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Published in:
WRRmod2021 Conference Proceedings

Publication date:
2021

Document Version
Publisher's PDF, also known as Version of record

P113 – Evaluating capacity liberation projects using a plant-wide model-based approach

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Keywords: digitalization, decision support systems, model based assessment, performance evaluation.

Introduction

The objective of this study is to develop a model based approach, to be used as decision support tool (DST), to assess capacity liberation /optimization options in a full-scale industrial wastewater treatment system. The proposed DST is fed by plant data (influent characteristics, operational and design conditions) and its prediction capabilities compared with reconciled measurements. *The main motivation of the research work is to provide process engineers with more informed decision-related removal efficiency, resource recovery and operational cost when running "what-if" scenarios*.

Methodological approach

Plant layout & measuring campaign

Figure 1 shows a schematic of the plant under study. Influent flow may be treated anaerobically or aerobically or both. Biogas goes through a cleaning process before being introduced to a gas motor for energy (electricity / heat) recovery purposes. Reject water from biomass dewatering can be sent to either the aerobic or anaerobic water lines (both is also an option). The effluent of the anaerobic line is sent to the activated sludge system.

Decision support tool: Main mathematical process model

The DST is based on: (1) a biological model, (2) a physico-chemical model and (3) model interfaces. The biological models comprise an anaerobic digestion model (ADM) and an activated sludge model (ASM). The physico-chemical model (PCM) includes an aqueous phase + precipitation model and a gas transfer model. Finally, the model interfaces include an ADM/ASM/ADM interface and PCM/ADM/ASM interface. The outputs of the ASM/ADM at each integration step are used as inputs for the PCM module to estimate pH, ion speciation/pairing, precipitation potential and stripping (Feldman et al.,2017; Flores-Alsina et al., 2019).

Results and discussion

Simulation of the BT, PRIM & PA units

Figure 2 shows that the influent fractionation algorithm can predict influent COD and pH measurements from the state variables used in the ADM1. Simulation results also show that the DST developed in this study is capable to describe the main transformations within the first three units of the flow diagram. In the buffer tank, mainly stream neutralization takes place, combined with volatile fatty acid (VFA) production and denitrification (see pH and NOx values in **Figure 2**). In the primary clarifier, a fraction of the CODp, TNp and TPp is removed and sent to the sludge line. Finally, in the pre-acidification tank there is a higher VFA production with a subsequent decrease of pH due to the presence of acidogenic microorganisms. Both model/data indicates that about 12% of COD is lost as N_2 and H_2 in both tanks and subsequently not recovered in form of energy

Simulation of the Anaerobic Water Line

Simulation results show that the DST correctly predicts hydrolysis, acidogenesis, acetogenesis, sulfidogenesis, methanogenesis, weak acid-base chemistry, and N and P release (see COD, SO_4^{-2}, NH_4^+, PO_4^{-3}, ALK, pH and VSS/TSS values in **Figure 2**). This provides a methane yield of 350 (Nm^3 CH_4/ton COD converted) which translated into 47.4 and 54.3 MWh.day^{-1} of electrical and thermal energy recovered, respectively.

Simulation of the Aerobic Water Line

Figure 2 shows that the proposed approach describes COD, N and P removal processes (chemically with $AlCl_3$). The model also captures the operational VSS, the secondary settling efficiency and the quantity of sludge sent for stabilization, dewatering and treatment at a nearby central biogas facility (see **Figure 1**).

Optimization scenarios

The DST was used to assess three scenarios (See **Table 1** for change in the main sources of revenue and cost of the plant). S1 consists of doing a separated dewatering of the waste activated sludge, which effectively bypasses the inactivation tank, reducing mainly chemical consumption (CaO) and aeration energy to process the extra load of soluble organics that the inactivation step releases. S2 is the inactivation of part of the production biomass stream, which has impact on chemical and power consumption but due to the fact that this stream is highly loaded in soluble N and COD that would otherwise be treated aerobically. S3 is both previous scenarios combined, the effect of both improvements increases by 5.2% the revenue of the plant due to more cake being sold to the off-site biogas plant; and reduces costs by 7.2% respect to the baseline scenario due to the mechanisms explain before. In S3 capacity liberation is achieved in the inactivation tanks due to lower influent volumetric flow rate (+46%), and in the activated sludge units due to the lower organic load, which allows to reduce VSS concentration in the tanks while maintaining the same sludge age (+18%).

