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Industrial Electrical Engineering and Automation

Generating Wastewater Treatment Plant Influent Data for Realistic Evaluation of Future Scenarios

Case Study for WWTPs in Stockholm, Sweden

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Contents

1. Introduction

Dynamic and high frequency influent data is a prerequisite for simulation of wastewater treatment plant (WWTP) process models. However, such data is not generally available (Martin & Vanrolleghem, 2014). The report describes a model-based approach to generate WWTP influent data for evaluating various future WWTP operational scenarios. The study is carried out as a part of SIMFRAM 2.0 project. The project aims to understand the impact of changes in infiltration and inflow on future WWTP operation using a combination of process models and life cycle analysis (LCA).

An overview of the influent generator model is presented. WWTPs in Stockholm are used as a case study for the report. Description of the current and future influent characteristics of the WWTPs is provided. The approach for model calibration and generation of future scenarios is described in detail. The document serves as a guide for future users of the influent generator model and also summarizes the research results from modelling current and future WWTP inflows in Stockholm. The finished models are delivered to Stockholm Vatten och Avfall (SVOA) and Svenska Miljöinstitutet (IVL).

2. Model Description

A modified version of the influent generator model (Gernaey et al., 2011) based on the benchmark simulation model for urban wastewater systems (BSM-UWS) (Saagi et al., 2016) is used for the study. It can describe different sources of wastewater generation (Figure 1). The influent generator model was successfully used earlier to predict influent flow rate at Bromma WWTP, Stockholm (Flores-Alsina et al., 2014).

Four different sources of wastewater generation from the catchment are considered:

1. Domestic,
2. Industrial,
3. Stormwater and
4. Infiltration to sewers.

Additionally, temperature of the influent wastewater is also modelled. Flow rate and pollutant state variables at the WWTP influent can be generated using the model. The pollutants considered are chemical oxygen demand (COD), ammonia (NH_4-N), total Kjeldahl nitrogen (TKN) and total phosphorus (TP). COD is further divided into soluble and particulate fractions (COD_{sol} and COD_{part}). The sewer network is modelled using tanks-in-series approach. A tunnel model for the Stockholm sewer system (Blomstrand & Jemander, 2017) is used for the future scenario. A fractionation model is used to convert the pollutants to Activated Sludge Model No. 1 (ASM1) (Henze et al., 2000) state variables.

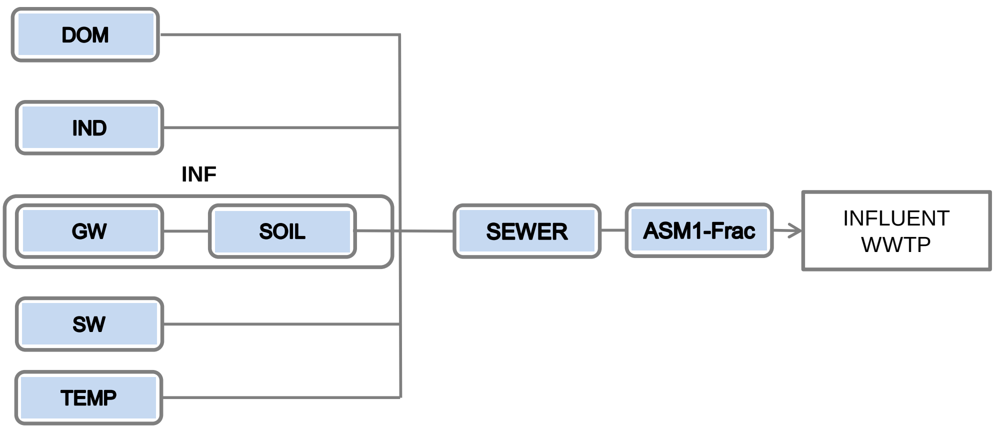

Figure 1: Graphical overview of the influent generator model with different model blocks (DOM – domestic, IND – industrial, GW – groundwater, SW – stormwater, INF – infiltration to sewers and ASM1-frac – ASM1 fractionation).

Domestic (DOM): Sewage from households is considered as domestic wastewater. Normalized dynamic profiles for variations in wastewater generation on a daily, weekly and yearly basis are used as source files. These profiles are multiplied with the number of population equivalents (PE) and daily average flow rate/pollutant load per PE (m^3/PE.d, kg/PE.d) to generate domestic wastewater.

Industrial (IND): Normalized weekly and yearly profiles are used as source files for generating industrial wastewater. Weekly profiles include the variation in production during different shifts and maintenance/cleaning times. Yearly profile includes reduced wastewater generation during holiday periods. The combined profile is then multiplied with the daily average flow rate/pollutant load generated (m^3/d, kg/d) to determine industrial contribution. Both domestic and industrial models use a random generator to produce white noise in order to avoid exact correlation between different state variables.

Stormwater (SW): The model describes runoff generation from precipitation (rainfall and snowmelt). Evaporation losses are subtracted from the rainfall intensity before computing runoff. The runoff from impervious and pervious areas is considered separately. While the impervious area runoff directly leads to stormwater generation that is discharged to the combined sewer system, the runoff from pervious area reaches the infiltration model block from which, a part of it will contribute to infiltration to sewers. Precipitation that occurs when the ambient temperate is less than 0 °C is considered as snow. It is stored as water depth in a conceptual tank and converted to runoff (snowmelt) when the ambient air temperature is greater than 0 °C. Pollutant generation during precipitation events is modelled using two approaches. For particulate pollutants (COD_{part}), an accumulation and washoff model is used. The model describes the accumulation of pollutants during dry weather and the subsequent washoff during rain events. This approach is essential to simulate high pollutant loads at the beginning of the rain events (first flush effect). However, it is generally difficult to calibrate the model due to lack of data. For soluble pollutants, constant event mean concentration (EMC) of pollutants for the entire duration of rainfall is considered. The EMC values can either be obtained from historic data or from literature.

