

Advanced phosphorus removal via coagulation, flocculation and microsieve filtration in tertiary treatment

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ABSTRACT

The applicability of microsieve technology together with coagulation and flocculation for advanced phosphorus removal was investigated. A pilot unit including a microsieve with 10 µm mesh size was operated continuously with secondary effluent from Ruhleben wastewater treatment plant in Berlin. By applying a pretreatment of 0.07–0.09 mmol/L (as metal) coagulant and 1.5–2 mg/L cationic polymer, total phosphorus values below 80 µg/L were achieved. Coagulation with polyaluminum chloride (PACl) produced a better effluent quality compared to FeCl₃, as less suspended solids and less residual coagulant were found in the microsieve effluent. In addition, the transmittance of UV radiation through the water was improved by using PACl. The produced amount of backwash water was always below 3% (on average 1.6%). Under optimized mixing conditions, polymer doses of 0.6 mg/L were possible without losses in water quality and filtration performance. Microsieving with chemical pretreatment is a viable option for high quality effluent polishing.

Key words | advanced phosphorus removal, coagulation, flocculation, microsieve

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INTRODUCTION

In the future, lower phosphorus levels in the effluent of wastewater treatment plants (WWTP) will be necessary to meet the quality goals of the European Water Framework Directive. Especially in sensitive areas, e.g. urban areas with low water flow, total phosphorus (TP) concentrations below 0.1 mg/L in WWTP effluents could be demanded. The state-of-the-art technology for advanced phosphorus removal from WWTP effluents is coagulation, either combined with a membrane or dual media filtration. Membrane filtration suffers from high energy demand, while dual media filtration requires a large footprint, which can be limiting in urban areas.

Microsieve technologies are increasingly being implemented for tertiary treatment, with pore sizes commercially available down to 10 µm. Well-defined cut-off is guaranteed by the woven textile filtration media, which categorizes the technique in the loose microfiltration range.

Microsieves used for effluent polishing have two advantages compared to the state-of-the-art solutions for tertiary treatment: a small footprint (approximately 30% of a conventional rapid sand filter) and low specific energy demand due to a low head loss (Persson *et al.* 2006).

In municipal wastewater treatment, microsieves are used for particle removal in primary and in tertiary treatment. The first installation for tertiary wastewater treatment was in 1950 in England (Diaper 1969). In the 1970s tests, microsieve filtration was combined with coagulation and flocculation in tertiary treatment (Ewing 1976; Hultmann 1979). Nowadays, microsieves are mainly used for effluent polishing. For example, at Ryaverket (820,000 PE, 350,000 m³/d, 15 µm, without chemical pretreatment) in Gothenburg (Sweden), a TP concentration in the effluent of <0.3 mg/L on an annual basis has been the design goal (Mattsson *et al.* 2009). Operational data of TP <0.2 mg/l

have been reported (Wilén et al. 2016). Within the OXERAM project, the possibility of using two-stage coagulation-flocculation in combination with a microsieve of 10 µm mesh size for advanced phosphorus removal is investigated. Together with UV disinfection, this could be a low energy option for P removal and disinfection. As there is limited experience with microsieves for TP effluent levels below 0.1 mg/L (e.g. Tooken et al. 2010), long-term investigations are necessary to assess the effluent quality, the process stability, the amount of backwash (BW) water, the demand of coagulant/polymer, the energy demand and the operational costs. Thus, a long-term trial (12 months) was started at the Ruhleben WWTP. After a short break for modifying tank volumes and improving mixing conditions of the chemical pre-treatment, the trials were extended for another 10 months.

MATERIALS AND METHODS

The secondary effluent

The treated water is the secondary effluent of Ruhleben WWTP. With 1.6 million population equivalent and a dry weather peak flow of 247,500 m³/d it is Berlin's largest WWTP (BWB 2007). The treatment includes nitrogen and biological phosphorus removal. The average effluent quality is already good: 5–10 mg/L for suspended solids (SS) and <0.5 mg/L for TP. Chemical oxygen demand (COD) values are in the range of 30–50 mg/L. The secondary effluent is well buffered and the pH is in the range of 7.2–7.3.

The microsieve pilot unit for advanced phosphorus removal is shown in Figure 1. It consists of a coagulation tank, a flocculation tank and a microsieve (Hydrotech DiscFilter™). The plant is designed for water flows between 10 and 30 m³/h, but is mostly operated at 10–23 m³/h (dry weather flows).

