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First full-scale combined MBBR, coagulation, flocculation, Discfilter plant with phosphorus removal in France

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Abstract

The suspended solids (SS) concentrations in effluent from moving bed biofilm reactors (MBBRs) used for secondary biological treatment can be up to 500 mg/L. Microscreens (Drumfilters or Discfilters) can be used as alternatives to traditional clarification or dissolved air flotation to remove SS and total phosphorus (TP). This study shows how a small-scale municipal WWTP for 5,700 population equivalent (PE) can be upgraded to 12,000 PE by combining MBBR with coagulation-flocculation tanks and a Discfilter with a total footprint of 160 m^2. This long-term investigation demonstrated that even though influent turbidity (range 146–431 NTU) and flow (25–125 m^3/h) varied considerably, very low effluent turbidities (below 10 NTU) could be achieved continuously. Furthermore, this compact treatment system can provide average reductions of ammonium (NH_4-N) from 19 to 0.04 mg/L, COD from 290 to 10 mg/L, and TP from 4.5 to 0.3 mg/L. The results show that effluent requirements can be reached by combining MBBR, coagulation-flocculation and disc filtration at full scale, without a primary clarifier upstream of MBBR.

Key words: coagulation, flocculation, microscreen, moving-bed biofilm reactor (MBBR), phosphorus, suspended solids

INTRODUCTION

The moving bed biofilm reactor (MBBR) process is well known and reliable, and has been used extensively for nitrogen and carbon removal from wastewater (Ødegaard *et al.* 1994; Rusten & Ødegaard 2007; Ødegaard *et al.* 2010). Suspended solids (SS) removal by microscreens with woven media (either Discfilters or Drumfilters) downstream of an MBBR has been studied and industrialized since 2005 (Persson *et al.* 2006; Mattsson *et al.* 2009; Wilén *et al.* 2012; Gustavsson & Cimbritz 2013; Rossi *et al.* 2013). The SS concentrations from an MBBR process designed for biological oxygen demand (BOD) removal from municipal wastewater are typically in the 100–250 mg/L range (Ødegaard *et al.* 2010) and even up to 500 mg/L (Rossi *et al.* 2013). Therefore, chemical pretreatment (flocculation alone or combined with coagulation) is needed upstream of microscreens with 40-micron pore openings to meet strict effluent discharge requirements. The advantages of combining a flocculation step with a 40-micron microscreen are increased SS removal efficiency and improved filtration flux, leading to decreased filtration area requirement, and hence lower investment cost and smaller footprint.

A coagulation-flocculation-filtration process configuration is necessary when chemical phosphorus precipitation is targeted (Väänänen 2017), and must be considered when there is a strict discharge requirement on effluent SS. Optimal dosages in total phosphorus (TP) removal applications are crucial to create flocs sufficiently strong to be retained by the sieving process (Väänänen 2017). Different wastewater characteristics (e.g. the influent chemical composition, particle characteristic size distribution, etc.) affect the optimum chemical dosage. Coagulant and polymer overdosing should be avoided, to keep the operating costs as low as possible, so careful dispersion and mixing design in the coagulation and flocculation stages, combined with precise process control, are necessary, especially when low TP concentrations are required (Väänänen *et al.* 2017).

Many small municipal WWTPs currently require upgrades due to population growth, legislation changes, and outdated treatment methods. Taninges WWTP was built in 1973 for 5,700 population equivalent (PE) using conventional activated sludge (AS) treatment. It was upgraded in 2015 and recommissioned in 2016 for up to 12,000 PE, with a pure MBBR process followed by 2-stage chemical pre-treatment and disc filtration to achieve <2 mg-TP/L and <10 mg-SS/L in the effluent.

Several pilot-scale studies have been carried out to gather comprehensive data for this process combination (Ødegaard *et al.* 2010), but it is important to show that long-term operation at full scale is successful. The aim of this work was to observe the performance of this first full-scale installation, and improve process knowledge on particle separation and TP removal efficiencies downstream of pure MBBR, without primary clarification upstream. An additional objective was to study whether lower effluent TP concentrations could be reached by adjusting coagulant dosing, thus preparing for stricter effluent TP requirements in the future.

