Evaluation of environmental impacts for future influent scenarios using a model-based approach

S. Andersson, M. Rahmberg, Å. Nilsson, C. Grundestam, R. Saagi and E. Lindblom

ABSTRACT

Changes in dilution of wastewater to a treatment plant due to infiltration or surface runoff can have a great impact on treatment process performance. This paper presents a model-based approach in which realistic influent scenarios are generated and used as inputs to a dynamic plant-wide process model of the wastewater treatment plant. The simulated operation is subsequently evaluated using life-cycle assessment (LCA) to quantify the environmental impacts of the future influent scenarios. The results show that increased infiltration led to higher environmental impact per kg nitrogen removed. The increase in surface runoff had a minor impact.

Key words | influent generator, life-cycle assessment, process simulation, scenario analysis, wastewater treatment

S. Andersson (corresponding author)
M. Rahmberg
Å. Nilsson
C. Grundestam
E. Lindblom
IVL Swedish Environmental Research Institute,
Stockholm,
Sweden
E-mail: *sofia.lovisa.andersson@ivl.se*

R. Saagi
E. Lindblom
Division of Industrial Electrical Engineering and Automation (IEA), Department of Biomedical Engineering,
Lund University,
Lund,
Sweden

INTRODUCTION

Swedish wastewater treatment plants (WWTPs) are challenged with more stringent effluent limits and many plants plan to upgrade to meet the new requirements. The WWTPs also often receive large volumes of stormwater runoff and infiltration water that has leaked into the sewer networks (Hey *et al.* 2016). This additional water is an undesirable input to the WWTPs, as it puts additional hydraulic load on processes and might make the treatment processes less efficient due to dilution of pollutant concentrations and decreased water temperature. Maintenance of leaking sewers is constantly ongoing but is costly both in terms of money and time. Meanwhile, increased precipitation (due to climate change) is expected to result in higher peak flows at the WWTP. These challenges put pressure on the operation and management of integrated urban wastewater systems.

Model-based simulation studies can be highly useful in analysing the preparedness of the WWTP for meeting stricter effluent limits while being exposed to various future scenarios (Takacs *et al.* 1995; Harremös *et al.* 2002; Sharma *et al.* 2013). Life-cycle assessment (LCA) is another valuable tool to evaluate a future scenario based on its environmental impact. LCA is a cradle-to-grave assessment of the environmental impact of a process/product/activity during its entire life cycle (Pasqualino *et al.* 2009; Corominas *et al.* 2013). It includes the direct impacts from the process as well as indirect impacts arising from energy production, manufacturing, transport, and disposal of chemicals, equipment and raw materials etc. Integrating model-based analysis of future scenarios with LCA will allow us to predict the environmental impacts of a future process, of great aid towards a holistic decision-making process.

The methodology of combining process simulations and LCA has been successfully used in several case studies. Previously, focus has mainly been on combining process models with LCA and with limited information and analysis of future influent flow rate and temperature scenarios (e.g. Bisinella de Faria *et al.* 2015). In Åmand *et al.* (2016), dynamic process models were implemented and calibrated for three WWTPs in Sweden. The process models were combined with LCA models to evaluate the environmental impact of operating the treatment processes to meet stricter effluent criteria for nitrogen and phosphorus.

The current study presents a further development of the work presented in Åmand *et al.* (2016) by addition of influent generation models to analyse the impact of potential future scenarios. The main objective was to provide a tool for the wastewater treatment plants to simulate different future scenarios and evaluate the environmental impact of the

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operation of the treatment plant. An additional objective was to evaluate the environmental impact of future influent scenarios, including changes in infiltration and high peak flows while meeting more stringent discharge criteria for nitrogen and phosphorus. The results are presented in a case study for three WWTPs in Sweden: Henriksdal and Käppala (both in the Stockholm region) and Kungsängen WWTP in Västerås.