Infiltration to sewers (INF): The model describes infiltration both during dry and wet weather situations. Groundwater level (modelled as a sine wave with annual periodicity) and pervious area runoff during rain events are the inputs to the soil model. The soil model is a conceptual storage tank with two outputs – infiltration to sewers and flow to downstream aquifer. The infiltration model block generates the slow response (higher influent flow rates at the WWTP even after the end of the rainfall event) from precipitation. It is assumed that no pollutant load is generated from infiltration to sewers. Evaporation losses from the soil are also considered.

Temperature (TEMP): Wastewater temperature is modelled using daily and seasonal variation. Temperature also drops during any precipitation event. The extent of temperature decrease is correlated to the rainfall intensity by a temperature correction factor.

Sewer network (SEWER): Conceptual models using tanks-in-series approach are used to simulate the sewer network. The total inflow (combined input from domestic, industrial, stormwater, infiltration to sewers) is the input to the sewer model. In order to represent the sewer system from multiple sub-catchments joining a trunk sewer, the flow rate and pollutant loads are divided into a number of fractions based on a model parameter (*subareas*). Each *subarea* consists of four reservoir models in series. Additionally, a tunnel model (Blomstrand & Jemander, 2017) is used to simulate the future scenario where it is planned to construct a large sewer tunnel. The tunnel model consists of series of reservoirs where the outflow from each reservoir is modelled using Manning's equation. It requires data regarding the tunnel dimensions and slope. The model also includes a pumping station that can be used to deliver wastewater at a constant rate as well as to implement various control strategies.

ASM1 fractionation (ASM1-Frac): Soluble COD is fractionated into inert (SI) and readily biodegradable substrate (SS). SI is assumed constant (30 g/m^3) and the rest is considered as SS. When input COD_{sol} is less than 30 g/m^3, it is completely mapped to SI (SS – 0). Particulate COD is divided into inerts (XI), slowly biodegradable substrate (XS) and heterotrophic biomass (XBH) based on pre-defined fractions. Autotrophic biomass (XA) and particulate substrate (XP) are assumed to be zero. Ammonia is directly mapped to SNH. Organic nitrogen, which can be fractionated between soluble (SND) and particulate (XND) organic nitrogen, is obtained by subtracting the nitrogen content of XI and XS from the input organic nitrogen (TKN – NH_4). Constant fractions are used to distribute the remaining organic nitrogen to SND and XND. Alkalinity (Salk) is assumed constant (7 g/m^3). Volatile suspended solids (VSS) are calculated as 62.5% of the particulate COD and inert suspended solids (ISS) as 12.4% of the VSS. Other state variables – nitrate (SNO), nitrogen (SN2) etc. are assumed to be zero. Four additional dummy state variables are available in the model for future use.

3. Case Study Details

An overview of the characteristics (year 2012) for Henriksdal (it has two inlets – north (HIN) and south (SIN)) and Bromma (BIN) WWTP influents is provided in Table 1. Future influent to Henriksdal will include wastewater from Bromma and Eolshäll as well. However, detailed inflow data from Eolshäll sub-catchment is not available (daily average flow rate – 40 800 m^3/d, population equivalents – 119 000 and catchment area – 2 000 ha). A 14 km long sewer tunnel will connect these two sub-catchments to the Henriksdal WWTP in the future. A 32% increase in population equivalents is expected until year 2040 for all the sub-catchments (Grundestam & Reinius, 2014).

Flow rate data is available at 15 min intervals and pollutant load data is accessible as weekly composite values and also as daily composite values (once every week). The pollutants measured are total organic carbon (TOC), 7-day biochemical oxygen demand (BOD_7), ammonia (NH_4-N), total nitrogen (TN), total phosphorus (TP) and total suspended solids (TSS). Temperature data is also available at high frequency. Other input data required for the model are rainfall intensity (mm/h), evaporation (monthly variation) and ambient air temperature (°C). TSS and BOD_7 data are not used for the model calibration as only TOC data is sufficient. TOC is converted to COD based on a conversion factor that is influent specific (HIN – 3.83, SIN – 3 .73 and BIN – 3.3).

Table 1. Key influent characteristics for the different WWTPs in Stockholm (year 2012).

	Henriksdal N (HIN)	Henriksdal S (SIN)	Bromma (BIN)
Total catchment area (ha)	4 500	14 700	9 900
Population equivalents (PE)	389 000	395 000	328 000
Flow rate (m^3/d)	124 000	160 000	142 000
TOC (g/m^3, kg/d)	149/21 300	117/20 600	80/11 100
BOD_7* (g/ m^3, kg/d)	208/25 500	146/21 800	100/13 500
NH_4-N (g/m^3, kg/d)	29/3 600	18/2 700	18/2 500
TN (g/m^3, kg/d)	44/5 400	32/4 900	27/ 3 700
TP (g/m^3, kg/d)	5.5/680	5/770	3/ 370
TSS* (g/m^3, kg/d)	266/ 33 200	267/41 100	192/ 26 300

* Daily composite sample once every week

4. Model Calibration

The calibration is performed systematically starting with generation of the dry weather flow (domestic, industrial and infiltration to sewer model blocks) followed by modelling the wet weather phenomenon (stormwater and infiltration to sewer model blocks). The procedure is described for Henriksdal S inlet (SIN). Table 2 provides a summary of all the major calibration parameters for SIN. A similar approach is used for the other influents as well.

