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Evaluation of Nutrient Recovery Potential through Wastewater Reclamation for Irrigation

To cope with water scarcity, assessing the viability of applying treated wastewater for irrigation – while preserving nitrogen and phosphorus – is gaining growing importance. For this objective, a small-scale activated sludge system receiving concentrated sewage with water demand for irrigation during summer was examined. This paper evaluates the facility's performance with various combinations of loading parameters using a probabilistic method, complying with a probability of 98% regarding requirements of organic matter removal and 79% concerning full nitrification. A sensitivity analysis was conducted where sludge age was shifted from 21 to 5 days during the irrigation period, allowing organic biodegradation while preserving nutrients in the water. Excess biological phosphorus removal could be observed at low aeration intensity; however, it became negligible as the dissolved oxygen concentration increased. Length of the transitional period from summer to winter operation regarding biomass activity was found to be approximately one week. Results of the study highlight the potential for reuse of treated municipal wastewater for irrigation, with robust operational performance and efficient retaining of nutrients in activated sludge plants.

Keywords: *irrigation, mathematical modelling, nutrient recovery, wastewater, water scarcity*

Introduction

Scarcity of water is a significant issue impacting several regions worldwide.[2] The availability of surface water and groundwater is proving to be a major concern as the human population grows and the demand for pure water by agriculture, industry and households increases. Supplementing freshwater resources with purified wastewater for irrigation is an increasingly common solution for addressing this challenge. Irrigation contributes to a large fraction of

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2 Liu et al. 2017: 545–559.

global water consumption, being an essential practice in agriculture.[3] The use of treated sewage for irrigation is becoming a widely accepted alternative as water scarcity progressively becomes more severe. Reclaimed wastewater is applicable for a variety of use cases including irrigation, since it undergoes mainstream treatment and effluent polishing processes that remove contaminants according to regulations.[4]

Reuse applications of municipal sewage for irrigation are present in many regions of our planet: the Middle East faces freshwater shortages, so for example countries such as Israel, Jordan and Saudi Arabia rely heavily on reclaimed water for agricultural irrigation.[5] Countries in Northern Africa also rely on purified sewage for aiding agricultural production, integrated technological and management tools have been implemented with regards to water reuse.[6] Effluent wastewater is used as a surrogate source of freshwater for agricultural irrigation in arid and semi-arid regions, within certain parts of Asia[7] and Latin America,[8] as well as in urban and peri-urban areas. Europe's Mediterranean region is also known to face freshwater challenges periodically. A golf course irrigation project in France revealed that the requirement for fertilisers had decreased by 67% because of using treated wastewater as a supplement for irrigation.[9]

The reuse of treated wastewater holds significant potential for military operations, particularly in arid or remote environments where water scarcity presents logistical challenges. By implementing systems for recovering nitrogen and phosphorus from wastewater, military bases and field camps can potentially reduce their reliance on external water sources while ensuring adequate supplies for irrigation and other non-potable uses.[10] This practice also promotes sustainability by providing a reliable source of nutrients for food production in isolated locations. Moreover, dynamic wastewater treatment systems can adapt to changing operational needs, offering flexibility for both peacetime and conflict settings. Incorporating these technologies into military infrastructure could strengthen the resilience and operational self-sufficiency of water-scarce regions.[11]

Numerous studies have examined the potential environmental impacts of irrigation by applying wastewater, showing considerable effects on water resources, soil and the growth of plants. Impacts on soil include heightened nutrient concentrations and organic material content, alterations in the microbial composition of soil, among other issues like salinisation. The nitrogen content of soil can be boosted by utilising treated wastewater for crop irrigation, serving as a fertiliser rich in inorganic nitrogen. Therefore, nitrogen availability of the soil is improved by wastewater-supplemented irrigation. Not only does it provide a nitrogen source,

[3] Chaturvedi et al. 2013: 389–407; Pathak et al. 2022: 941–954; Bontemps–Couture 2002: 643–657.
[4] Hashem–Qi 2021; Ofori et al. 2020.
[5] Bahadir et al. 2016: 1284–1304.
[6] Frascari et al. 2018: 447–462.
[7] Chen et al. 2022.
[8] Soto-Rios et al. 2023.
[9] Ait-Mouheb et al. 2018: 693–705.
[10] Medina–Waisner 2011: 357–376.
[11] Dénes 2011: 163–172.