METHODS

Taninges WWTP

Taninges WWTP is 2 km from the village centre, very close to popular ski resorts in south-eastern France. The only primary treatment methods for the wastewater are screening (15 and 3 mm), and fat and grit removal. During upgrading, the existing AS process at the WWTP was replaced by pure MBBR, in 2 lines of 2 reactors each in series (Figure 1). Carbon removal occurs in the first 193 m^3 reactor (60% filling with AnoxKaldnes K5™ carriers, Veolia Water Technologies AB, Sweden) and nitrification in the subsequent 285 m^3 reactor (50% filling with AnoxKaldnes K5™). The MBBR filling proportion enables treatment up to 12,000 PE, leaving the possibility to increase to 17,000 PE, if required, by adding a further MBBR line.

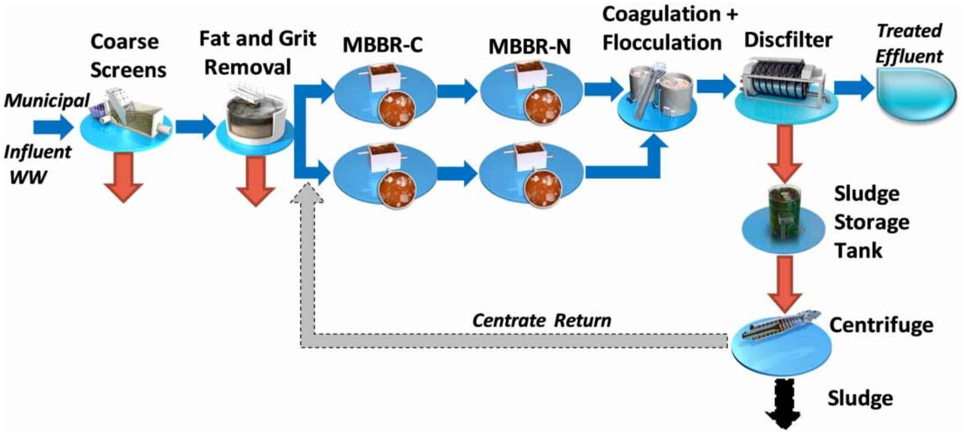

Figure 1 | Schematic layout of Taninges WWTP.

The MBBR is followed by 2-stage chemical pre-treatment for TP precipitation and a 40-micron Discfilter (HSF2212/11-1F, Veolia Water Technologies AB, Sweden), which has 11 vertically mounted discs. One more disc can be added to increase plant capacity, if required. The filter was dimensioned for a maximum flow of 280 m^3/h. Part of the effluent is reused for backwashing the filter panels at 0.7 MPa without interrupting filtration, the rest is discharged to the river Le Giffre. Backwashing sludge is discharged to a buffer tank and then dewatered in a decanter centrifuge, whose centrate is returned upstream of the MBBR.

Selection of chemicals for pre-treatment

Before construction of the separation process after the MBBR and upgrading P removal with chemical treatment, coagulant and flocculation aids, dosing ranges for phosphorus removal were studied using conventional jar tests on site. Chemical doses of 3.7 mg-Al^{3+}/L (polyaluminum chloride, PAX-18, Kemira Ltd., Finland) and 3 mg/L cationic emulsion polymer (Hydrex 6631 with 47% polymer content, Hydrex Veolia Ltd, France) were found to be suitable for initial operation of the recommissioned full-scale plant.

Once the plant was back in operation, a second set of bench-scale jar tests (Flocculator 2000, Kemira Kemi AB., Sweden) combined with filtration was required to optimise chemical dosing upstream of the filter. Effluent concentrations between 1 and 1.5 mg-TP/L were targeted, to ensure that the $\leq$2 mg-TP/L discharge requirement is fulfilled. During the three monitoring periods described here, the Al-based coagulant dose was varied between 3.7 and 5.5 mg-Al^{3+}/L, on the basis of jar test results, and the cationic polymer was decreased from 3.0 to 1.9 mg/L.

Monitoring

Performance was monitored continuously using online instruments at 5 minute intervals, covering daily and seasonal variations from December 2016 to May 2017. Optical turbidity probes (Solitax SC, Hach Lange GmbH, Germany) and an online TP analyser (Phosphax Sigma, Hach Lange GmbH) were connected to a controller (SC1000, Hach Lange GmbH) to monitor SS and dissolved phosphorus (orthophosphate, PO_4^{3-}) in the Discfilter influent and effluent.

Conversion factors were calculated from the correlations between turbidities measured online and SS. They were determined as 1.7 for the MBBR effluent and 2.5 for the filter effluent. Turbidity was also determined in the laboratory with a portable turbidity meter (Hach 2100Q, Hach Lange GmbH, Germany) to verify the accuracy of the values given by the online turbidity probes.