The coagulant is dosed into the inlet pipe in front of a static mixer. The polymer is dosed into the overflow of the coagulation tank, which leads to the flocculation tank. Both the coagulation and the flocculation tank are equipped with stirrers. At 28 m³/h (storm water peak) the hydraulic retention time for coagulation is 3 minutes and for flocculation 4.5 minutes. Through another overflow, the water flows into the microsieve. The microsieve discs have a mesh size of 10 µm and are operated inside-out. The discs are mounted vertically in the filtrate tank at a submergence of approximately 50%. Due to the design of a microsieve, there is continuous filtration during the BW. A sensor initiates the BW when a certain water level on the feed side (300 mm maximum head loss) is reached. The discs start rotating and the clean halves of the discs submerge into the water. At the same time, the upper part of the filter material is flushed outside-in with filtrate via spray nozzles at approximately 8 bar. The BW water is collected by a sludge trough. During BW, the filtrate flow increases and the water level on the feed side decreases again until a certain level is reached and the BW, as well as the disc rotation, are stopped. The BW time percentage is a useful indicator of the quality of the chemical pre-treatment. The objective is to avoid a continuous BW (=higher energy demand and BW water production) by creating shear resistant and easily removable flocs. The pilot plant was designed assuming there is 100% BW time at 30 m³/h and, accordingly, 33% at 10 m³/h for the given influent water quality. Furthermore, the pilot plant is equipped with online measurement of flow (Siemens SITRANS FM MAG5000) and turbidity (Hach Lange Ultraturb plus sc) in the influent and effluent. The online PO₄-P signal (Hach Lange PHOSPHAX SC) of the WWTP effluent is embedded into the process control of the pilot unit for load proportional coagulant dosing. Transmittance was determined after DIN 38404.

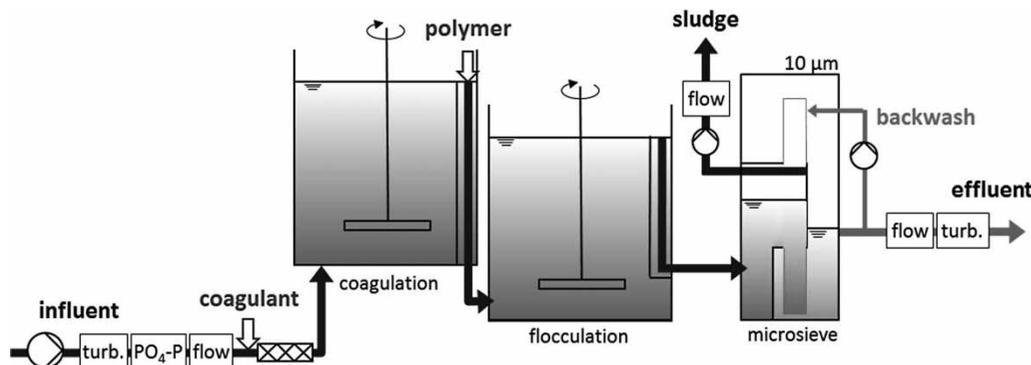


Figure 1 | Pilot plant including two stirring tanks and the microsieve (initial configuration).

Applied chemicals

For coagulation, ferric chloride (FeCl_3 , 13% Fe) or PACl (6% Al) were applied. Both were supplied by Brenntag GmbH, Germany. FeCl_3 was diluted 1:2 with tap water, whereas PACl was dosed pure. With the aid of jar tests and some pilot trials, two cationic polymers were identified as the most suitable for the given application. The polymers were supplied by PolyChemie, Germany and Kemira Kemi AB, Sweden. The polymer stock solutions contained 1 or 1.5 g/L active material and were made up with tap water in an automated polymer station.

Chemical monitoring

The certified laboratories of the Berliner Wasserbetriebe measured TP, aluminum and iron with inductively coupled plasma optical emission spectrometry (ICP-OES) in accordance with DIN EN ISO 11885. The limits of detection were 3 $\mu\text{g/L}$ TP, 0.4 $\mu\text{mol/L}$ Al and 0.5 $\mu\text{mol/L}$ Fe. SS was determined after DIN EN 872.