Conclusion, Outlook & Opinion

The plant under study is the largest iWWS in northern Europe, and handles the solid and liquid streams from two biotech and pharma companies. The proposed set of models correctly describe all the main treatment processes of the flow diagram depicted in **Figure 1** and can be used for plant wide optimization purposes. The global deviation between model predictions and reconciled measurements, for all components and locations, is 12.7%.

Having a well calibrated plant-wide model is a useful tool that can support the decision making process with both technical insights in the process and with economic information for a proper investment analysis. Besides economics, the evaluated scenarios presented in this work contribute to improve sustainability of the process in form of lower chemical and energy usage and increased organic matter availability for off-site biogas production. Scenario 3 will be fully implemented in full scale, having been commissioned the part corresponding to S1 and S2 in project phase.

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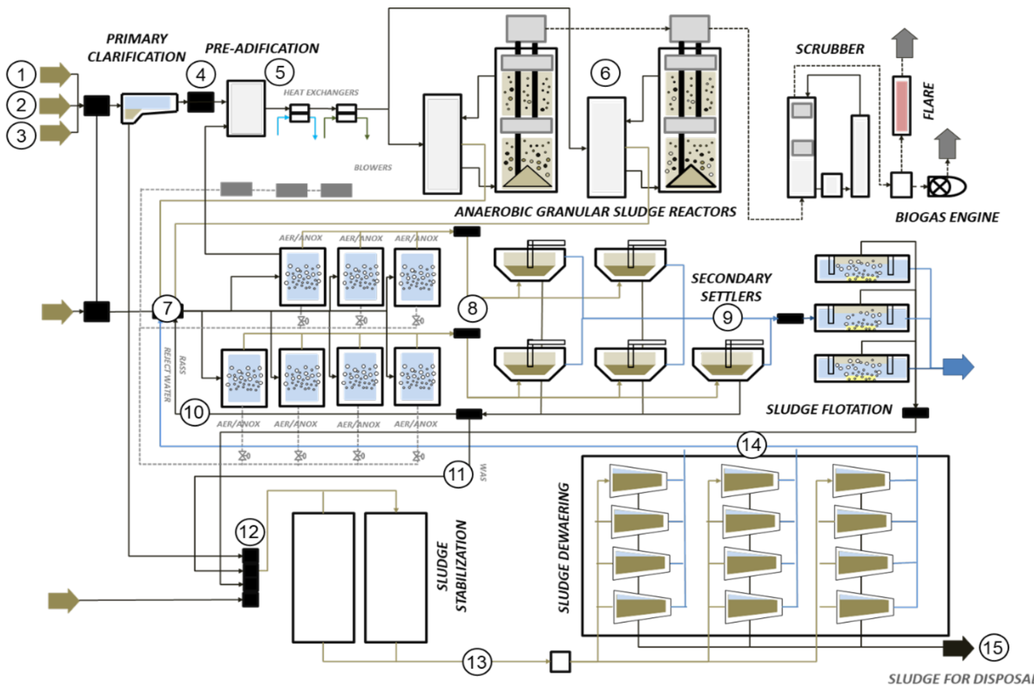

Figure 1 Flow diagram of the iWWS under study. Measured and model-predicted streams: 1, Influent factory 1; 2, Influent factory 2; 3, Influent factory 3; 4, Primary settler overflow; 5 Pre-acidification tank effluent; 6, Anaerobic digesters effluent; 7, Activated sludge influent; 8, Activated sludge effluent; 9, Secondary clarifiers overflow; 10, Returned activated sludge; 11, Waste activated sludge; 12, Inactivation influent; 13, Inactivation effluent; 14, Dewatering reject water; 15, Dewatered cake.