MATERIALS AND METHODS

Influent generation and process simulation is performed using calibrated dynamic models implemented in MATLAB®/Simulink®. The Benchmark Simulation Model No. 2 Greenhouse gases (BSM2G) (Flores-Alsina *et al.* 2014) is used to simulate the plant-wide dynamic operation of the three WWTPs. A description of the process model calibration can be found in Åmand *et al.* (2016) for all three case studies. The process model calibration for the WWTP model followed the steps described in Rieger *et al.* (2013) starting with model structure followed by influent fractionation, calibration of nitrification parameters, denitrification parameters and calibration of other models such as aeration model.

The model used for influent generation is based on BSM-UWS (Benchmark Simulation Model for Integrated Urban Wastewater Systems) (Saagi *et al.* 2016) describing four main components of the combined wastewater: domestic and industrial wastewater, infiltration water and stormwater. A dynamic dry weather profile is modelled using daily, weekly and yearly variation profiles, which are multiplied by the average flow rate and pollutant loads from domestic and industrial sources. Runoff due to rainfall or snowmelt is described in the stormwater model. Runoff from impervious and pervious surfaces is modelled separately. Infiltration is modelled dynamically based on annual variations in groundwater level and runoff from pervious areas. Additionally, wastewater temperature is modelled using daily and seasonal variations along with reduction in temperature due to precipitation or snowmelt events. The influent generation model calibration is performed in a series of steps beginning with the calibration of dry weather flows, followed by the calibration of wet weather flows and temperature as presented in Saagi *et al.* (2018).

The LCA is performed using the software GaBi Professional 8.6. Two functional units are used: (1) m^3 of treated water and (2) kg N removed. The method is summarised in Figure 1.

The expected future flows, connections, process configurations and discharge criteria of the studied WWTPs are summarised in Table 1.

Four scenarios have been studied and compared with a base-line scenario:

1. increased infiltration due to deterioration of pipes;
2. reduced infiltration due to sewer maintenance;
3. increased fast stormwater runoff, achieved by increasing the impervious area;
4. reduced stormwater runoff due to fewer incorrect network connections.

Scenarios 1 and 2 were achieved by adjusting the model parameter gw_{bias}, which corresponds to the yearly average groundwater flow rate leaking into the sewer. For scenarios 3 and 4 the impervious area (*imp_area*) was used to achieve effects on the peak flows in the influent. Both parameters were adjusted to ±50% of the base case values in order to achieve realistic changes in the influent of each WWTP.

The influent generation model did not include temperature changes related to the amount of infiltration water. To get an estimation of the effect of colder water temperature, scenario 1 for Henriksdal WWTP was simulated twice, first with no temperature effects due to the increased infiltration, and then with an assumed 2 °C reduction of the influent wastewater temperature.

RESULTS AND DISCUSSION

Process simulations were carried out for the base scenario and the four influent scenarios for all three WWTPs. The

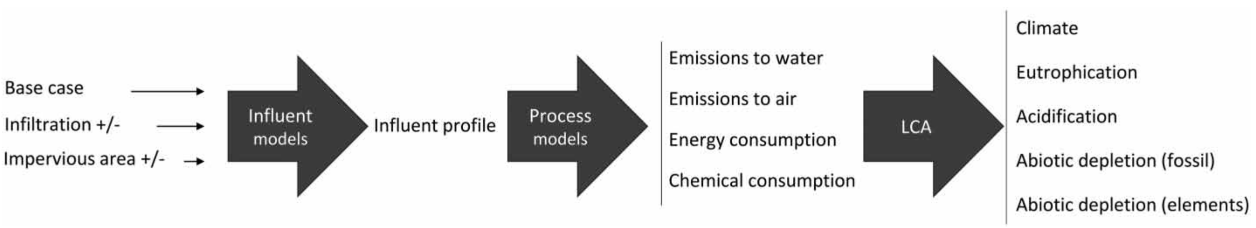

Figure 1 | Summary of the method, combining influent generation, process simulation and LCA.