Hourly composite samples were also collected from the MBBR (before the coagulant dosing point) and the filter effluents, using two auto-samplers (AS950, Hach Lange GmbH) over three-day periods at three different locations, in December 2016, and April and May 2017. A grab sampling campaign was carried out parallel to the online measurement campaign (Table 1), and the online meters were calibrated regularly via the lab measurements.

Water quality analyses

The SS content was determined according to APHA Standard Methods (APHA 2005). Spectrophotometer based cuvette tests LCK348, LCK349 and LCK 350 (Hach Lange GmbH, Germany) were used for TP measurement. Cuvette tests (Hach Lange GmbH) LCK303 and LCK304 were used to measure ammonium (NH_4-N), LCK238 for total nitrogen (TN), and LCK114 and LCK314 for COD in the composite samples. All cuvette analyses were measured in a DR 2800 spectrophotometer (Hach Lange GmbH).

Table 1 | Operating conditions and sampling during investigation

Test duration	Aim of study	Al^{3+} dosing (mg-Al^{3+}/L)	Polymer dosing (mg/L)	Sample type	Number/ frequency of samples
Dec 2016 (3 days)	Evaluate and optimise chemical dosing, and its effect on particle and TP removal by the filter	3.7–4.0	3.0–1.9	Hourly composite samples	41
Dec 2016–April 2017	Evaluate long-term continuous operation of the filter with 2-stage pre-treatment	4.0–5.5	1.9	Online measurement	Every 5 min
April 2017 (3 days)	Evaluate chemical dosing, and its effect on particle and TP removal by the filter	4.7–5.5	1.9	Hourly composite samples	45
April and May 2017	Evaluate long-term continuous operation of the filter with 2-stage pre-treatment	5.0	1.9	Online measurement	Every 5 min
May 2017 (3 days)	Evaluate MBBR and the filter performance	5.0	1.9	Hourly composite samples & grab samples	9
May and June 2017	Evaluate long-term continuous operation of the filter with 2-stage pre-treatment	5.0	1.9	Online measurement every 5 min	Every 5 min

RESULTS AND DISCUSSION

Impact of coagulant dosing in pre-Discfilter coagulation-flocculation

Typically, the post pure-MBBR SS concentration entering the solids separation unit is between 150 and 250 mg-SS/L when treating municipal sewage (van Haandel & van der Lubbe 2012). At Taninges WWTP (without primary treatment), the daily average SS concentrations in the MBBR effluent varied between 90 and 360 mg/L (Figure 2(a)). SS concentrations below 10 mg/L could be reached consistently using chemical pre-treatment (with 4.7 to 5.5 mg-Al^{3+}/L and 1.9 mg/L polymer) and disc filtration. The Al^{3+} dose required was in the same range as in settling/flotation combined with chemical pre-treatment, where effluent SS is expected to be around 10–15 mg-SS/L (van Haandel & van der Lubbe 2012).

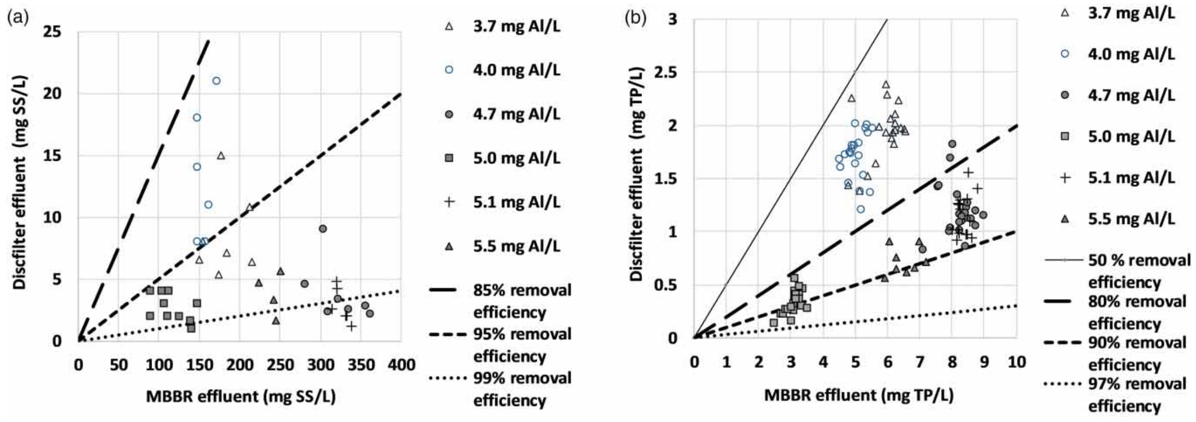

Figure 2 | Concentrations of (a) SS, and (b) TP in the coagulation-flocculation-Discfilter process influent and effluent (at different Al^{3+} doses and 1.9 mg/L polymer addition), during 3-day campaigns in December 2016 and April and May 2017.