Table 1. Overview of Revenues and Costs change in three different optimization scenarios. **S1**: Separate dewatering of waste activated sludge; **S2**: Dry inactivation of production biomass; **S3**: S1+S2.

REVENUES	S0	S1	S2	S3	
Electricity Produced	0	0	0	0	%
District Heat Sold	0	0	0	0	%
Cake Out	0	0.8	11.6	13.2	%
Total percentage	**0**	**0.4**	**5.1**	**5.8**	**Total %**
COSTS	**S0**	**S1**	**S2**	**S3**	
Electricity Aeration	0	-5.4	-12.5	-16.5	%
Gate fee Cake	0	-0.1	0.1	-0.1	%
NaOH Anaerobic Digesters	0	0	0	0	%
NaOH H_2S Removal	0	0	0	0	%
PAX SEC	0	-5.2	-13.5	-16.2	%
PAX DW Main	0	-4.4	-11.1	-14.3	%
PIX DAF	0	-0.9	-0.5	-1.2	%
Polymer SEC	0	-5.2	-13.6	-16.3	%
Polymer DAF	0	-0.9	-0.5	-1.2	%
Polymer Dewatering	0	-4.4	-11.1	-14.3	%
CaO Stabilization	0	-46.7	-8.8	-47.2	%
Pumping CAS	0	-5.2	-13.5	-16.2	%
Pumping AGS	0	0	0	0	%
Pumping Stabilization	0	-2.2	-11.3	-12.8	%
Pumping Dewatering	0	-4.4	-11.1	-14.3	%
Discharge fee	0	-0.9	-0.5	-1.3	%
Total percentage	**0**	**-4.8**	**-3.4**	**-7.2**	**Total %**