Table 1 | Description of the future flows, connections, processes and discharge criteria for the three case studies

Case study (year)	Daily average flow rate (m^3/d)	Population equivalents (PE)	Process configuration	Effluent limits
Henriksdal (2040)	541,000	1,621,000	MBR with pre- and post DN, pre- and direct precipitation, wet weather treatment	TN 6 mg/L TP 0.2 mg/L
Käppala (2050)	198,000	900,000	ASP with pre- and post DN, pre- and post precipitation, anammox process for reject water treatment, wet weather treatment	TN 6 mg/L TP 0.2 mg/L
Kungsängen (2021)	49,000	140,000	ASP with pre-DN, pre-precipitation	TN 10 mg/L TP 0.2 mg/L

MBR, membrane bioReactor; ASP, activated sludge process; DN, denitrification; TN, total nitrogen; TP, total phosphorus.

effluent concentrations were kept below the effluent limits by process control strategies for aeration and chemical dosage. For Henriksdal, the infiltration in the base case accounted for 44% of the total inflow. When the parameter gw_{bias} was adjusted ±50% it resulted in infiltration corresponding to 50% and 35% of the total inflow for scenario 1 and 2 respectively. A comparison of the simulation results for Henriksdal WWTP for scenarios 1 and 2 shows increased flow to the wet weather treatment and increased effluent phosphorus peaks at increased infiltration (Figure 2). The effluent nitrogen concentrations show more variation with increased infiltration.

The scenarios were designed so that the variations in infiltration and peak flow events studied did not affect the pollutant load to each WWTP. This, in combination with concentration-based effluent limits, entails that increased infiltration, with diluted influent wastewater, result in a lower amount of pollutants to be removed in order to reach the effluent target concentration. The reverse was true for the scenario with decreased infiltration.