The two major parameters for generating domestic wastewater flow rate are *QperPE* (0.15 m^3/PE.d) and *PE* (395 000). Both values are based on design guidelines for the WWTP. The product of these two parameters gives the daily average flow rate, which is then multiplied with the combined profile of daily, weekly and yearly variations. For this case study, no weekly variation is assumed and holiday season is assumed in the summer (01 July – 16 Aug) and Christmas (20 Dec – 31 Dec) periods. The holiday periods are based on the flow rate and pollutant concentration data. For pollutant loads, the domestic contribution to the WWTP pollutant load (daily average load based on data – industrial contribution) is divided by PE to compute the pollutant load per PE (kg/PE.d) for each of the pollutants (0.032, 0.126, 0.007, 0.012 and 0.002 kg/PE.d for COD_{sol}, COD_{part}, NH_4-N, TKN and TP, respectively). The ratio of particulate COD to total COD is determined as 0.8 based on an earlier version of influent generator and process model for the SIMFRAM 1.0 project. The ratio is used for both domestic and industrial pollutant loads.

There is no detailed data regarding domestic and industrial contributions to dry weather pollutant load. Hence, a 10% industrial contribution is assumed for both flow rate and pollutant loads. This can be used to compute the daily average flow rate (15 930 m^3/d) and pollutant loads from industries (1385, 5539, 290, 513 and 79 kg/d for COD_{sol}, COD_{part}, NH_4-N, TKN and TP, respectively) based on average influent data. Similar to domestic wastewater generation, the average values are further multiplied with the weekly (high wastewater generation on Fridays) and yearly variation (no variation assumed) to generate dynamic industrial wastewater.

Major calibration parameters for the stormwater model are impervious area (*imp_area* – 192.5 ha) and pervious area (*perv_area* – 2400 ha). The data for these two parameters is available based on a hydrological model but a significant correction to those values was made. The calibrated areas are approximately 20% of the values estimated from the hydrological model. Two possible hypotheses for the large differences are: i). the hydrological model considers the entire catchment area while the influent generator is only looking at the combined sewer system that is connected to the WWTP, ii). underlying model differences between the hydrological model and influent generator. Parameters *imp_area* and *perv_area* determine the extent of direct surface runoff (fast response) and infiltration of rainfall runoff to sewers (slow response), respectively. Additionally, rainfall runoff coefficients (*rrc*) can be further used to reduce the impervious area although it is set to 1 in the current model. For modelling the pollutant loads from stormwater runoff, two different approaches are available. For COD_{part}, an accumulation and washoff model is used. However, since we do not have high frequency pollutant data during rainfall events, we cannot calibrate the accumulation and washoff model for the particular catchment and default values are used. For COD_{sol} and NH_4-N, event mean concentrations (EMC) (constant concentration for the entire rain event is assumed) (*emc_codsol* – 9 g/$m^3$and *emc_nh4* – 0.56 g/m^3) are assumed based on literature (Butler & Davies, 2004).

The parameters *gwbias* (80 000 m^3/d) and *amp* (0.05) represent the mean groundwater flow rate and amplitude of seasonal variations in groundwater levels. The values are calculated based on the expected levels of infiltration to sewers. An initial guess for the infiltration flow can be considered as the dry weather flow during nights. The frequency for the modelled sinewave is $2\pi/365$. A phaseshift ($-3\pi/2$) was used to initiate the curve in January. It is expected that the groundwater level is higher in winter and lower in summer. Additionally, the amount of pervious area runoff that can percolate into the soil model is computed based on the parameters area (*A* – 4800 ha) and permeability of soil (*K* – 0.6 m/d). The area parameter used here is only a model calibration parameter and not the exact area. Any flow excess of $K \times A$ reaches the sewer system directly as runoff (consider that the soil is saturated and cannot take in any more rainfall) while the rest reaches the soil model. Groundwater and pervious area runoff are the inputs to the soil model. The model consists of a virtual tank with different outlets (infiltration to sewers and flow to downstream aquifers). The relationship between the tank level and the outflow are determined by the parameters (*Kinf* – *gwbias*×30, *Kdown* – *gwbias*×0.2). The parameters *Kinf* and *Kdown* represent the extent of infiltration to sewers and flow to aquifers. Hence, in order to increase the infiltration to sewers, one can increase the *Kinf* value. Additionally, effect of evaporation on the infiltration flow is also considered (*Kevap* – 0.05). Evaporation data (monthly variation) is available. Hence, a proportional amount of water is removed from the soil model as evaporation. It is assumed that no pollutants reach the sewer system through infiltration.

For the sewer network, two sewer network blocks in series are used, each with the parameter *subareas* set to 9, with four reservoir models in series for each *subarea*. The residence time constant for each reservoir is 6 min. The calibrated ASM1 fractionation parameters are taken from a previous implementation for the SIMFRAM 1.0 project.