RESULTS AND DISCUSSION

Results with constant flow and volume proportional dosing

Overall performance

In the first 2 months of operation, different amounts of FeCl_3 (0.07 and 0.09 mmol/L Fe) and polymer (1 and 2 mg/L) were dosed. The average effluent TP concentration was 60 $\mu\text{g/L}$. The TP removal averaged 86%. The first 2 months also showed reliable removal of COD (20–31%)

and SS (34%). However, there were 0.01–0.05 mmol/L residual iron in the effluent, which means that temporarily over 60% of the dosed iron passed the microsieve. Further testing and optimization showed that clearly better results can be attained when applying PACl. With PACl, the removal of TP and SS was higher than with FeCl_3 . In contrast to FeCl_3 , dosing PACl led to an improvement of the water transmittance. The transmittance could be increased from 47% in the influent to 60–66% in the effluent, which would simplify a subsequent UV disinfection. Besides this, less coagulant residuals (<0.020 mmol/L Al) in the effluent and a lower BW time were achieved with PACl. Thus, during the following test periods, PACl was applied.

Plant performance at peak loads

The plant performance under two different peak loads is shown in Figure 2. Figure 2(a) shows that the influent turbidity exceeded the upper limit of the online measurement (15 NTU) of the pilot plant during the peak. The reason for the peak was probably the melting of ice (water temperature: 12.8 °C). Due to the peak, the BW time raised to 100% and the peak load exceeded the pilot plant capacity. At 17:00 h, the BW time jumped back to the previous level of around 60% although the turbidity peak lasted until 18:00 h. During the peak events only, there was a clear influence of the influent turbidity on the BW time. During the whole period displayed in Figure 2(a), the effluent turbidity was comparatively stable below 2 NTU and not influenced by the turbidity peak in the influent.

Figure 2(b) shows an example where a turbidity peak load resulted in neither 100% BW time nor in increased effluent turbidity. Table 1 gives the TP and SS values of influent and effluent of grab samples taken on the same day. During the peak at 14:00 h, only a slightly increased content of SS in the

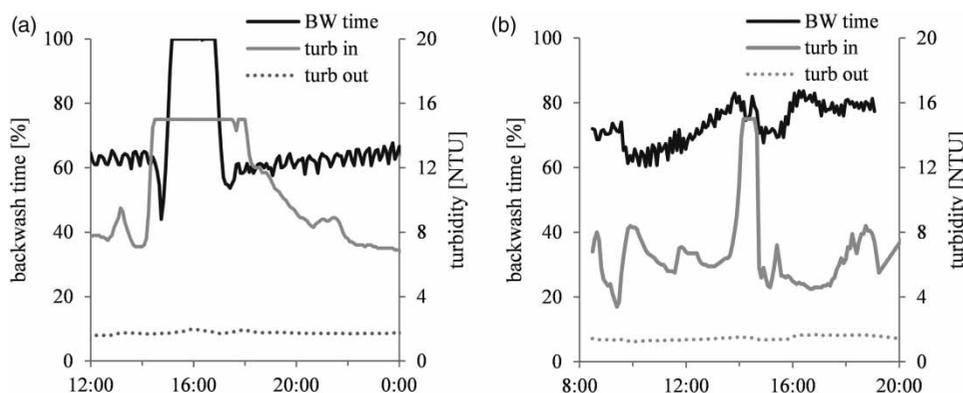


Figure 2 | Pilot plant performance at peak loads when dosing 0.07 mmol/L Al (a) and 0.11 mmol/L Al (b). Upper limit for online turbidity measurement: 15 NTU (influent).

Table 1 | Pilot plant performance at peak load when dosing 0.11 mmol/L Al and 1.5 mg/L polymer

Time	TP [$\mu\text{g/L}$]		P removal [%]	SS [mg/L]	
	In	Out		In	Out
09:00	410	51	88	11.0	3.2
11:00	490	59	88	9.4	4.2
14:00	1,200	110	91	22.0	4.8

effluent (4.8 mg/L) could be observed. The TP removal remained at about 90% as observed before the peaks at 09:00 and 11:00 h. As the influent TP amounted to 1.2 mg/L at 14:00 h, this resulted in effluent TP values just above 100 $\mu\text{g/L}$.

The examples illustrate that the microsieve in combination with chemical pre-treatment can cope with peaks of turbidity, SS and TP. In example 2B, the peak did not lead to an increase in BW time and the achieved effluent water quality was comparatively good (91% removal).