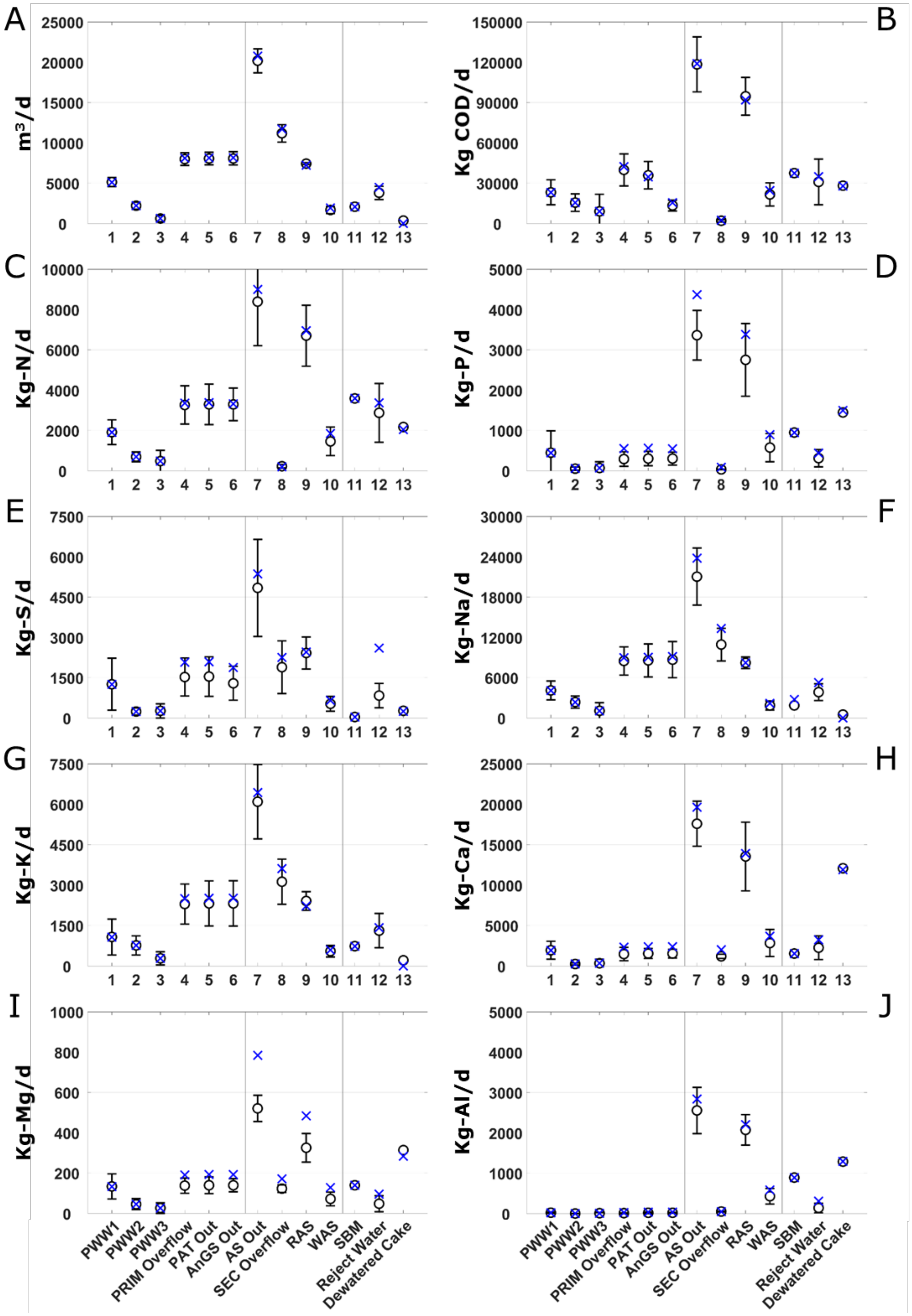

Figure 2 Steady state model predictions (blue crosses) and reconciled measurements mean and standard deviation (Black circles and whiskers) for several plant locations. A: volumetric flow rate (0.5%); B: TCOD (0.1%); C: TN (1.3%); D: TP (35.2%); E: TS (-0.3%); F: TNa (5.5%); G: TK (1.1%); H: TCa (25.7%); I: TMg (38.4%); J: TAl (18.5%). Numbers in bracket indicate the median deviation across all plant locations.

P114 – Integrated modelling for systems of hydraulically connected WRRFs – Analysis on the potential to holistically reduce energy use, costs and indirect GHG emissions

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Keywords: Carbon footprint; decentralized treatment; integrated modelling; load shifting; urban water management; water-energy nexus

Introduction

As growing peri-urban regions continue to expand, the global discourse concerning municipal wastewater management has shifted toward decentralized wastewater treatment (Garrido-Baserba et al., 2018; Libralato et al., 2012). Decentralized water resource recovery facilities (WRRFs) that are hydraulically connected to the centralized sewer collection system are known as satellite WRRFs (Larsen et al., 2013). The expectation for satellite WRRFs is not to replace existing centralized infrastructure, but to gradually be integrated within existing urban water systems thus establishing hybrid systems (Daigger and Crawford, 2007).

Satellite WRRFs are able to provide cheap and reliable recycled water to meet local water demand needs. As water stressed cities continue to expand, so will the installation of decentralized treatment facilities in peri-urban areas. Therefore, the progressive implementation of decentralized water solutions will require the harmonious integration with pre-existing centralized urban infrastructure and services.

The adoption of integrated modelling tools has served the ability to analyze holistic strategies that optimize the operation of the various sub-systems that make up the integrated urban wastewater system (IUWS), such as sewer networks, wastewater treatment plants, and riverine ecosystems (Bach et al., 2014; Benedetti et al., 2013). However, little to no consideration has been given to the spatiotemporal interactions that occur between systems of hydraulically connected WRRFs, and furthermore how such interplay can be leveraged to improve the overall performance of the IUWS.