but it also promotes nitrogen uptake in crops as it enhances the mineralisation rate.[12] Likewise, the phosphorus content of soil could also be ameliorated by reclaimed wastewater serving as an indirect recycling mechanism.[13]

Plants not adapted to higher salt concentrations are particularly vulnerable to negative impacts, however, the effect of salinity may vary depending on the species of plant – ones tolerant to high salt content are affected to a lesser extent. To prevent the salinisation of soil when applying sewage for irrigation, regulating salinity is crucial.[14] Microorganisms in soil are also impacted by irrigation with recycled wastewater, microbial activity and biomass content may show notable increases. A higher diversity of microbial populations can increase the rate of cellulose degradation, making nutrients more accessible to plants. Furthermore, promoting microbial diversity and activity can assist in maintaining the integrity of soil and the overall health of plants – growth is stimulated, soil quality is improved, and protection is provided for both plants and soil against contaminants.[15] Particulate matter in wastewater reclaimed for irrigation has the potential to obstruct pores in soil, thus, the risk of runoff is increased as the infiltration rate diminishes.[16]

Preserving and improving the quality of freshwater resources can be supported by recovering wastewater for irrigation. This is feasible by reducing water pollution through avoiding the discharge of sewage into water bodies and by decreasing the usage of mineral fertilisers in agriculture.[17] Certain countries have stringent policies implemented for administering the reuse of wastewater, however, most of them lack regulations.[18]

Due to requirements involving low sodium concentrations, reverse osmosis applications are common in the production of water for irrigation. However, the feasibility of this technology is limited when it comes to productive use in agriculture due to the removal of essential nutrients. Consequently, research was conducted on methods of desalination without removing nutrients. An integrated system has been proposed that incorporates microfiltration, nanofiltration and reverse osmosis membranes capable of retaining crucial nutrients while reducing salinity for irrigation. Suspended solids are rejected by microfiltration equipment and divalent ions and nutrients such as Ca^{2+} and Mg^{2+} are concentrated by nanomembrane filters. Due to molecular cutoff weight, nanofiltration is more likely to reject divalent ions than monovalent ions, such as Na^{+} and K^{+}.[19] Nanofiltration concentrate is then diluted with reverse osmosis permeate so that the sodium content is balanced. In a comparative study the reclamation of tertiary treated sewage effluent using nanofiltration and reverse osmosis was evaluated. According to the results, reverse osmosis is a suitable method for supplying

12 Quemada et al. 2016: 341–368.
13 Damalerio et al. 2022: 343–348.
14 Zikalala et al. 2019.
15 Mkhinini et al. 2020.
16 Liu et al. 2022: 4171–4181.
17 Chojnacka et al. 2020.
18 Hashem–Qi 2021.
19 Mrayed et al. 2011: 144–149.

polished effluent wastewater to irrigate crops grown for food production. However, due to its low rejection ratio of monovalent ions, nanofiltration was found not to be suitable.[20]

In another study focusing on reuse applications, a two-step treatment technology was presented, incorporating a conventional activated sludge system for organic biodegradation combined with a biological aerated filter; featuring a flexible operation mode that allows the production of discharge water that is rich in nutrients during periods with irrigation and nutrient-scarce during seasons without irrigation. The nutrient removal step is only necessary when the effluent requires storing or discharging. It was found that implementing nitrification after a standby period was faster than during the initial start-up procedure. Moreover, the storage conditions of the biomass during the standby interval affect the time required to achieve full nitrification during periods involving irrigation.[21]

Modelling encompasses two fundamental approaches – either following the principles of the Life Cycle Assessment where a wide range of influencing factors are considered with a particular emphasis on water footprint,[22] or evaluating the efficiency of wastewater treatment plants on a mass balance basis. The first approach is holistic, whilst the latter – derived from the description of biokinetic processes – is deterministic. The Regional Water Reuse Model proposes a decision-support tool utilising a general algebraic modelling platform. It was developed to evaluate the cost-effectiveness of various treatment alternatives for producing source water from reclaimed sewage that meets crop requirements regarding irrigation. The model identifies optimal solutions using a cost-minimisation framework.[23] Another study presents an integrated modelling approach focusing on contaminants of emerging concern. Thirteen pollutants were investigated based on their chemical properties and potential hazardous characteristics to evaluate their environmental and human health risks. Predicted concentrations of the constituents were in good agreement with measured data, suggesting that – because of their limited attenuation – some of these pollutants could pose potential concerns surrounding ecotoxicity.[24]