Parameters for calibration of the temperature model are yearly (*TBias* – 16 °C, *TAmp* – 4°C) and daily (*TdBias* – 0 °C, *TdAmp* – 0.7 °C) variations in temperature. Effect of precipitation on temperature is modelled using a drop in temperature correlated to the rainfall intensity (*temp_correction* – 2).

Table 2: Key calibration parameters for each model block for Henriksdal S inlet.

Model section	Parameter	Value	Units	Remarks
Domestic	*QperPE*	0.15	m^3/PE.d	Domestic wastewater flow rate per population equivalent
	PE	395 000	PE	Population equivalents
	domestic_avg	0.032 0.126 0.007 0.012 0.002	(kg poll/PE.d)	Average daily pollutant loads per PE for COD_{sol}, COD_{part}, NH_4-N, TKN,TP
Industrial	*Qind_daily*	15 930	m^3/d	Daily average wastewater flow rate from industry.
	industry_avg	1 385 539 290 513 79	kg poll/d	Average daily industrial pollutant loads for COD_{sol}, COD_{part}, NH_4-N, TKN, TP
Stormwater	*rrc*	1	-	Rainfall runoff coefficient
	imp_area	192.5	ha	Impervious area
	perv_area	2 400	ha	Pervious area
	Kacc	5	kg/ha.d	Surface accumulation rate (accumulation and washoff model)
	kdecay	0.2	1/d	Decay rate constant (accumulation and washoff model)
	Kwashoff	0.3	1/mm	Wash-off constant (accumulation and washoff model)
	emc_codsol	9	g/m^3	EMC for COD_{sol}
	emc_nh4	0.56	g/m^3	EMC for NH_4-N
	kreservoir	6	min	Reservoir time constant for surface runoff model
Infiltration	*gwbias*	80 000	m^3/d	Mean yearly groundwater flow rate
	amp	0.05	%	Amplitude of groundwater flow rate variation (annual)
	freq	2π/365	rad/d	Frequency of the sine wave (1 year)
	phase	-3π/2	rad	Phase shift
	A	4 800	ha	Area (soil model)
	K	0.6	m/d	Soil permeability (soil model)
	Kinf	2 400 000		Tuning parameter for infiltration (soil model)
	Kdown	16 000		Tuning parameter for flow to aquifers (soil model)
	Kevap	0.05		Parameter for evaporation of water from soil (soil model)
Sewer	*subareas*	9	-	Number of sub-areas in the sewer system
	ksewer	6	min	Time constant for each sewer tank
Temperature	*TAmp*	4	°C	Amplitude of temperature variation (annual)
	TBias	16	°C	Mean annual temperature
	TFreq	2·π/365	rad/d	Frequency of temperature model (yearly)
	TPhase	-0.8π	rad	Phase shift for yearly temperature model
	TdAmp	0.7	°C	Amplitude of daily temperature variation
	TdBias	0	°C	Bias for daily temperature model
	TdFreq	2π	rad/d	Frequency of daily temperature model
	TdPhase	0.25π	rad	Phase shift for daily temperature model
	temp_correction	2	-	Temperature correction factor for precipitation
ASM1 fractionation	*SALK_cst*	7		ASM1 fractionation parameters
	SI_cst	30		
	XI_fr	0.23		
	XS_fr	0.62		
	XBH_fr	0.15		
	XBA_fr	0		
	XP_fr	0		
	SNO_fr	0		
	SNH_fr	1		
	SND_fr	0.247		
	XND_fr	0.753		

5. Results

Figures 2a & 2b demonstrate a good match between data and model results for influent flow rate at high frequency (15 min intervals) and daily average values. The model can successfully simulate the flow rate dynamics, which include: i). diurnal variation during dry weather, ii). peak flows during rain events and iii). infiltration to sewers.