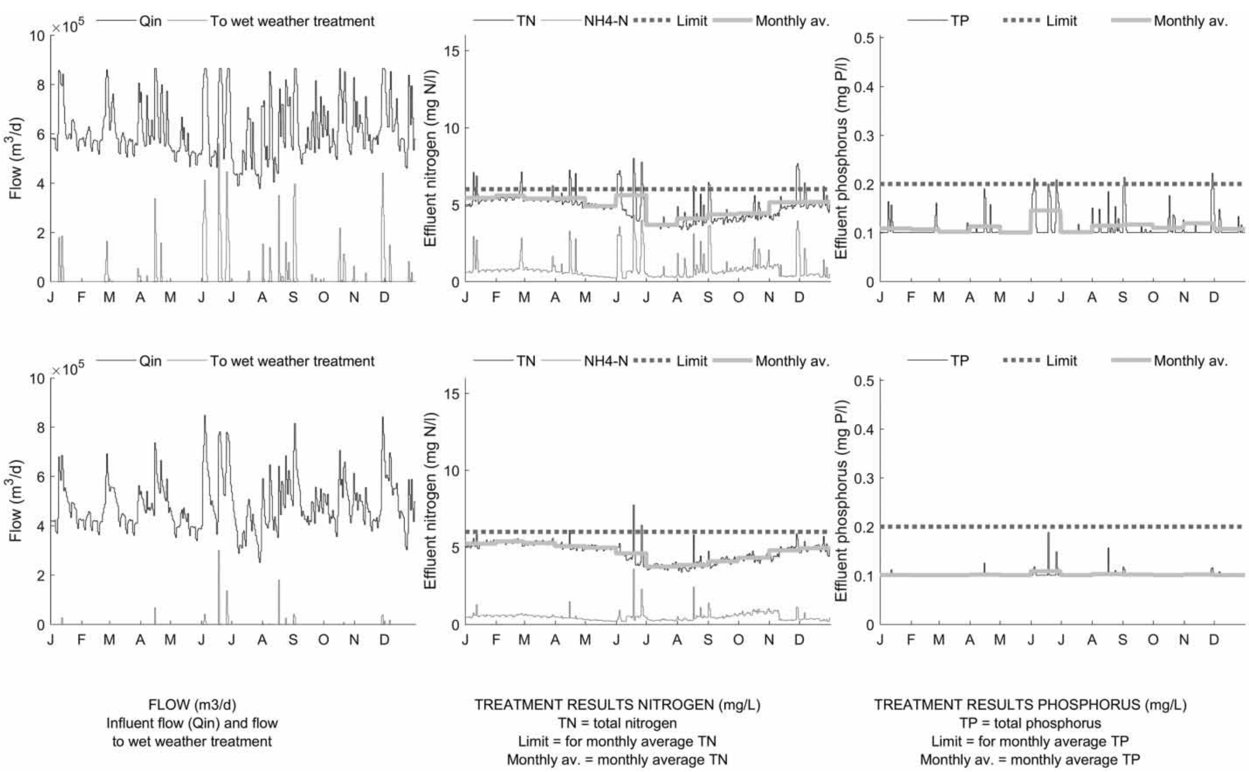

Figure 2 | Results from process simulations of Henriksdal WWTP for scenario 1 – increased infiltration (upper) and scenario 2 – decreased infiltration (lower).

For all case studies, the contribution from the peak flow events in scenarios 3 and 4 were small in relation to the total water volume treated. Peaks causing the influent to be directed either to wet weather treatment or to bypass the biological treatment only corresponded to 0.1%–2% of the total influent. For Käppala the scenario with increased infiltration resulted in a larger volume to the wet weather treatment than the scenario with increased fast stormwater runoff (Figure 3). The same was true for Henriksdal.

For Kungsängen, fast stormwater runoff corresponded to about 11% of the total influent in scenario 3. Even so, only about 2% of the total volume exceeded the capacity of the biological treatment and was bypassed to the effluent. Thus, the modelled effluent concentrations were not at risk of violating the effluent discharge limits (Figure 4). However, it is uncertain to predict limited settler performance during elevated flow rates, which in practice often results in increased effluent concentrations of total suspended solids, phosphorus and organic nitrogen. Moreover, problems such as sludge bulking that frequently occur during snowmelting and heavy rain events are not included in the settler model at all. This implies that the negative environmental impact of such events might be underestimated in the evaluation.

LCA results show that infiltration has a larger environmental impact than stormwater surface runoff and that the environmental impact per kg N removed decreases with decreased infiltration for all impact categories and for all case studies (Figure 5). However, the percentage decrease from the base case differs between the different plants. For instance, reduced infiltration from 44% to 34% for Henriksdal results in 17% less eutrophication potential, 8% less fossil resource consumption and 5% less climate impact. The positive effects would probably be even higher if temperature effects of changes in infiltrated water were modelled since reduced infiltration can result in an increased inlet water temperature, which facilitates efficient wastewater treatment.

When studying the environmental impact per m^3 of treated water, it is clear that the environmental impact has a reversed correlation to the amount of wastewater treated (Figure 6). For example, all impact categories decrease for all three WWTPs when infiltration increases (scenario 1). As the load is constant in all scenarios, the amount of pollutants removed is less with increased influent flow rate, which results in lower environmental impact per m^3 of treated water.