BW dynamics with FeCl_3 and PACl

The effluent flow of an individual microsieve unit fluctuates in accordance with the BW cycle. Due to growing pore blocking, the effluent flow is at its minimum the moment before the BW starts. It is initiated when the maximum water level is reached, and thus the maximum operational differential pressure. The high pressure in combination with clean filter panels during BW leads to an enormous increase in the effluent flow. When the BW stops the flow decreases again due to progressive filter clogging. Figure 3 presents the fluctuation of the effluent flow and the effluent turbidity for FeCl_3 and PACl respectively. The chemicals lead to very different effluent flow dynamics. With FeCl_3 , the BW intervals

were larger (see grey colored areas) and the effluent flow fluctuated in a smaller range. The effluent flow with FeCl_3 was in the range between 12 and 22 m^3/h (Figure 3(a)) and with PACl between 7 and 29 m^3/h (Figure 3(b)).

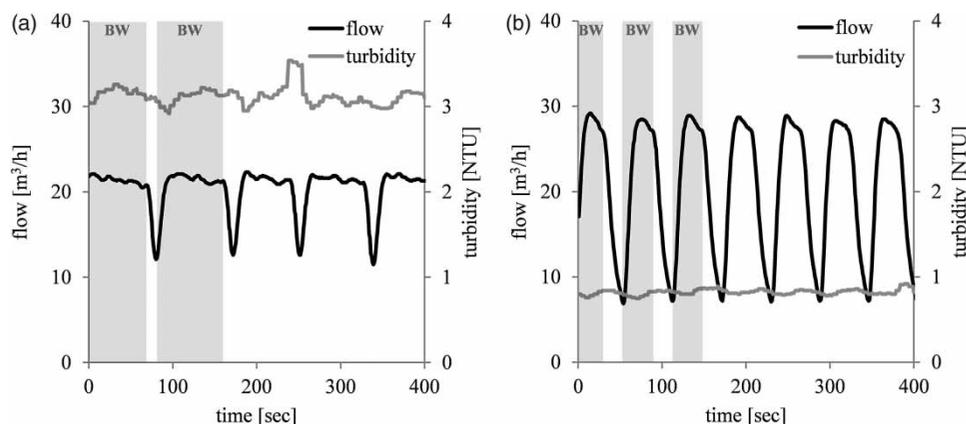
Due to the longer BW intervals, it can be assumed that FeCl_3 formed flocs that could be removed less easily from the filter panels by the BW due to different floc characteristics.

Furthermore, when FeCl_3 was dosed the effluent turbidity was at a higher level >3 NTU and fluctuating about 0.2 NTU, whereas with PACl the turbidity only slightly varied between 0.80 and 0.85 NTU. Although the maximum flow and thus the shear forces on the flocs and the probability of floc breakage are higher with PACl, a better water quality was achieved. Most probably, PACl creates less sticky but stronger flocs than FeCl_3 . For subsequent treatment steps, it should be noted that the large effluent flow variation will be evened out when several filters are operated in parallel.

Occurrence of residual phosphorus and Fe/Al in the filtrate

The ratios of the particulate and dissolved fractions of phosphorus, iron and aluminum in the microsieve filtrate were analyzed and the results are shown in Figure 4. Two samples were analyzed for dosing with FeCl_3 and PACl respectively. With PACl, there was 40% less TP in the filtrate, (Figure 4(a)). The amount of dissolved phosphorus (30–40 $\mu\text{g/L}$) was similar for all four samples. Thus, the lower TP values achieved with PACl were due to a superior removal of the particulate phosphorus fraction in comparison to FeCl_3 .

The secondary effluent of the Ruhleben WWTP contains 60–70 $\mu\text{g/L}$ of soluble non-reactive phosphorus.

**Figure 3** | Fluctuation of effluent flow and turbidity in the microsieve when FeCl_3 (a) and PACl (b) were dosed (0.07 mmol/L Fe or Al; 1.5 mg/L polymer; 20 m^3/h). The grey areas show the first 2–3 BW cycles.