P removal from wastewater involves precipitating phosphate as SS and the subsequent removal of those solids (Tchobanoglous *et al.* 2003). The filter TP removal efficiency was between 50 and 97% (Figure 2(b)), depending on the Al^{3+} dose and the influent TP concentration. The filter effluent TP concentrations were below 2 mg/L, with Al^{3+} doses above 4.7 mg-Al^{3+}/L for TP concentrations of 3–9 mg/L in the MBBR effluent.

The required molar ratios of Al^{3+} dosed/TP in the influent were between 0.7 and 2.3 to achieve <2 mg-TP/L in the filtrate (Figure 3). Previous studies indicated that a molar ratio of 5–7 mol-Me^{3+}/mol-influent-TP was required to achieve <0.1 mg-TP/L consistently in the effluent from an activated sludge plant combining 2-stage chemical pre-treatment and disc filtration (Väänänen 2014, 2017). Such reported molar ratios were higher since the tests were performed on a different wastewater application with a lower influent TP concentration (0.2–0.5 mg-TP/L) and different target effluent quality (0.1 mg-TP/L). The coagulant doses recorded in this study were also lower than those used by Väänänen *et al.* (2016) in primary treatment (5–20 mg-Al^{3+}/L or 10–30 mg-Fe^{3+}/L), where <0.3 mg-TP/L was targeted in the effluent. In other words, the molar ratios of dosed coagulant to TP in the influent vary depending on the application, the target effluent TP concentration and the amount of phosphorus in soluble form.

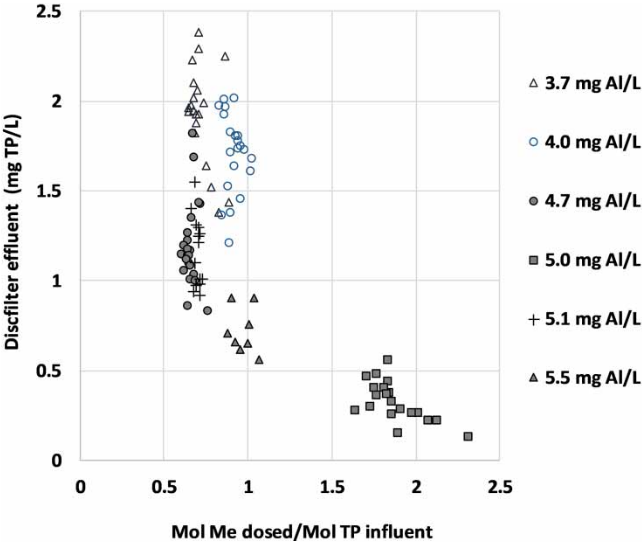

Figure 3 | Effluent TP concentration achieved versus molar ratios of metal dosed/TP in influent.

In order to combine coagulation and flocculation with microscreen filtration, polymer doses of 1–5 mg-polymer/L can be required for primary and 0.5–1.5 mg-polymer/L for tertiary treatment (Väänänen 2017). The 1.9 mg/L emulsion dose added in this study would correspond to about 0.9 mg/L of active polymer dose (based on active matter fraction in the emulsion).

Long-term performance evaluation

The average flow over 5 months was 61 m^3/h, much lower than the design flow (280 m^3/h). The online flow measurements indicate significant daily variations with flow peaks up to 125 m^3/h (Figure 4). This suggests that, with the current chemical pre-treatment and filtration process, it is possible to take care of future increases in flow and loading, if required.