This study provides a new conceptual framework for the dynamic management of hybrid systems comprised of both centralized and satellite wastewater treatment plants. An integrated model is developed using data from a regional hybrid system comprised by 8 WRRFs. Our analysis shows the potential to lower GHG emissions, power demand, energy use, and costs by dynamically shifting the diurnal influent wastewater loads between hydraulically connected treatment facilities.

Methodological Approach

For the case study, a system of 8 hydraulically connected plants is considered (see Figure 1a). The Matlab/Simulink® environment provides the ability to describe the dynamics via a system of interconnected block diagrams. The main inputs of the integrated model are influent flow, concentrations of influent constituents, energy generation emission factors, time-of-use energy tariff structure, and dynamic □F factors. The main biological processes occurring in the bio-reactors are modelled using the ASM1 structure. Diurnal influent flow and concentration profiles for two of the eight facilities (Sat2 and Sat4) were obtained from facility records. For the other six facilities, the circadian load and concentration curves were constructed consistently from the available profiles. The characterization of the influent aggregate variables, such as chemical oxygen demand (COD) and total Kjeldahl nitrogen (TKN), was conducted by implementing daily average grab sample measurements. To ensure that the fractional proportion of each aggregate variable was in the typical range for municipal wastewater, the influent fractionation toolbox from SUMO® v.20 (Dynamita; Nyons, France) was utilized. A 2-tier energy tariff structure is adopted by a local energy provider with a high energy cost between 16:00 and 21:00 (on-peak) and a lower energy cost during the remaining hours (off-peak).

Three different scenarios are considered in this study, and each is based on a scheduled load shifting of the influent load of each satellite wastewater treatment plant to the centralized treatment facility. The underlying concept of such strategy relies on exploiting the hydraulic delay of the sewer system for the deferral of the treatment intensity between hydraulically connected facilities (see Figure 1b). The dynamic load shifting strategy of each scenario is illustrated in Figure 1c considering a single satellite plant and the receiving centralized WRRF.