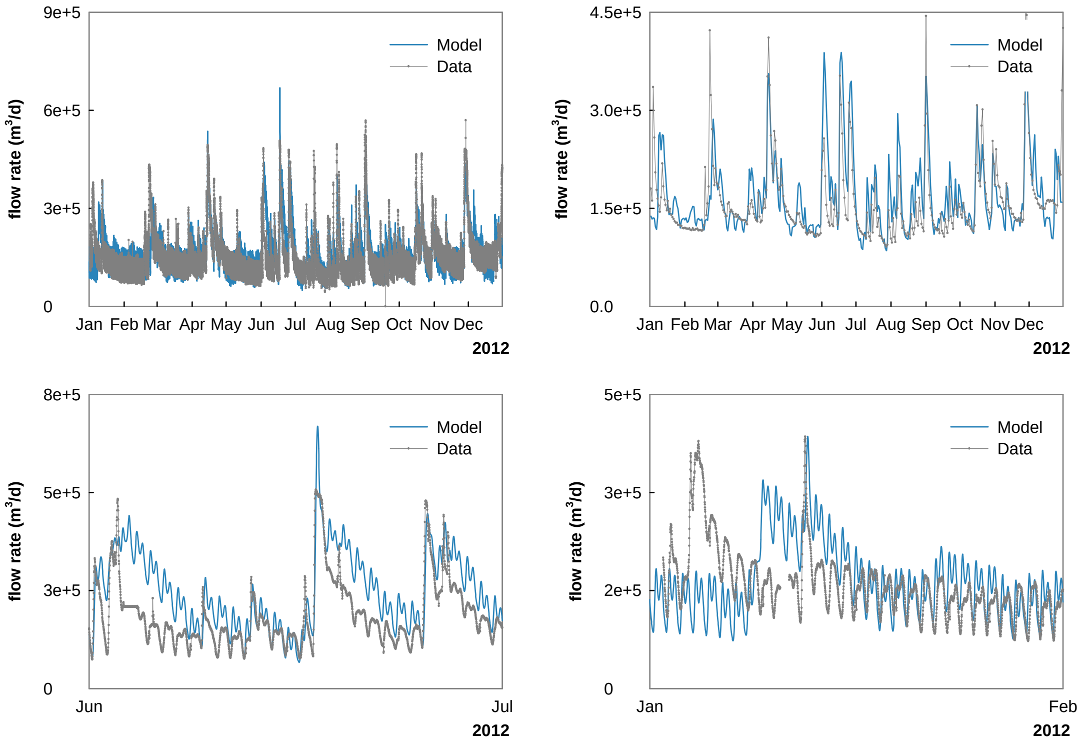

Figure 2. Calibration results for the influent flow rate at Henriksdal WWTP at 15 min intervals (a) and daily average values (b). Flow rate dynamics during June (c) and January (d) 2012.

The two major discrepancies noticed are: i). estimation of the peak flows (June) (Figure 2c) and ii). predicting the snowmelt runoff (Jan) (Figure 2d). The reasons for over estimation are attributed to possible inaccuracies in inflow measurements at high flows and model simplifications in describing rainfall runoff. Since, the sewer system is modelled in a conceptual manner without any sewer overflows, all inflow is considered to arrive at the WWTP, which may not be the case in reality. The snowmelt runoff predictions are linked only to ambient temperature.

Figures 3a & 3b present the weekly composite concentrations for chemical oxygen demand (COD) and ammonia (NH_4-N), respectively. The model can successfully reproduce the weekly variation in pollutant concentrations. Although high frequency data for pollutant concentrations is not available, the model results can be used to fill this gap. It should be noted that the model uses constant load for the entire year except for holiday periods with lower loads. Hence, the dynamics in concentration are mainly due to the flow rate dynamics.

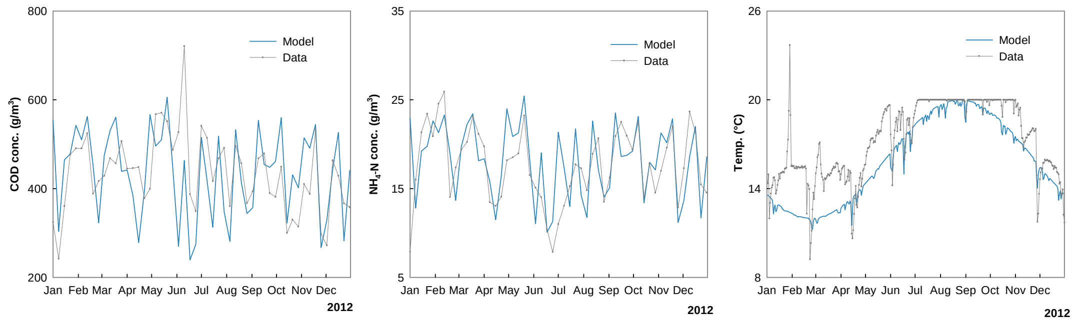

Figure 3. Influent COD (a), NH_4-N (b) concentrations and temperature (c) predicted by the model (blue) compared to the data (grey) at Henriksdal WWTP for the year 2012.

Figure 3c describes the temperature at the WWTP compared to actual data. For Henriksdal WWTP, the temperature model represents the general trend but does not model the actual yearly temperature variation accurately. Since, the temperature model is only based on daily and yearly sine wave model, it cannot describe other factors that affect temperature apart from daily and yearly variations. The model also describes the drop in temperature during precipitation events. The results for Henriksdal N and Bromma WWTP inlets are presented in the Appendix (Figures 5, 6 & 7).

6. Future Scenarios

Four future scenarios are simulated. The default scenario considers 32% increase in population equivalents and no changes to the impervious/pervious areas.

1. 10% increase in infiltration to sewers due to aging of the sewer network (S1).
2. 10% decrease in infiltration to sewers due to structural improvements in the sewer system (S2).
3. 10% increase in percentage impervious area due to urbanization (S3).
4. 10% decrease in impervious area due to improvements in green infrastructure (S4).

Two model parameters are used to generate the scenarios. For scenarios related to infiltration, the parameter *gwbias_corr* modifies the default *gwbias* parameter (for S1 and S2). However, a trial-and-error exercise is required to achieve a specific percentage change in infiltration (e.g. *gwbias_corr* is set to 1.15 in order to achieve a 10% increase in infiltration). The parameter *area_corr* modifies the percentage impervious area (for S3 and S4). In this case, a 10% increase in impervious area requires setting the *area_corr* to 1.1. Hence, the change is exactly correlated to the parameter.

The scenarios S1 and S2 lead to increase and decrease, respectively, in the influent flow rate to the WWTP for the entire duration (Figures 4a & 4b). This is obvious due to changes in the infiltration. The effect is not very significant for the peak flow rates as infiltration mainly contributes to the slow response after rainfall events. Hence, it can be expected that the changes in infiltration will not lead to strong effects in the wet weather performance of WWTPs. However, with changes in infiltration, the concentration of pollutants vary (although loads remain the same), the effect can hopefully be mitigated by optimising the process marginally. In case of changes to impervious areas (S3 and S4), surprisingly the effect is minimal (Figures 4c & 4d).