The variations in neither the MBBR influent turbidity (146–431 NTU) nor the flow affected the daily Discfilter effluent turbidity values, which remained between 0.6 and 10 NTU (Figure 4). The high influent variations could be explained by the lack of a primary clarifier at this WWTP. These effluent

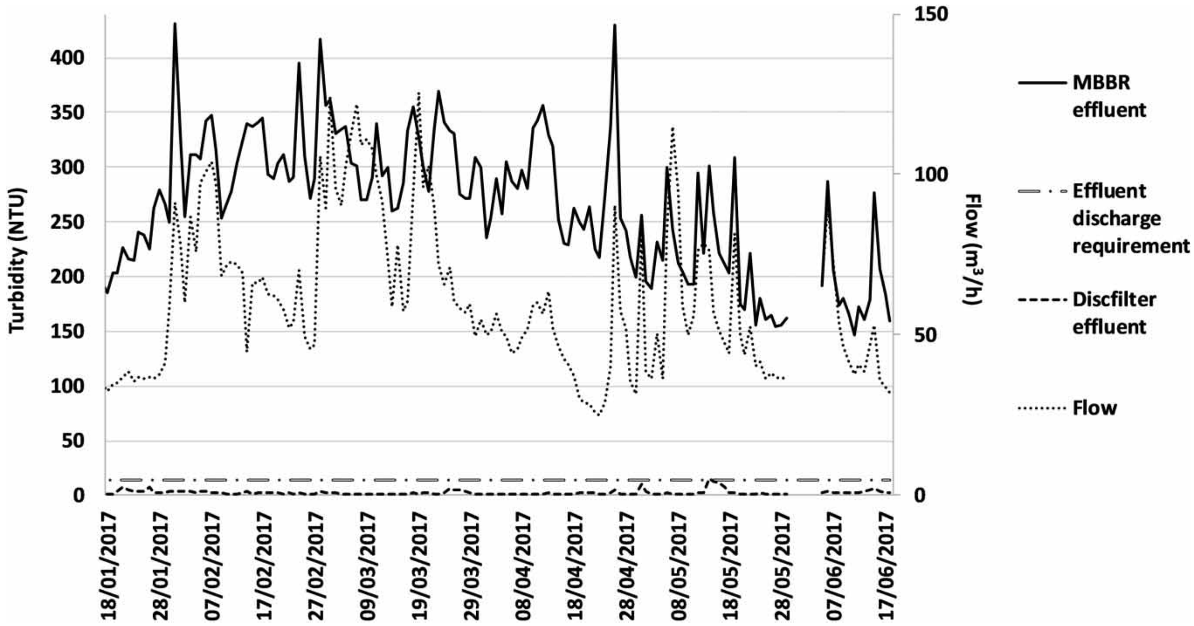

Figure 4 | Online measurements of flow and turbidity, and the required effluent SS concentration limit of 35 mg-SS/L (corresponding to 13.8 NTU, calculated value).

turbidity values would correspond to SS concentrations between 1.5 and 25 mg-SS/L, using the conversion factor reported in the Methods section. All turbidity values in the effluent (except for one day) were below the required effluent limit value of 35-mg SS/L (corresponding to 13.8 NTU).

The online measurements show that turbidity and flow peaks often occur simultaneously (Figure 4). SS loading to the Discfilter was between 20 and 300 g-SS/m^2/h, leading to a backwash frequency of about 12%, on average, during the monitoring period. The loading and backwash frequency values indicate that the filter's capacity was not fully utilized, as the SS loading to the plant was much lower than the design value. The unit was sized to deal with the maximum instantaneous flow so that the plant could treat all wet weather flows during seasonal high loading events. The filtration process could also be used to target even lower TP effluent concentrations, with more aggressive coagulant and flocculant doses. According to Väänänen (2017) it is possible to achieve very low TP concentrations (<0.1 mg/L) in tertiary treatment effluents using high coagulant doses (up to 5 mg-Al^{3+}/L).

The total solids (TS) content in the filter sludge varied between 4.0 and 6.8 g/L. The centrifuge dewatered the sludge to 19–25% dry solids. The centrifuge centrate, pumped back upstream of the MBBR, represented about 8% of total influent flow, when in operation. The SS and TP concentrations in the centrate were between 0.3 and 1.8 g-SS/L, and 4 and 13 mg-TP/L, respectively, contributing little to the MBBR load.

Evaluation of overall WWTP performance and treatment method

Further results from the sampling campaign in May (Table 2) show that, on average, reductions of 97% of COD and 99.8% of NH_4-N were achieved, fulfilling the effluent requirements. Average TN removal was 43% and nitrogen leaves the WWTP mainly as NO_3-N (the plant was not designed for denitrification). Average SS removal was 91%, which also met the effluent demands of the plant. This result is supported by turbidity removal results up to 99%.