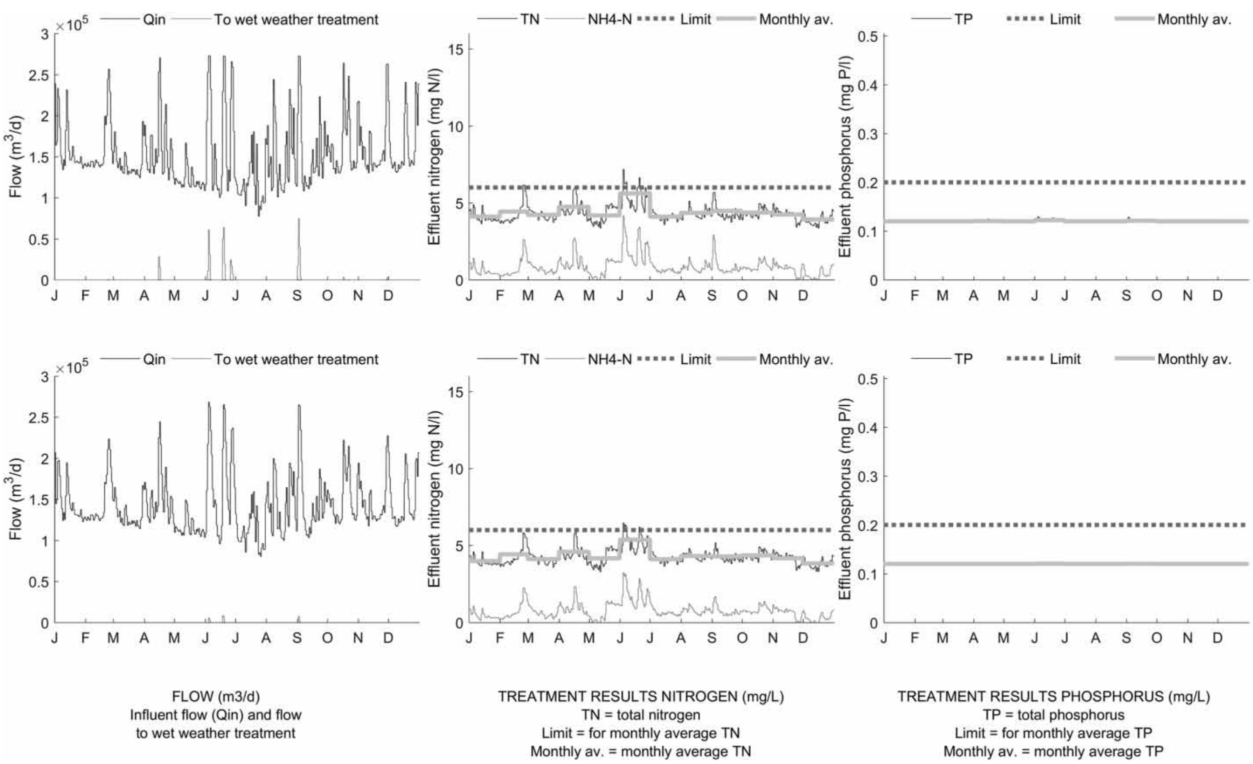

Figure 3 | Results from process simulations of Käppala WWTP for scenario 1 increased infiltration (upper) and scenario 3 increased fast stormwater runoff (lower).