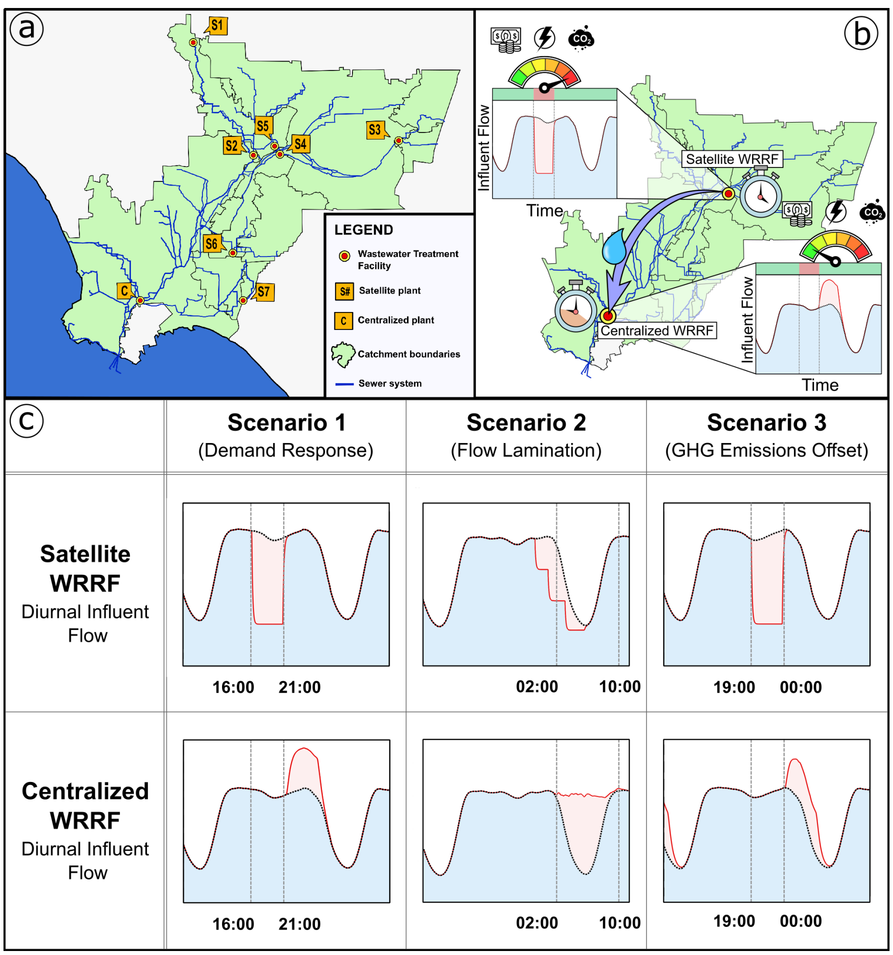

Figure 1 (a) Schematic of the system of WRRFs considered for the case study. (b) Conceptual illustration of the load shifting strategy between facilities. (c) Three load shifting scenarios considered.

In Scenario 1, the load shifting strategy is employed as a means to shift the power demand required for wastewater treatment to the centralized facility following the electrical grid ramping hours.

In Scenario 2, the equalization of the influent flow of the centralized plant is prioritized. Three monotonically decreasing influent set points are considered for each of the satellite plants, with the lowest being the minimum daily flow average. The scheduling times of the three setpoints are parameterized and are used as decision variables during an optimization phase.

In Scenario 3, the time intervals of the load shifting events are centered around the peak indirect GHG emission hours for the system of facilities. Such emissions typically fall between 19:00 and 00:00. The peak emission hours were retrieved by multiplying the power demand of the facilities at each time step by the local instantaneous dynamic energy emission factor.

Results and Discussion

For Scenario 1, the reduction in power demand during grid ramping hours is highlighted by the shaded light blue area seen in Figure 2a, with an estimated average and maximum power reduction of 3.7 MW and 5.5 MW (or 25%), respectively. Such scenario also provides the most cost-effective option with a monthly savings of 138,000 USD mo^{-1} (or 8.5% - see Figure 2d). This finding suggests the ability of hybrid WRRFs systems to introduce flexibility into the power markets by shifting energy consumption between hydraulically connected plants, without the need to shutdown treatment operations.