Mathematical process simulation incorporates several sub-models describing wastewater treatment using dynamic computations – integrated using an ordinary differential equation solver – accounting for environmental and operational conditions that change over the course of time. Based on input data, such methods can predict the water quality of treated effluents.[25] One such application features the simulation environment GPS-X coupled with CapdetWorks to estimate the performance of different wastewater treatment technologies and concludes that microbial risks could effectively be reduced by employing adequate tertiary treatment on wastewater for the purpose of irrigation.[26]

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[20] Hafiz et al. 2021.
[21] Norton-Brandão et al. 2013: 85–98.
[22] Moretti et al. 2019: 1513–1521.
[23] Tran et al. 2016: 9390–9399.
[24] Delli Compagni et al. 2019.
[25] Sadri Moghaddam – Pirali 2021: 67–76.
[26] AbdelMoula et al. 2021.

The referenced studies stress that irrigation by reclaimed water entails technical, legal, as well as socio-economical aspects. The present study focuses on the improvement of existing wastewater treatment technologies that feature biological nutrient removal. It examines shifts in operating conditions involving summer periods when the effluent wastewater can be utilised for irrigation. It seeks to determine the amount of nutrients potentially recovered by varying the sludge age, the required adjustment to aeration intensity according to these conditions, along with the time requirement associated with the transition between two operational periods.

Materials and methods

To provide effluent quality estimation and recommendations regarding operational parameters, biokinetic models were simulated dynamically. Biochemistry-based mass balance analysis is a widespread practice in the process design and optimisation of water resource recovery facilities. The novelty of this paper lies in presenting an operational setup oriented towards use cases in irrigation. Even though certain treatment plants may meet water quality criteria regarding irrigation, there is no general guideline to facilities for operational adaptation between periods with and without irrigation.

Description of the studied facility

According to this paper's objectives, a low-capacity wastewater treatment plant in Hungary incorporating an activated sludge process – with a dry weather peak flow of 810 m^3/d – was selected as the site of the study, broadly corresponding to a population equivalent of 7,500. The process layout consists of mechanical pre-treatment featuring screens and sand traps, primary clarifiers to remove settleable solids, and a biological reactor cascade in a Modified Ludzack-Ettinger configuration including anoxic zones followed by aerobic zones for implementing pre-denitrification and nitrification – nitrate transport is facilitated by internal recirculation from the last aerobic cell to the first anoxic cell. The mixed liquor suspended solids – separated by a secondary clarifier from the water phase – are pumped back to biological treatment via the recirculated activated sludge stream. Prior to secondary sedimentation ferric ions are dosed for chemical phosphorus removal. Solids treatment processes (thickening and dewatering) in the sludge line are implemented in a combined unit for sludge volume reduction, with reject water redirected prior to the bioreactor cascade. As this is a small-scale treatment plant, it does not incorporate anaerobic digestion, the dewatered sludge is transferred to another, higher capacity facility. Figure 1 illustrates the process configuration set up in the simulation software GPS-X 7.0. – the model layout is simplified and does not show details regarding internal recirculation or chemical dosing. Biological treatment consists of a cascade of six – three anoxic and three aerobic – completely mixed zones.

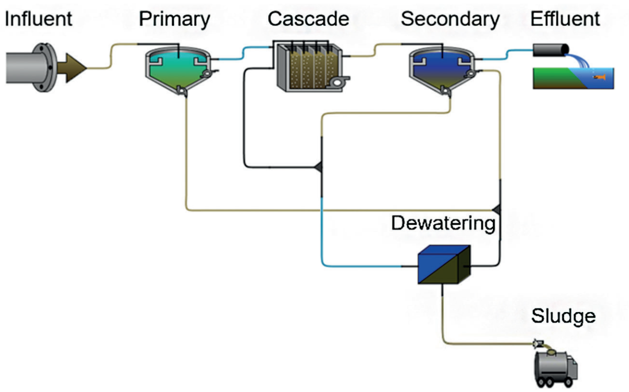

Figure 1: Process model configuration of the studied wastewater treatment plant
Source: compiled by the author

The actual loading conditions of the studied facility involve influent wastewater temperature in the range of 11 to 23 °C, operated at an average sludge age of 21 days with the concentration of mixed liquor suspended solids at 3.5 g/l, the dissolved oxygen concentration ranging from 1.5 to 2 mg/l in the aerobic compartments. The flow rate of internal recirculation averages to 3 times that of the influent, while the mean ratio of flow rate between recirculated activated sludge and influent is 1.2. The combined sludge treatment unit process features solids capture of 92.5%. Table 1 summarises the parameters regarding dimensions of unit operations.