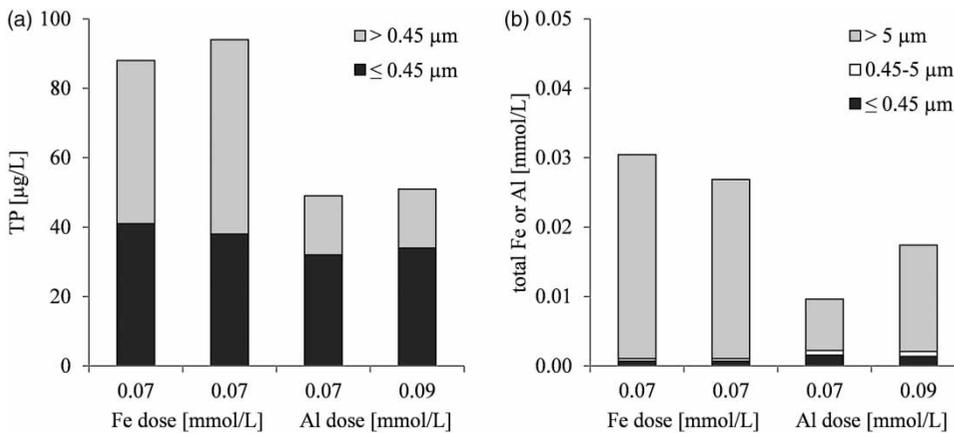


Figure 4 | Fractionation of the microsieve filtrate when FeCl_3 and PACl were dosed (1.5 mg/L polymer; 20 m³/h) and analysis of TP (a) and total Fe or Al (b).

Approximately 40% of this phosphorus fraction can be removed by coagulation and filtration for the applied dosing range of coagulant (Miehe 2010). Thus, about 40 µg/L dissolved phosphorus remains in the water, presenting a lower limit for conventional filtration technologies.

When dosing PACl, there was also significantly less coagulant breakthrough compared to dosing of FeCl_3 (Figure 4(b)). Nearly all Fe and Al were found in the size fraction >5 µm. Only 0.001 mmol/L of iron and 0.001–0.002 mmol of aluminum were dissolved.

Flocs formed during the chemical pre-treatment are exposed to high shear forces when approaching the pores of the microsieve. Consequently, flocs can break and the fragments <10 µm will most probably not be retained by the microsieve. Due to the thinness of the filter media, a microsieve offers less chance for a particle to be captured compared to a dual media filter. Thus, particles >5 µm containing phosphorus and coagulant occur in the microsieve filtrate.

Results achieved under dynamic operation

Dynamic operation of the microsieve pilot unit included a fixed daily flow pattern and load proportional dosing of PACl (0.07–0.11 mmol/L Al) and polymer (1.5–2.0 mg/L). The dosage of PACl was linked to the online $\text{PO}_4\text{-P}$ measurement, whereas the polymer was applied in a fixed minimum ratio to PACl (0.79 mg polymer/mg Al). On top of that, the polymer dose was automatically increased by 10–30% at high influent turbidity values (6 to >10 NTU, maximum polymer dose 2 mg/l). Figure 5 gives the resulting diurnal water flow and the quality variation for TP, Al and SS. The corresponding doses of PACl and polymer are displayed in Figure 5(a). Twelve mixed samples (2 h) were taken over 24 h. It should be noted that during the previous night

there was a peak load of turbidity (15 NTU) and $\text{PO}_4\text{-P}$ (280 µg/L; normally about 100 µg/L). Thus, the peak load caused high concentrations in the first 2 to 3 samples. The effluent content of TP was only slightly influenced by the variation of the influent content (see Figure 5(b)) and at a very low level of around 50 µg/L. During the 24 h, there were three peaks of the residual Al in the effluent (see Figure 5(c)). The first peak can be ascribed to the nightly peak load. The other two Al peaks were accompanied by very low SS influent contents, and thus could be caused by poor floc formation. Initially, the high influent contents of SS caused increased effluent contents (see Figure 5(d)). From 8:00 h on, the effluent SS content develops contrary to the influent SS content. A decrease of the SS in the influent resulted in a slight increase of SS in the effluent. At SS influent contents below 4 mg/L, there is no SS removal when comparing influent and effluent contents. The dotted curve presents the SS load on the microsieve including the estimated SS formed by precipitation (4 g SS per g of dosed Al in accordance with (ATV-DVWK 2004)). The actual SS removal through the filtration step amounts to 59–86%.