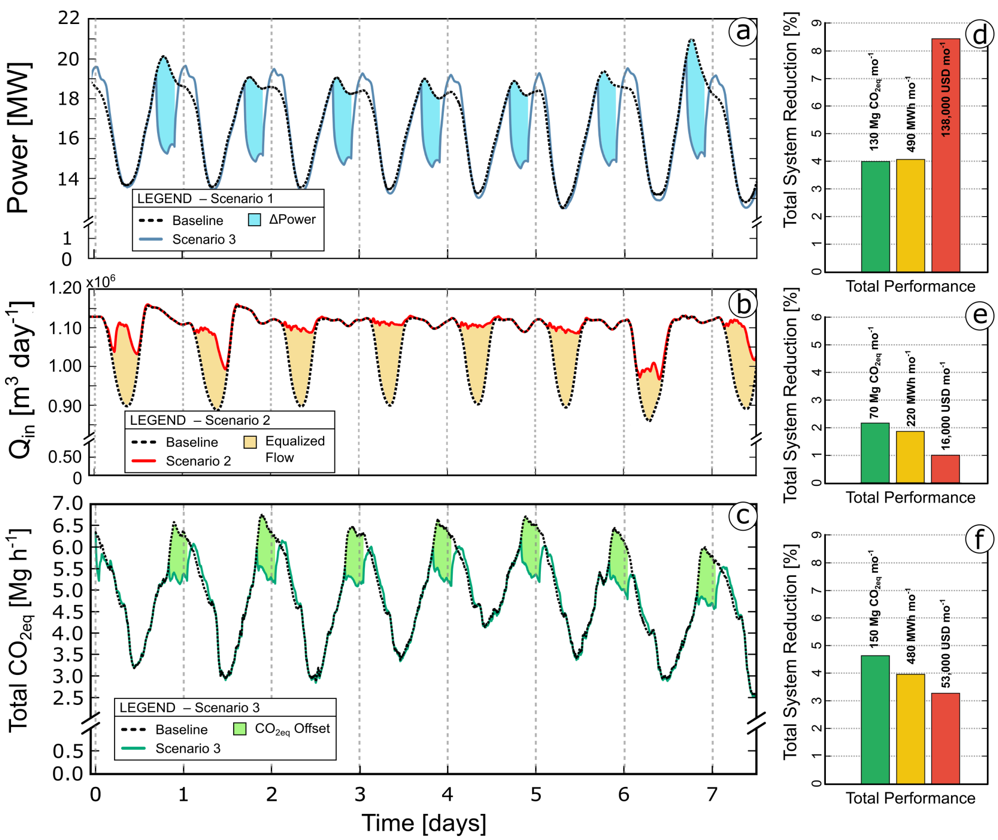

Figure 2 (a) Total power demand profiles for baseline conditions and for the demand response load shifting strategy (Scenario 1). (b) Baseline and Scenario 2 flow profiles for the centralized plant. (c) Total GHG emissions profiles for baseline conditions and for the GHG offset strategy (scenario 3). The reduction in terms of GHG emissions, energy and costs is shown for scenario 1 (d), scenario 2 (e) and scenario 3 (f).

In Scenario 2, by correctly timing the influent set point according to a 3-tier strategy, the compounded diverted flows of the satellite plants allow the significant reduction of the drop in influent flow of the centralized plant during low loading hours, as shown by the orange shaded area in Figure 2b. This type of equalization provides a resourceful tool for centralized facilities that do not have access to neighboring land for the construction of equalization tanks. As such, flow equalization can still be achieved without the need to undertake expensive equalization projects.

For Scenario 3, Figure 2c shows the equivalent CO2 emission rate expressed in megagrams (or metric tons) per hour, and the indirect GHG emissions avoided during the load shifting events (green shaded area). Thus, hybrid systems have the ability to curtail their indirect carbon emissions by shifting their electricity use to periods when the power supplied has a lower carbon intensity. Such a capability expands the ability of local sanitation districts to enter climate change solution initiatives.

It is worth mentioning that when considering the implementation of inter-facility influent load shifting strategies, it is important to perform an analysis of the volumes of water displaced. In fact, as satellite systems often stem from the need to provide locally reclaimed water, the diversion of influent flows toward the centralized facility may conflict with the reclamation targets of the individual satellite plant. In our study only 6.8 to 12.7% of the total influent flow of each satellite plants is diverted to the centralized plant for each of the three scenarios. Therefore, the ability to meet the water reclamation targets of each satellite facility is unaffected. For more details on this analysis the reader is referred to the work presented in Reifsnyder et al., 2021. However, it is noteworthy to point out that the constraints posed by water reclamation targets will also vary seasonally with the winter months usually defined by a lower demand for reclaimed water when compared to the summer months. Therefore, integrated load shifting strategies are expected to also vary according to the seasonal water reclamation constraints of the region. This analysis, although not considered here, should be informed by future studies.

Conclusions

1. A novel integrated modelling analysis based on intra-facility influent load shifting shows the potential to reduce overall energy use, power demand, costs and GHG emissions.
2. In contrast to isolated decentralized treatment facilities, hydraulically connected WRRFs systems have the ability to improve their overall performance by dynamically shifting the influent load between plants.
3. This study invites wastewater treatment facilities that would normally operate in isolation to pursue integrated dynamic strategies that align with commonly shared goals which benefit the system as a whole.

Opinion

This research provides a new facet to the ongoing modelling discourse in the field of integrated modelling by extending the analysis of IUWS to other sectors of the urban sphere, such as the local economy, the power supply, and the regional carbon footprint. Such analysis embraces the adoption of interdisciplinary studies in the field of integrated urban water modelling (Bach et al., 2014).

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