Although, it is intuitive to expect a change in peak flows during rain events with changes in impervious areas, the results are due to: i). limited changes to impervious area (only 10% change in impervious area), ii). minimal contribution of impervious area to the total runoff (30%, 7% and 6% for HIN, SIN and BIN, respectively), and iii). smoothing effect of the long sewer tunnel. Similarly, there is also limited variation in the influent concentrations. Hence, although it is expected that changes to infiltration are less significant than changes to impervious area, it is important to consider factors like percentage of impervious areas and the presence of any long sewer tunnels before coming to such conclusions. The dynamic profile for concentration of COD and NH4-N under different scenarios is depicted in the Appendix (Figures 8 & 9).

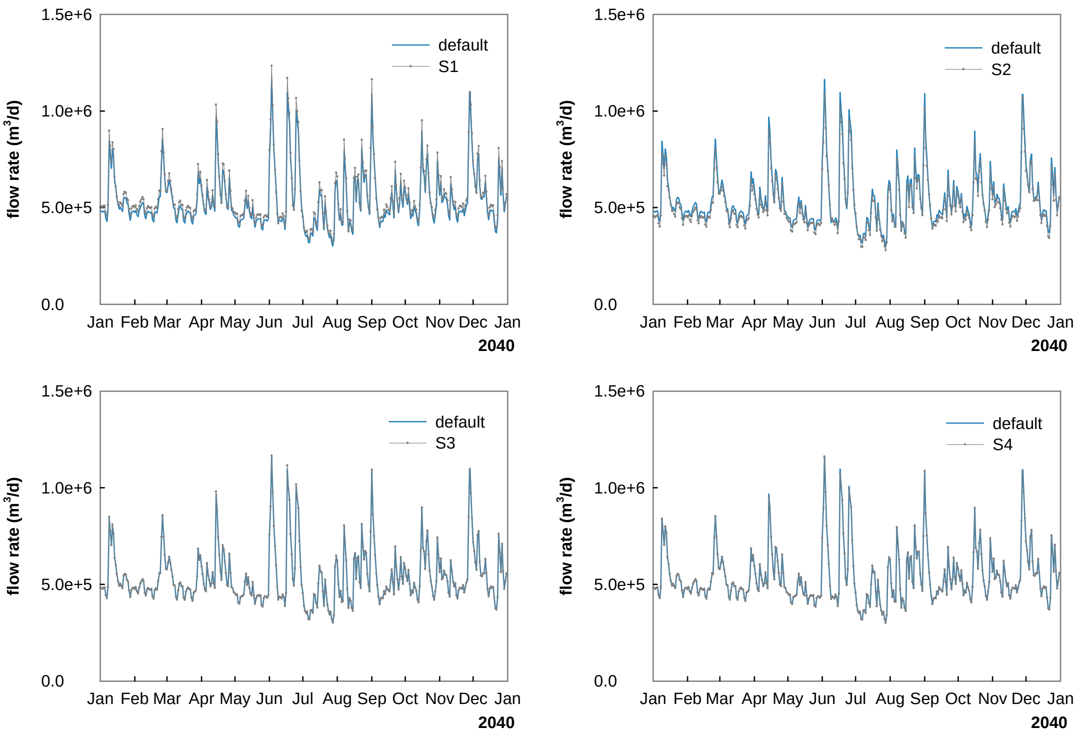

Figure 4. Comparison of the different future scenarios (S1 (a), S2 (b), S3 (c) and S4 (d)) to the default 2040 scenario.

7. Conclusions

A model-based approach to generate dynamic influent data for different WWTPs in Stockholm, Sweden, is presented in this report. The results show the ability of the BSM-UWS catchment model in predicting the influent flow rate and pollutant loads based on available data. It is possible to generate realistic future scenarios using the calibrated model as illustrated by the four scenarios presented. The next step is to simulate and evaluate the WWTP performance for the different scenarios using plant-wide biochemical process models.

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Appendix 1: Henriksdal N WWTP Inlet 2012