The effluent TP requirement was achievable, giving a total removal efficiency of about 90%. As an alternative to chemical P removal, enhanced biological phosphorus removal (EBPR) is now a well-known and established process. In a long-term study, Tykesson *et al.* (2005), showed that it is possible

Table 2 | Treatment performance of MBBR coupled with 2-stage chemical pre-treatment and Discfilter (average ± standard deviation)

Parameter	Influent to MBBR (mg/L)	Effluent from MBBR (mg/L)	Effluent from Discfilter (mg/L)	Min and max removal efficiencies by plant (%)	Discharge requirements (mg/L)	Required removal efficiencies (%)
COD	290 (±81)	116 (±14)	9.6 (±1.7)	96.6–98	125	80
NH_4-N	19 (±6)	0.06 (±0.05)	0.04 (±0.01)	99.7–99.9	3.1	94
TN	54 (±17)	41 (±9)	28 (±7)	17–72	**	**
TP	4.5 (±1.6)	2.9 (±0.2)	0.3 (±0.1)	88–92	2	80
SS	120 (±33)	103 (±9.6)	11 (±16)	61–100	35	90
Turbidity	79 (±31)*	103 (±10)*	1 (±0.2)*	97–99	–	–

*Turbidity values are expressed in NTU.

**Requirements on total Kjeldahl nitrogen (TKN) of 14 mg/L and 82% removal efficiency.

to produce effluents containing less than 0.5 mg-TP/L using EBPR. However, they also point out that meeting a low effluent requirement of 0.3 mg-TP/L consistently is difficult, as even minor and short operating problems can lead to sudden instability in the biological process. Such variations can be handled instantly using chemical precipitation combined with microscreens, where rapid chemical dosing responses can help achieve more stable overall process performance (Väänänen 2017).

Cost evaluation

Van Haandel & van der Lubbe (2012) observed that MBBR biomass does not settle well and as phosphate removal is required in most countries, the cost of pre-treatment chemicals needs to be included in the operating costs of separation techniques. The estimated average annual cost of chemical pretreatment in conjunction with the Discfilter installed at Taninges WWTP is about 14 kEUR (Table 3). The 0.027 EUR/m^3 cost of treated wastewater is 4 times higher than for a comparable WWTP in Sweden, where coagulation-flocculation-Discfilter (10 micron) is used to polish activated sludge effluent (Kängsepp *et al.* 2016). This arises because of the higher SS and TP loads in the MBBR effluent at Taninges, which require higher coagulant and flocculant doses, and probable overdosing on site due to flow proportional control. If, for example, load-proportional feed-forward or feedback control of chemical dosing could be applied, annual chemical consumption could be reduced and the operating costs of the plant reduced even further.

Table 3 | Consumption and costs of chemicals for coagulation-flocculation-disc filtration

	Consumption (kg/a or L/a)	Annual cost (EUR/a)	Cost of treated water (EUR/m^3)
Chemical pre-treatment			
Coagulant**	29,500*	11,500	0.022
Flocculation aid**	1,000*	2,800	0.005
Chemical cleaning			
HCl (10%)***	210	25	Negligible
NaClO (<10%)***	250	20	Negligible
Total		**14,345**	**0.027**

*Based on 534,000 m^3/a average flow, 5.7 mg-Al/L of coagulant and 1.9 mg-polymer/L.

**PAX-18 costs 0.39 EUR/kg and polymer 2.78 EUR/kg.

***HCl (33%) costs 0.36 EUR/L (dilution 1:3 to obtain working solution).

***NaClO (55%) costs 0.47 EUR/L (dilution 1:7 to obtain working solution).

The microscreen panels are cleaned chemically three times annually at Taninges WWTP. The cleaning chemicals cost about 0.6 EUR/a/m^2 filter area, about one third of the cost (about 1.9 EUR/a/m^2) for the Discfilter installation in Sweden (Kängsepp *et al.* 2016), where chemical cleaning is carried out every six weeks. Chemical cleaning can be done less frequently at Taninges because high pressure cleaning (80 bar) is done monthly and the pores are 4 times larger (40 micron).

The total footprint of the MBBR process combined with coagulation-flocculation-filtration is about 160 m^2. Microscreens can be delivered with their own stainless-steel tank, which together with the reduced footprint, significantly reduces the construction costs of the plant.

CONCLUSIONS

This study has shown that a small-scale WWTP (5,700 PE) can be upgraded (to 12,000 PE) by combining MBBR with a coagulation-flocculation-Discfilter process to meet current and future treatment needs. It has also shown that this compact and robust treatment system can yield very good reductions in turbidity, NH_4-N and COD. The discharge limits of 2 mg-TP/L and 35 mg-SS/L have been achieved easily.

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