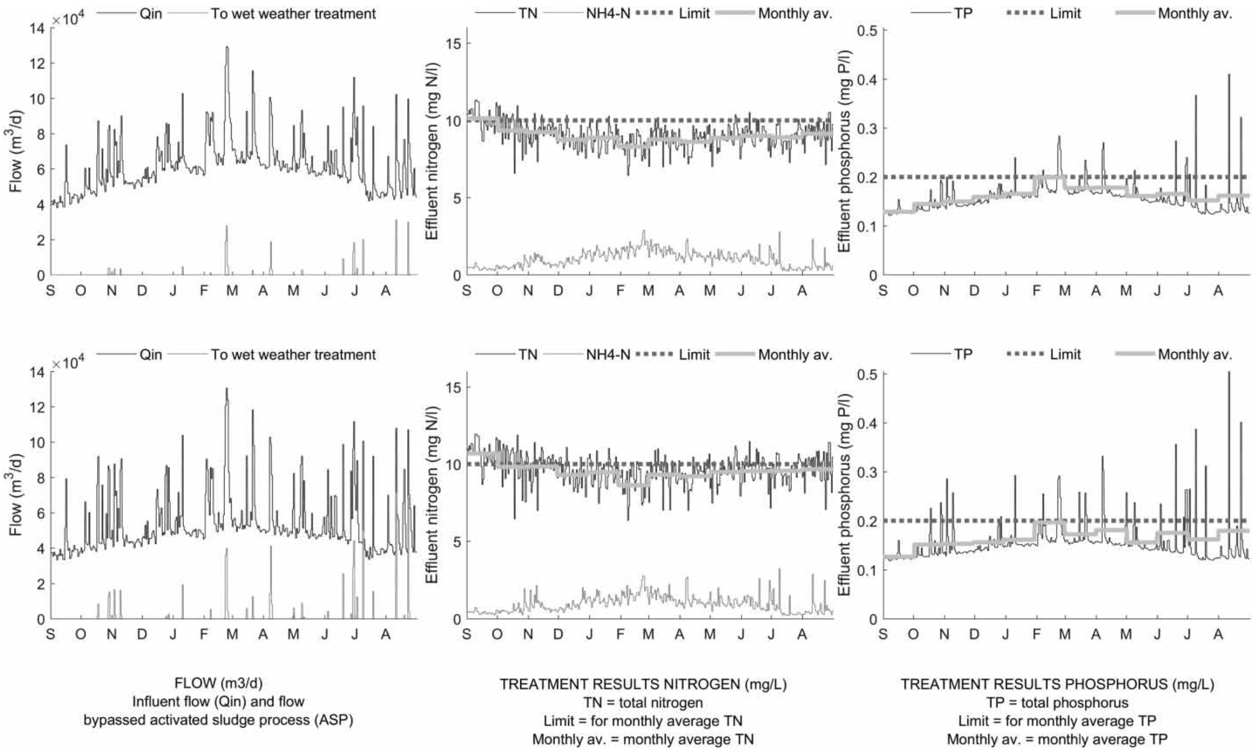

Figure 4 | Results from process simulations of Kungsängen WWTP for scenario 1 increased infiltration (upper) and scenario 3 increased fast runoff (lower).

The major contributors to changes in environmental impact per kg N removed due to changes in the influent for each impact category are presented in Table 2. Climate impact is mainly related to the direct emission of nitrous oxide from the treatment processes. Effluent nitrogen has the largest impact on eutrophication potential. Sludge storage impacts the acidification potential and the different process chemicals used have an impact on the abiotic depletion potential for both fossil and element resources. The environmental impact of pumping per m^3 of water does not change between the scenarios. However, it is notable that only influent pumping for Kungsängen and Käppala is included in Table 2 and it is only a major contributing factor to abiotic depletion potential for element resources. For Henriksdal the changes in abiotic depletion potential for element resources are mainly affected by the chemical usage.

The size and process configuration of the WWTP results in performance variation for the different impact categories. For instance, Henriksdal has the lowest climate impact but

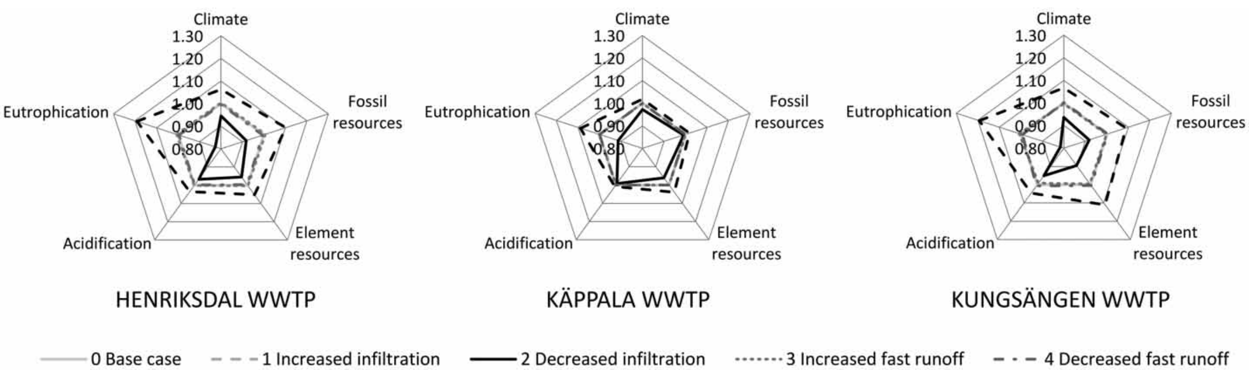

Figure 5 | Results from LCA evaluation of process operation in different influent scenarios. All results are normalised to the base case for each plant, respectively. The functional unit is 1 kg N removed.