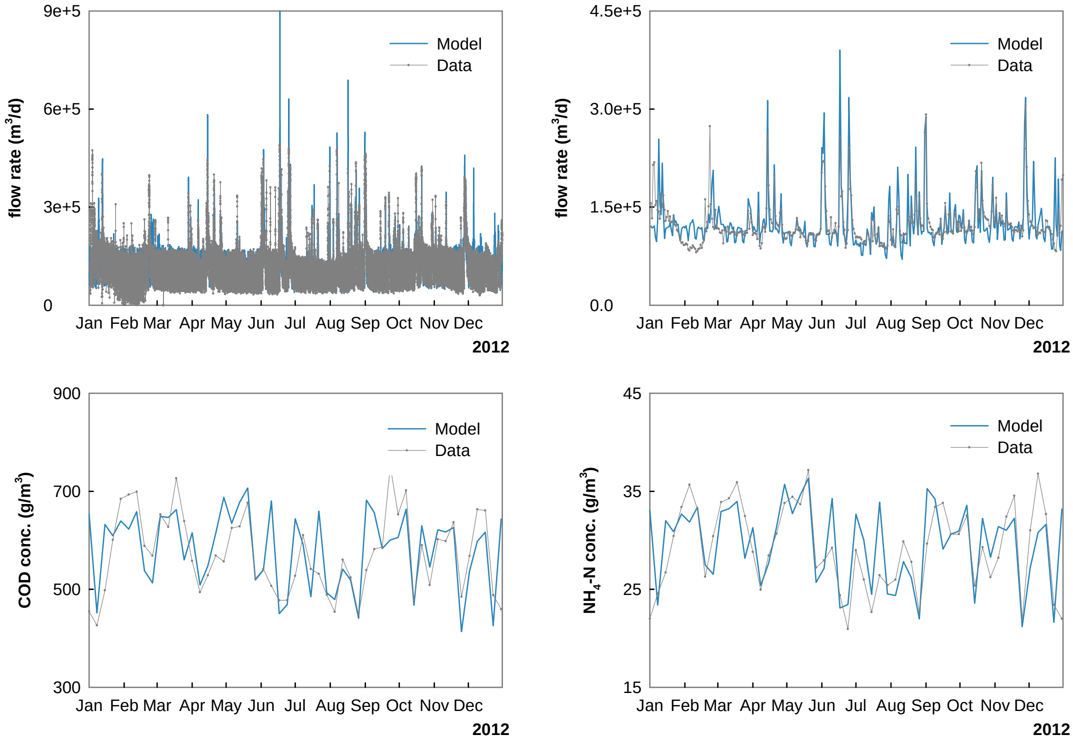

Figure 5: Comparison between model results and data for flow rate (15 min frequency (a) and daily average values (b)) and weekly composite pollutant concentrations (COD (c) and NH_4-N (d)) at Henriksdal N inlet (HIN) for year 2012.

Appendix 2: Bromma WWTP Inlet 2012

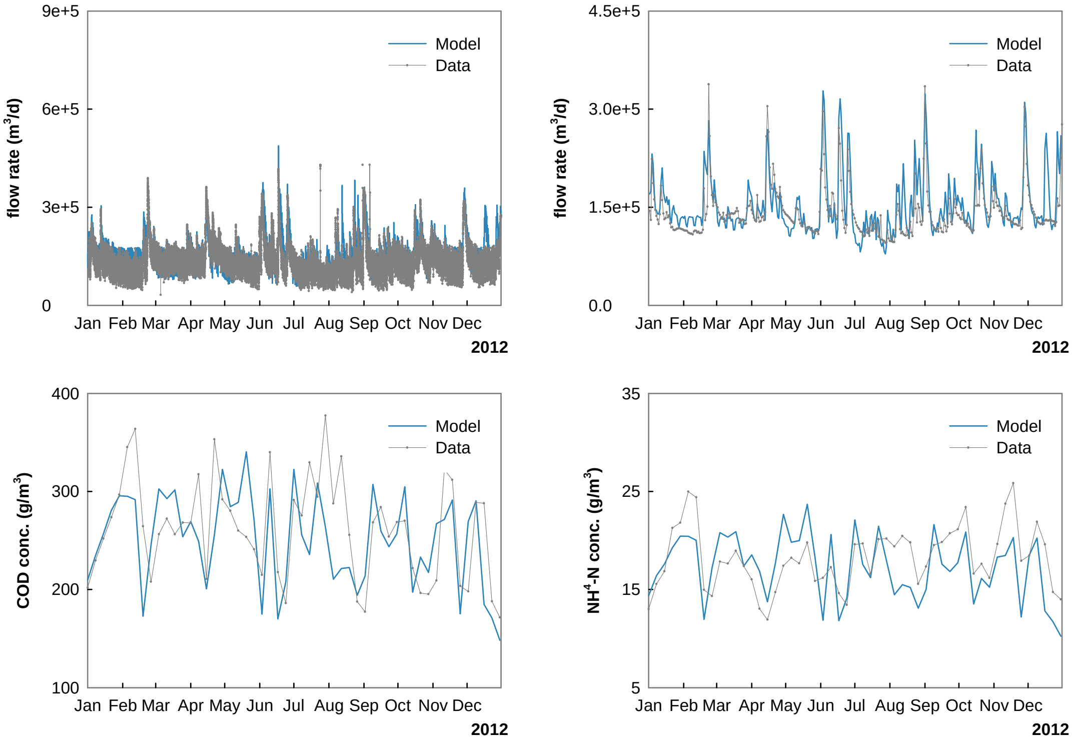

Figure 6: Comparison between model results and data for flow rate (15 min frequency (a) and daily average values (b)) and weekly composite pollutant concentrations (COD (c) and NH_4-N (d)) at Bromma WWTP inlet (BIN) for year 2012.

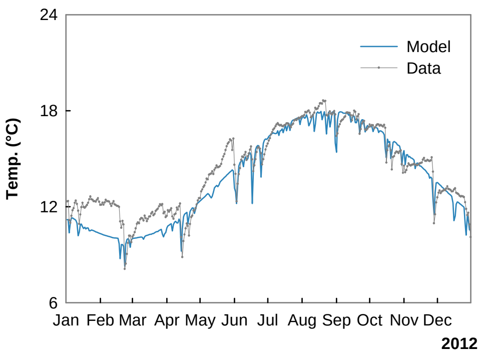

Figure 7: Modelling of temperature dynamics at Bromma WWTP for year 2012.