Table 1: Main input parameters regarding dimensions of the studied configuration

Parameter	**Value**	**Unit**
Surface area of primary clarifier	38.5	m^2
Depth of primary clarifier	3.5	m
Biological reactor anoxic zone volume	600	m^3
Biological reactor aerobic zone volume	600	m^3
Depth of biological reactor cascade	4.0	m
Surface area of secondary clarifier	77.0	m^2
Depth of secondary clarifier	4.0	m

Source: compiled by the author based on design specification

Numerical methods of modelling wastewater treatment

Simulating processes in water resource recovery is complex and relies on numerous sub-models, such as hydraulic models, units fractionating influent wastewater constituents,[27]

[27] Orhon–Çokgör 1997: 283–293.

phase separation concepts,[28] equations describing gas exchange, process control logic, as well as biokinetic matrices. Biokinetic simulation is a widely adapted approach of describing biochemical reactions that take place in water resource recovery facilities. Activated Sludge Models are biokinetic models that rely on Monod-kinetics to simulate microbial growth and decay metabolisms in the activated sludge technology, one of the most applied processes in municipal sewage treatment.[29] Good Modelling Practice guidelines in the field of wastewater treatment have been developed by the International Water Association. Aiming for the utilisation of models in a rigorous and consistent manner, these procedures present an outline for mathematical model development and application regarding treatment plants. The modelling practice focuses on issues such as sensitivity analysis and uncertainty analysis, also covering other areas such as model implementation, calibration and validation.[30]

Simulating the mass balance of state variables (components) using Activated Sludge Models draws upon integrated scalar transport equations with simplified hydraulics where diffusion rates are assumed to be negligible – of which a general form is described by equation (1).

$$V_r \frac{dL_i}{dt} = Q_{in}\left(L_{i,in} - L_i\right) + rateF_{L_i} \quad (1)$$

where V_r is the useful reactor volume (m^3), L_i is the concentration of state variable i (g/m^3), Q_{in} is the volumetric flow rate of the reactor influent (m^3/d), $L_{i,in}$ is the concentration of state variable i in the influent to the reactor (g/m^3) and $rateF_{Li}$ is the mass reaction rate of state variable i (g/d).

The kinetics of Activated Sludge Model No. 2 are extensively applied for biological wastewater treatment when the purpose of simulation is to describe the microbiological transformations in activated sludge regarding carbon, nitrogen and phosphorus. Modelled phenomena include the uptake of substrate, growth and decay of biomass involving heterotrophs and autotrophic nitrifiers; therefore, predicting the removal of organic contaminants, biological nitrogen removal by nitrification and denitrification, as well as enhanced biological phosphorus removal. With the model containing both heterotrophic and autotrophic organisms, it considers various factors impacting microbial activity and treatment performance – temperature, pH, among the availability of nutrients and dissolved oxygen.[31] Process rates derived from stoichiometric and kinetic terms – expanded for individual components from a Gujer matrix – are incorporated into equation (1) to describe state variable mass balances around the activated sludge process.[32]

28 Patry–Takács 1992: 473–479.
29 Henze et al. 1999: 165–182.
30 Rieger et al. 2012.
31 Brun et al. 2002: 4113–4127.
32 Hauduc et al. 2010: 825–839.

Parameter estimation and performance analysis

In the process of model parameter estimation, parameters are tuned with the target of fitting simulated variables to measured data. This can either be executed manually or by employing an optimiser algorithm dedicated to minimising the error between measured and calculated values. A typical algorithm utilises the sum of errors squared as an objective function that must be minimised during the calculation procedure, as shown by equation (2).

$$f = \sum_{y=1}^{m} \sum_{x=1}^{n_y} \left(z_{x,y} - f_{x,y}\right)^2 \quad (2)$$

where f is the objective function, m is the number of response variables, n_y is the number of tests for response y, $z_{x,y}$ is the measured value of response y in test x, $f_{x,y}$ is the value of response variable y computed by the model in test x.