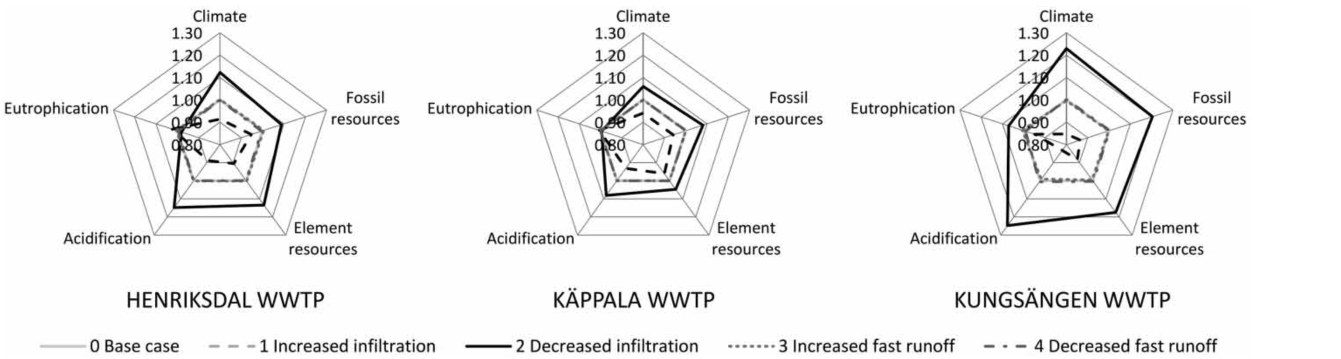

Figure 6 | Results from LCA evaluation of process operation at different influent scenarios. All results are normalised to the base case for each plant, respectively. Functional unit is 1 m^3 of treated water.

the highest element resource consumption for both functional units compared with Käppala and Kungsängen. This is illustrated in Figure 7, which shows the environmental impact per kg N removed. The relations between the different plants are similar for the functional unit m^3 of treated water. As Kungsängen has higher allowed nitrogen concentration in the effluent, the eutrophication potential is higher compared with Käppala and Henriksdal. Kungsängen also has the highest consumption of fossil resources, both per m^3 of treated water and per kg N removed. This is mainly caused by the addition of external carbon source (more than 50% of the fossil resource consumption for the Kungsängen base case is due to usage of external carbon source).

For Henriksdal, increased infiltration was also simulated with a decreased water temperature of 2 °C resulting in a yearly average of 13.7 °C. Compared with the default settings of scenario 1, without temperature effects, the most important changes due to lower temperature were increased external carbon source consumption (+140%), reduced nitrous oxide emissions from the biological treatment (−15%) and increased effluent total nitrogen (from 5.0 mg/L to 5.3 mg/L). The increase in carbon source consumption was large, however, initially the dosage was relatively low (6 mg COD/L) and accounted for 5% of the total contribution to abiotic depletion potential for fossil resources. The dosage at the lower temperature was in the same range as for Käppala (14 mg COD/L).

CONCLUSIONS

An influent generation model, plant-wide biochemical process models and LCA models have been successfully combined and used to demonstrate the evaluation of the environmental impact of future influent scenarios for three WWTPs in Sweden.

The results show that the environmental impact per kg N removed decreases with decreased infiltration. The

Table 2 | The major contributing factors to changes in environmental impact due to changes in influent for each environmental impact category for each of the three case studies when functional unit was 1 kg N removed

	Henriksdal	Käppala	Kungsängen
Climate	Direct N_2O emissions, Precipitation chemicals	Direct N_2O emissions	Direct N_2O emissions
Element resources	Precipitation chemicals, MBR cleaning chemicals	Precipitation chemicals, Influent pumping	External carbon source, Polymer, Influent pumping
Fossil resources	Precipitation chemicals	Precipitation chemicals, External carbon source (reversed impact)	External carbon source, Polymer
Acidification	Precipitation chemicals, NH_3 emissions from sludge storage	Precipitation chemicals	NH_3 emissions from sludge storage
Eutrophication	Effluent N	Effluent N	Effluent N