By applying load proportional dosing, 13% coagulant and 15% polymer could be saved compared to a previously tested volume proportional dosing of 0.09 mmol/L Al and 2.0 mg/L polymer. During both testing periods, very good phosphorus removal was achieved. With volume proportional dosing, TP in the effluent averaged 40 µg/L. Applying load proportional dosing there were on average 46 µg/L of TP in the effluent, but on average there were also 30 µg/L more TP in the influent. The tests with load proportional dosing showed that the amount of coagulant and polymer could be reduced while maintaining the effluent water quality. For comparison, at pilot experiments treating the same secondary effluent at Ruhleben WWTP using membrane ultra filtration (100 kDa

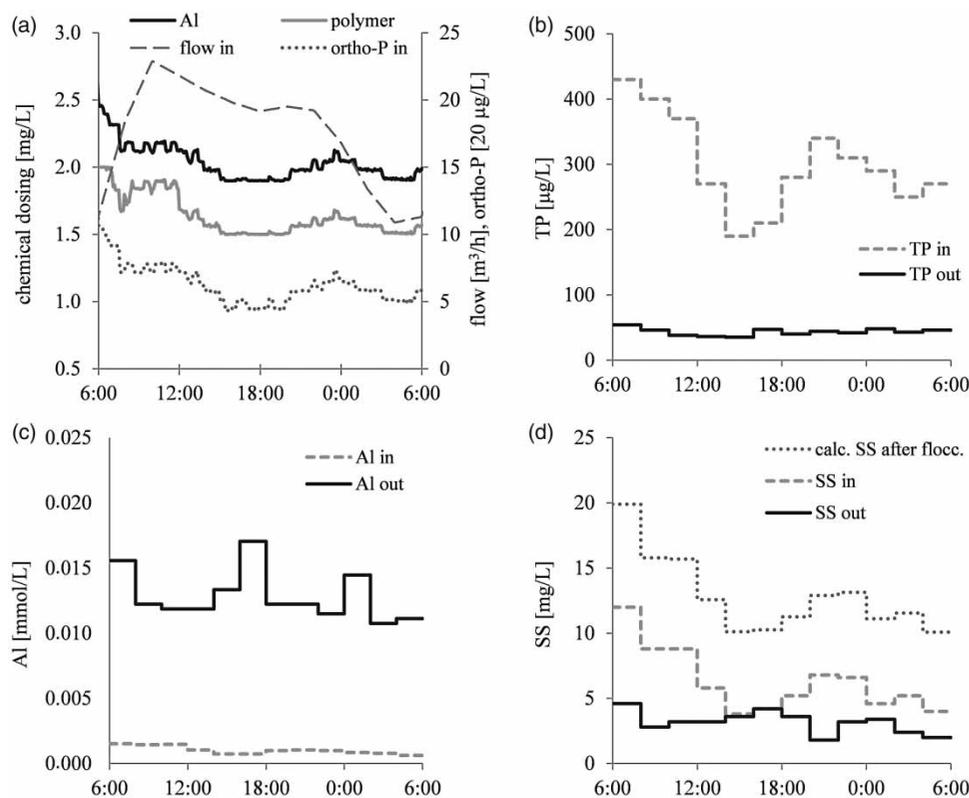


Figure 5 | Diurnal variation of the water quality during load proportional dosing. Operating conditions (a) dosing range: 1.9–2.9 mg/L (0.07–0.11 mmol/L) Al and 1.5–2.0 mg/L polymer) and variation of influent and effluent contents of TP (b), Al (c) and SS (d).

molecular weight cut off) with the addition of 0.037–0.148 mmol/L Al or Fe, TP effluent values of 20–50 µg/L have been reported (Zheng *et al.* 2012). Moreover, pilot experiments treating secondary effluents with continuous sand filtration or dual media filtration and with a coagulant dose of about 0.058 mmol/L (4 mol Fe/mol secondary effluent ortho-P) effluents containing around 150 µg/L and 75 µg/L TP respectively have been reported (Scherrenberg *et al.* 2008). For full scale installation conducting tertiary clarification and applying around 0.11 mmol/L Al (55 mg/L alum) and 0.4 mg/L of polymer followed by conventional granular media filtration, an effluent TP of 20–60 µg/L has been reported (Johnson & Briggs 2011).

Optimization of the pilot plant configuration

The first months of pilot operation confirmed the general process performance observed during the pre-trials but also revealed a need for process optimization with regard to the removal of SS and the reduction of coagulant residues. In particular, up to 60% of the applied iron was found in the effluent. An improved performance was achieved through changing from FeCl₃ to PACl. In the presented case, PACl

gave clearly better results for the removal of phosphorus and SS (Figure 6). Additionally, the occurrence of coagulant residues could be reduced noticeably.