Monte Carlo simulation was performed for performance analysis of the treatment plant, assuming uniform distribution of input parameters and accordingly, evaluating outputs relied on effluent quality parameter distribution.[33]

Data collection and reconciliation

Data preparation involved variable sets involving total suspended solids, biochemical oxygen demand, chemical oxygen demand, alkalinity, total phosphorus, total nitrogen and ammonium nitrogen. Water quality datasets concerning raw and treated wastewater were collected for a year-long period with a weekly sampling frequency. Data manipulation encompassed outlier removal based on engineering sanity checks to confirm the reliability of data by calculating the ratio of biochemical to chemical oxygen demand and the ammonia nitrogen to total N ratio. After the reconciliation of the datasets, they were grouped into two subsets according to a summer timeframe – from 1 May to 30 September with irrigation requirements – and a winter period – from 1 October to 30 April without the need for irrigation. The intervals were determined based on the climate characteristics of Hungary, mainly based on average quantities of precipitation.[34] A method of influent wastewater fractionation[35] was applied for input data generation regarding the model configuration. The selected approach for influent characterisation is based on chemical oxygen demand, meaning that dissolved and suspended fractions ought to be fine-tuned until measured figures of biochemical oxygen demand and total suspended solids are reasonably matched. Online data regarding discharge flow rate and temperature were also collected and daily average data series were prepared after sanity checks against sensor errors. Hourly peak values of influent loading were compared to daily average flow values, to evaluate fluctuations regarding diurnal flow patterns.

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33 Benedetti et al. 2011: 2219–2224.
34 Pongrácz et al. 2014: 305–321.
35 Haider et al. 2003: 203–209.

Results and discussion

Simulation and result interpretation required a model scenario setup for exporting variables related to sludge retention, organic biodegradation, nutrient removal, dissolved oxygen and air supply. According to the objective of this study the model configuration was simulated using the combined global and local solvers of GPS-X 7.0 to conduct the following series of runs:

1. Steady-state scenario: averaged quantity and water quality of influent wastewater
2. Probabilistic scenario: thousand parallel runs with normal distribution of annual input parameters to evaluate treatment performance
3. Probabilistic scenario for summer period: thousand parallel runs with parameters specific to the period with irrigation to evaluate summer-specific plant performance
4. Variable sludge age scenario: sludge age varied to analyse the relationship of nutrient removal and sludge age with summer-specific loading and environmental conditions
5. Variable dissolved oxygen scenario: dissolved oxygen concentration varied to analyse the relationship of nutrient removal and dissolved oxygen availability with summer-specific loading and environmental conditions
6. Transient scenario: dynamic run conducted to quantify the duration of the transitional phase between operational periods with irrigation and without irrigation

Treatment plant performance

The treatment facility is fed with a high concentration of pollutants based on data concerning raw sewage. On account of a separate rainwater and wastewater collection system, the daily amount of hydraulic loading is relatively stable without significant seasonal variation. However, there are greater variations in parameters considering organic matter and nutrients. Annual raw influent and treated effluent data are compiled in Table 2, containing averaged values and ranges representing the distribution of data values between the 10th and 90th percentile.

Table 2: Influent and effluent wastewater characteristics

Parameter	Influent value			Effluent value			Unit
	Average	Minimum	Maximum	Average	Minimum	Maximum	
Volumetric flow rate	810	785	833	–	–	–	m^3/d
Chem. oxygen demand	980	660	1,210	45.0	28.5	55.0	mg/l
Biol. oxygen demand	559	395	696	–	–	–	mg/l
Total suspended solids	588	415	715	–	–	–	mg/l
Total nitrogen	88	74	115	9.8	6.2	16.3	mg/l
Total phosphorus	14.9	10.0	17.1	0.52	0.20	1.50	mg/l
Alkalinity	442	425	468	65	45	80	mg_{CaCO3}/l

Source: compiled by the author based on measured data

The sewage treatment plant reflects stable operation based on the processed data. Due to long sludge age the high nitrogen load is efficiently nitrified and denitrified – alkalinity is also sufficiently available and does not limit nitrification. In terms of effluent quality, requirements of a directive by the European Union for environmentally responsible disposal are also met.[36]

The characterisation of influent chemical oxygen demand is implemented based on four separate fractions, consisting of roughly 4% soluble unbiodegradable organics, 35% soluble readily biodegradable substrate, 12% unbiodegradable particulate organics and 49% particulate slowly biodegradable substrate. Most of these fractions are biologically degradable in nature – dissolved components being readily degradable and suspended constituents with larger particle size being slowly degradable. According to further parameter fine-tuning during fractionation, the ratio of volatile to total suspended solids was set as 0.7, the ratio of particulate COD to VSS was adjusted to 1.5 and the biodegradable fraction of particulates was assigned a value of 0.82. Based on practical experience involving the typical properties of municipal sewage, the described input parameters were found to be in reasonable ranges.