Appendix 3: Henriksdal WWTP Inlet 2040 – COD Concentration

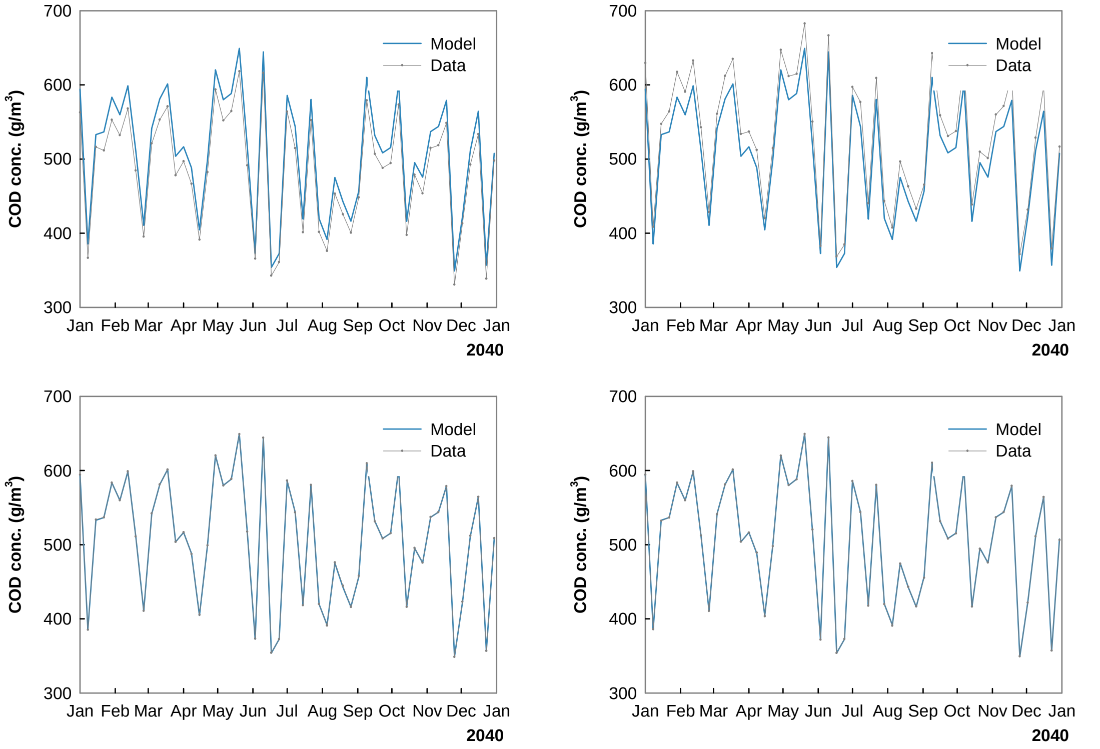

Figure 8: Weekly composite COD concentration for different future scenarios (S1 (a), S2 (b), S3 (c) and S4 (d)) compared to the default scenario for year 2040.

Appendix 4: Henriksdal WWTP Inlet 2040 – NH_4-N Concentration

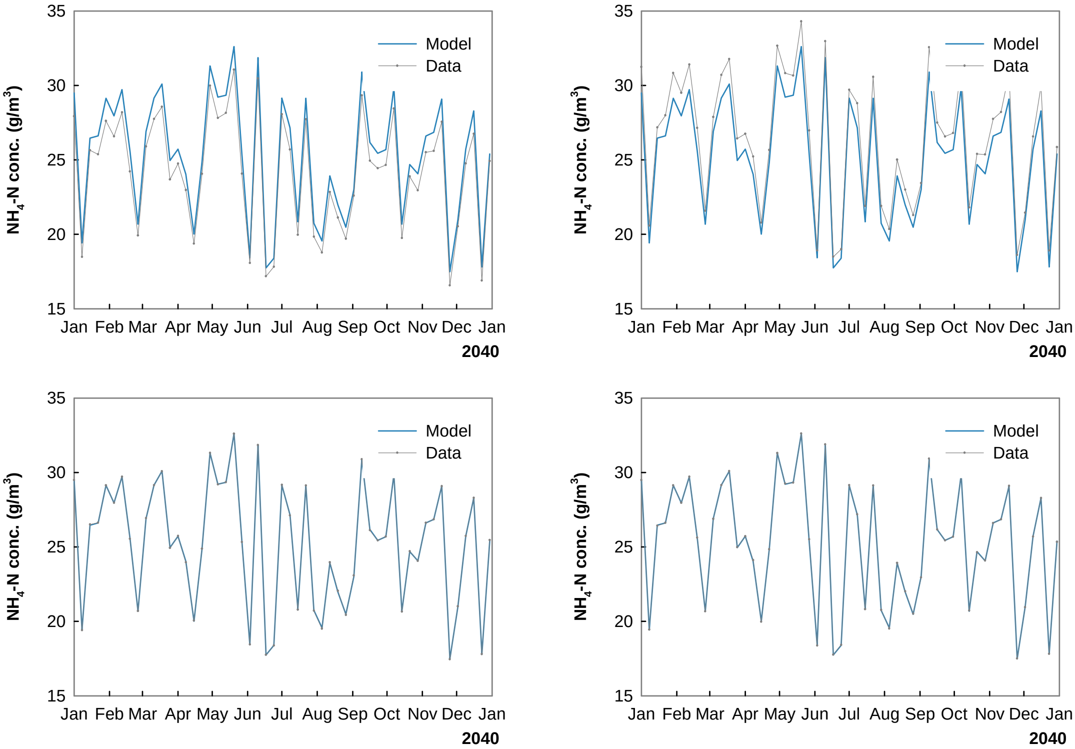

Figure 9: Weekly composite NH_4-N concentration for different future scenarios (S1 (a), S2 (b), S3 (c) and S4 (d)) compared to the default scenario for year 2040.