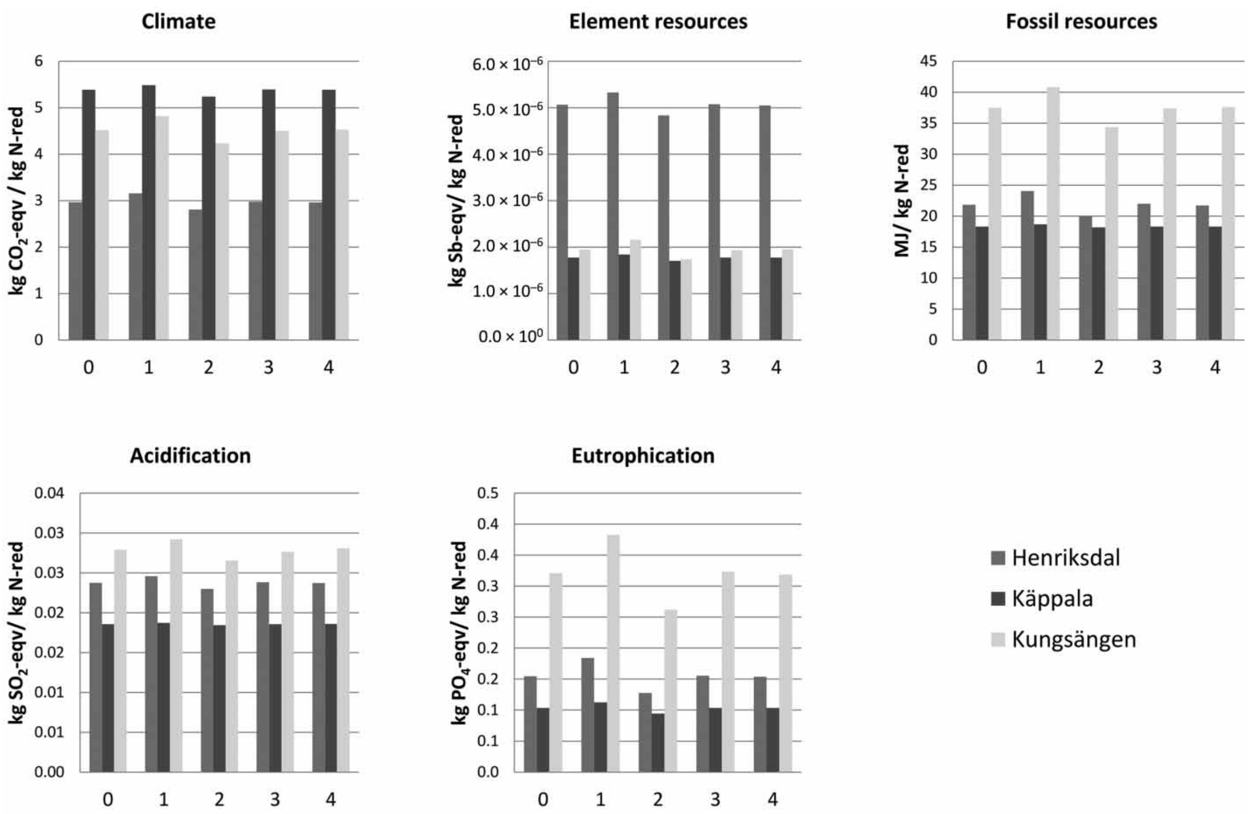

Figure 7 | Results from LCA evaluation of the different influent scenarios, 0 = base case, followed by scenarios 1–4. Functional unit per kg N removed.

changes in surface runoff have only a limited impact on the evaluation (less than 1% change from base case).

Lower water temperature caused by increased infiltration runoff resulted in reduced nitrogen removal and a large increase in carbon source consumption. This is important for the estimation of fossil resource consumption; future work should consider the implementation of temperature models for infiltration in the influent generator.

The presented methodology could be further used for numerous scenarios, including, for example, changes in precipitation and load as well as evaluation of process configuration or process control strategies.

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