Due to possible industrial sources contributing to the raw influent composition, it was concluded that kinetic model parameters may be fine-tuned to reproduce the measured effluent quality more accurately.[37] Assuming averaged influent water quality at quasi steady-state conditions, an experimental run was conducted where the maximum specific growth rates of heterotrophic and autotrophic biomass species were adjusted to match the observed effluent total nitrogen more closely. The adjusted growth rate of heterotrophs was specified as 4 d^{-1} and the nitrifying biomass growth rate was tuned to a value of 1 d^{-1}.

A probabilistic method was applied to assess system performance on a yearly basis. This consisted of one thousand model runs with input data varied and analysis of treated water concentration distributions as response functions, with regards to chemical oxygen demand, total phosphorus, total nitrogen and NH_4 nitrogen. Figure 2 displays cumulative distribution functions of total nitrogen (TN), ammonium nitrogen (NH_4-N), total phosphorus (TP) and chemical oxygen demand (COD). The described procedure was repeated with wastewater characteristics specific to the summer season, keeping the same design settings of the facility.

36 Preisner et al. 2020: 694–708.

37 Rieger et al. 2012.

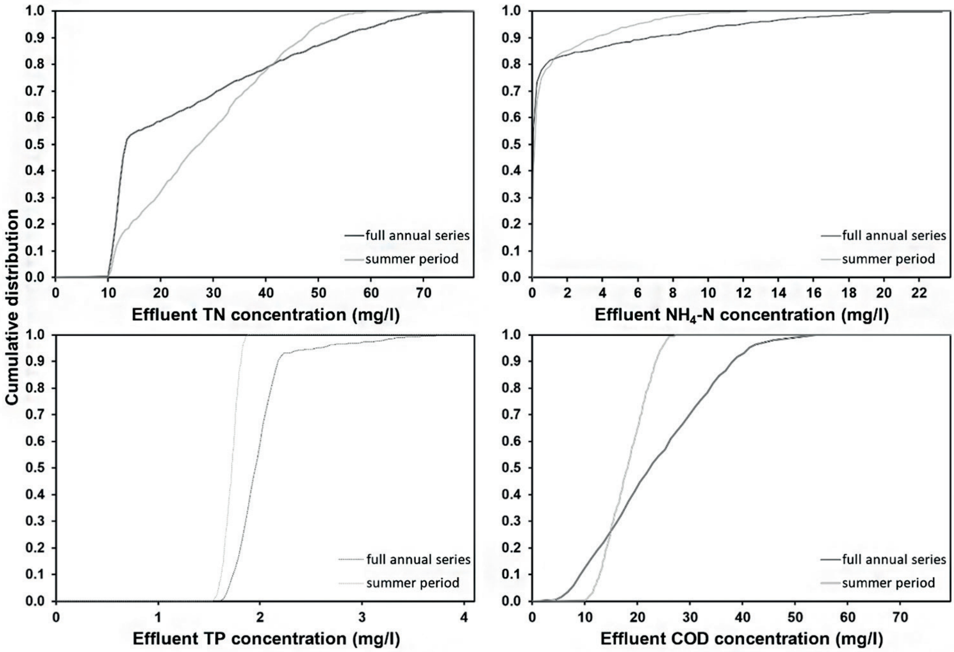

Figure 2: Treatment plant performance analysis using annual and summer-specific datasets
Source: compiled by the author

Through the application of chemical removal, phosphorus precipitation can be achieved to comply with a water quality requirement set at a concentration of 2 mg/l. The annual average remains compliant with this limit, but implying that this as an absolute threshold, a target below 2 mg/l would be recommended for the sake of environmental security. A maximum requirement of 60 mg/l regarding chemical oxygen demand can be met during the summer period as well as annually. These concentration boundaries were arbitrarily defined based on reasonable typical ranges from experience with sizing projects. Increased feed temperatures enhance biodegradation, thereby boosting treatment performance. Ammonium nitrogen concentrations indicate that wastewater undergoes complete nitrification with 79% probability, potentially limited by low temperatures in winter. Since the plant is configured with a dissolved oxygen setpoint of 2 mg/l throughout the year, a total N effluent quality target of 20 mg/l is more difficult to maintain during summer due to the bioreactors potentially getting over-aerated.

