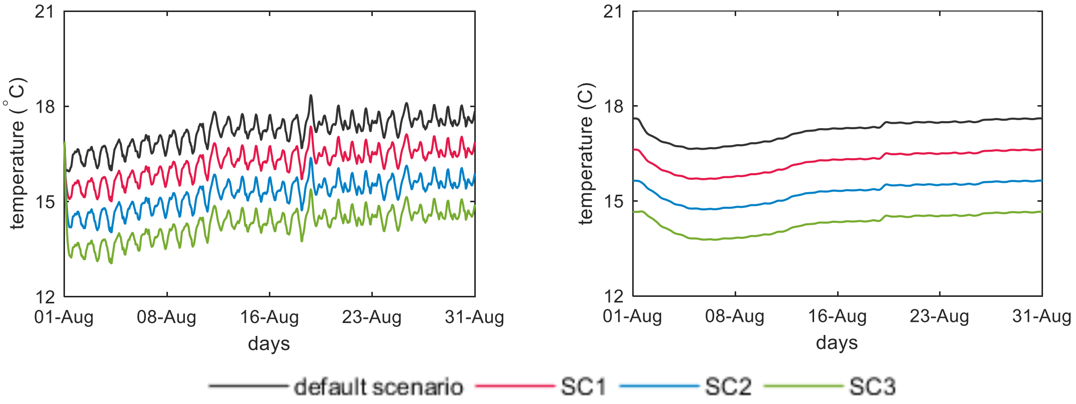

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Figure A1.4: Scenario analysis results for the WWTP inlet and outlet temperatures (Aug 2019).

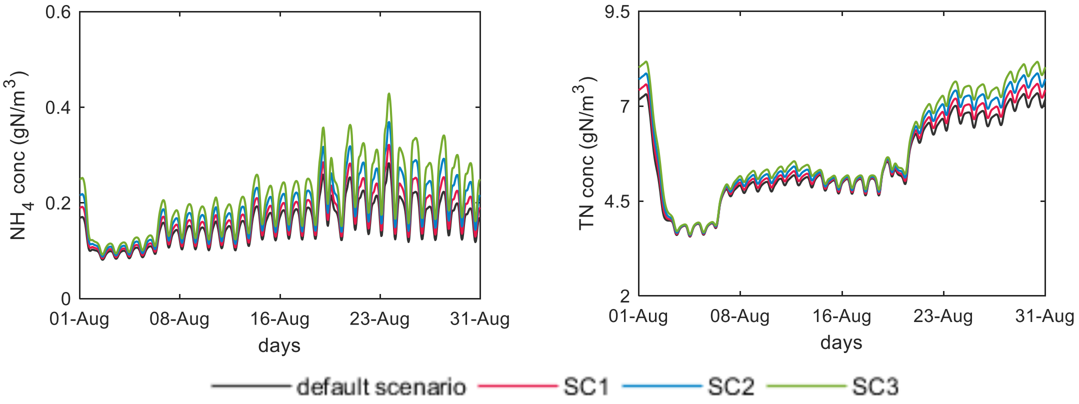

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Figure A1.5: Dynamic results for the WWTP effluent NH4-N and TN concentrations for the different scenarios (Aug 2019).

Table A1.1: Key evaluation metrics for the WWTP inlet temperature, effluent NH_4-N and TN for the different scenarios (Aug 2019).

		Default	SC1	SC2	SC3
WWTP inlet temperature (°C)	Mean	17.2	16.2	15,2	14.3
	Max	18.4	17.4	16.9	10.5
WWTP effluent NH_4-N conc (gN/m^3)	Mean	0.29	.0.34	0.41	0.51
	Max	0.53	0.61	0.71	0.90
WWTP effluent TN conc (gN/m^3)	Mean	6.40	6.48	6.59	6.71
	Max	7.53	7.67	7.84	8.05