Nutrient recovery potential in function of sludge age and dissolved oxygen

When total nitrogen removal is not mandatory, reducing sludge age is a good practice – suggesting an alternative operational status for maintaining nutrient concentrations. Without requiring denitrification and internal recirculation, the total biological reactor volume may be aerated. Likewise, operators may also suspend metal dosing for chemical phosphorus precipitation. The present scenario's main objective is to determine the sludge age suitable for effective carbon removal without substantial nitrification taking place.

To quantify the mass of nitrogen and phosphorus recovered, the discharged water volume was multiplied by the effluent TN and TP concentrations, simulated for summer-specific conditions.

After identifying an appropriate sludge age, the aeration intensity was varied. Chemical oxygen demand (COD) of the treated water, along with N and P recovery were plotted, as the process air flow was increased from 0 to 14,000 m^3/d – demonstrated by Figure 3.

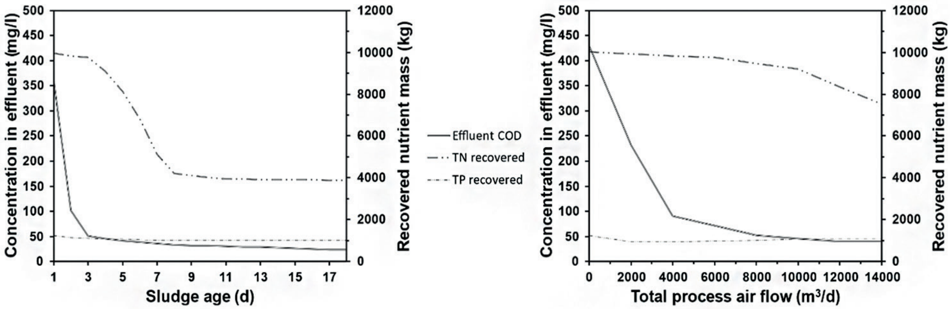

Figure 3: Effluent COD, recovered TN and TP mass in function of sludge age and air flow
Source: compiled by the author

The minimum sludge age was found to be 4 days long for safely implementing efficient carbon degradation. Due to the persisting inert fraction of carbon, no significant decrease in oxygen demand could be observed beyond 5 days. At shorter ranges – being insufficient for proper biological nutrient removal – a higher TN recovery was perceived. Increasing the sludge age results in more nitrification and denitrification, explaining the drop in recovered TN mass. As chemical P removal was stopped for the summer operation, no considerable trend was observed in TP recovery. A sludge age of 5 days was deemed ideal for aeration sensitivity analysis.

Under non-aerated conditions organic matter removal was shown to reduce severely due to carbon degradation slowing down in the absence of an aerobic environment. With the aeration intensity raised, decreased oxygen demand was observed to remain in the effluent – above 9,000 m^3/d that corresponds to dissolved oxygen concentration of roughly 1 mg/l, no further boost in carbon removal could be observed. Nitrification is much more dependent on oxygen supply, thus, the air flow exceeding 9,000 m^3/d entailed a steep decline in N recovery. Excess biological phosphorus removal activity could be observed in case of anaerobic and aerobic zones co-existing at low aeration intensities. On the contrary, the possibility of this phenomenon is eliminated by higher process air flow rates preventing zones with anaerobic conditions.

Determination of the transitional interval

As of this section of the paper two modes of operation had been presented – one featuring seasonal irrigation, and another dedicated to lowering the environmental impact on the receiving body of water. The difference between them is that outside of the period with irrigation no effective removal of TN or TP is necessary. While the stoichiometry-based removal of phosphorus by chemical addition relies on a fast reaction, restoring the biological activity necessary for nitrification and denitrification proves to be more challenging. To assess the time required for this transitional period, transient simulations – initialised from a summer operational status – were executed where the target sludge age was raised from 5 days to 21 days, starting from the second day simulated. The pumps for internal recirculation were activated, chemical dosing for P removal was switched on, a dissolved oxygen setpoint of 2 mg/l was specified in the aerobic compartments, and aeration was disabled in the first half of the reactor cascade. The resulting N and P concentration profiles are portrayed in Figure 4.

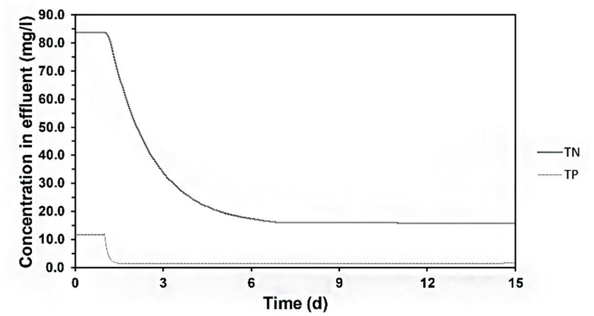

Figure 4: TN and TP profile during a transition from summer to winter operation
Source: compiled by the author

The chemical means of phosphorus removal allow for fast rates, but stabilising biological N removal involves a considerably longer transition. Treated water TN sharply decreases along with the growth of nitrifying bacteria. Consistently with the residence time requirement of nitrifying sludge at 20 °C, the length of this transitional phase was found to be nearly 7 days.

Discussion

According to the implemented methods of parallel simulation runs, a probabilistic approach was used rather than relying on a time series to vary input parameters. Beneficially, this evades the interpretation of time intervals between discrete sampling points that would create false concentration profiles dynamically.[38] In contrast, the probabilistic method pointed out that there may be combinations of influent parameters where the plant would not meet absolute thresholds of water quality requirements during periods not monitored using on-site

[38] Glass–Rodi 1982: 337–358.

measurements. In this aspect the process of nitrification is most sensitive, as in 21% of the cases based on results of the study complete nitrification could not be achieved. According to current regulations of the European Union, absolute limit-based effluent requirements are in place, not reflecting the nature of this phenomenon; however, it could be more advantageous to develop adaptive control regulations regarding the frequency and probability of exceeding thresholds, from the aspect of environmental security and long-term sustainability.[39]

It shall be noted that this paper focuses on the field of process engineering, to determine optimal conditions for nutrient recovery; thus, a complete technical feasibility of irrigation was out of scope and not examined. It must also be stressed that reducing sludge age may raise the risk of discharging pathogenic microorganisms,[40] therefore, disinfection is crucial prior to recycling treated water for agricultural irrigation.[41] To remove potential suspended solids discharged from the supernatant of secondary clarifiers, sand filtration may also be needed as an additional phase separation step. Adsorption by activated carbon may serve as an advanced treatment step to remove certain organic micropollutants.[42] These stages of treatment are primarily for polishing clarifier effluents but can also slightly reduce the nutrient recovery potential. To enhance energy efficiency in conventional activated sludge systems[43] or configurations featuring sequenced batch reactors,[44] operational parameters may require further fine-tuning.

Adaptation of biomass to another operational setup takes time, however, from summer-specific environmental conditions the transition to winter operational settings is relatively fast due to warmer influent sewage and the consistently lower retention time requirement for nitrifiers. Transitioning from a winter-specific to a summer-specific operational status would prove to be more difficult, yet in that case according to the goal of the study, biological nutrient removal could be avoided. Regarding activated sludge technologies, transitions may occur at faster rates than in case of biofilm systems without sludge recirculation;[45] this shall be the topic of further studies, along with detailed incorporation of hydraulics within an activated sludge process.[46]

Summary

The reuse of treated municipal wastewater is in growing demand, a typical use case of this is the supplementation of water resources for irrigation. Its feasibility presents various challenges, with this study focusing on the specific topic of retaining nutrients in the water through operational changes in a treatment plant. A small-scale system was studied for this purpose, receiving concentrated influent sewage, with requirements of source water for irrigation

[39] Preisner et al. 2020: 694–708.
[40] Ferrer et al. 2010: 2972–2980.
[41] Nasser et al. 2006: 83–88.
[42] Gutiérrez et al. 2021.
[43] Karches 2022.
[44] Bába–Karches 2021: 61–66.
[45] Liu et al. 2020.
[46] Karches–Buzás 2011: 117–125.

throughout the summer-specific operational period, provided that the load on the receiving stream of water for discharge is reduced during seasons without irrigation.

To summarise the main findings of the study, robustness of the system was assessed by performance analysis of biotreatment using a probabilistic method. Compliance regarding effluent water quality requirement on chemical oxygen demand was achieved in case of 98% of scenario runs, while a probability of 79% was calculated with regards to attaining full nitrification. Systemwide sludge age can be reduced from 21 to 5 days during summer intervals with irrigation demand, sustaining carbon removal while retaining nutrients in the treated water. Low aeration intensities may allow aerobic and anaerobic zones to co-exist and lead to excess biological P removal, but sufficient concentrations of dissolved oxygen prevent this. The adaptational time requirement for activated sludge from summer environmental conditions with irrigation requirements to a winter operational parameter set was found to be close to 7 days, corresponding to requirements of sludge age for nitrifying sludge at standard temperature.

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