Furthermore, load proportional dosing of PACl and polymer were introduced in order to avoid under as well as overdosing of the chemicals. Thus, the coagulant and polymer dosing could be slightly reduced while maintaining good effluent water quality.

The dose of cationic polymer had a significant impact on water quality and BW time: With the initial process configuration, 1.5–2 mg/L cationic polymer was recommended for safe and stable operation with adequate BW time, resulting in an average polymer dose of 1.7 mg/L.

However, after improving the mixing conditions through constructional changes, the polymer dose could be reduced to 0.6 mg/L without losses in water quality and filtration performance.

During the reconstruction, the hydraulic retention time was reduced to one minute at peak flow. To avoid short-circuiting, the conventional stirrer was replaced by a TurboMix™. The stirring speed is now linked to the retention time. Furthermore, the turbulence in the flocculation tank was increased by correcting the stirrer blades. A polymer

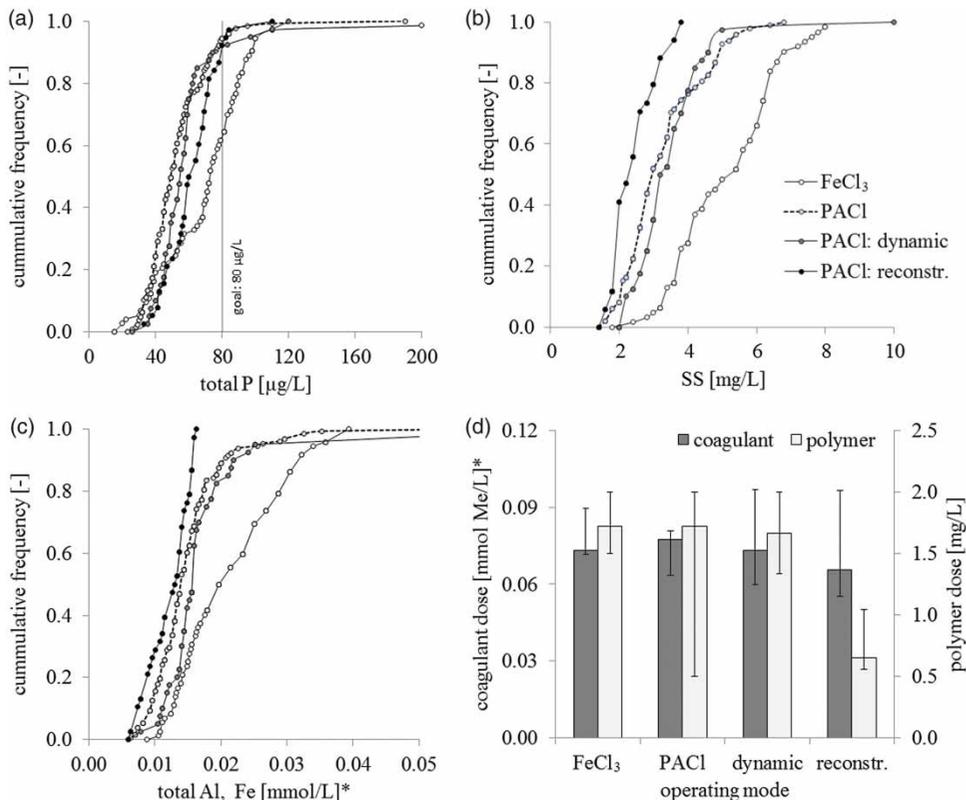


Figure 6 | Comparison of the main optimization advances – change of coagulant type (FeCl₃ to PACl), load proportional dosing of chemicals (PACl dynamic) and constructional changes (PACl: reconstr.).

dosing range of 0.56–1.2 mg/L with an average dose of 0.6 mg/L was identified as optimum. Despite the noticeably reduced polymer dose, the intensified mixing resulted in improved reduction of SS (mean value 2.2 mg/L) and coagulant residues in the microsieffluent. The effluent phosphorus concentration was slightly increased during this trial period, which can probably be ascribed to seasonal changes in the influent water quality.

Operational experiences

Amounts and characteristics of the BW water

While dosing chemicals, the BW water amounted to 1.0–3.0% (on average 1.6%) of the treated water flow. During load proportional dosing of PACl, the BW water contained 580–1,000 mg/L of SS. The concentration of Al was between 88 and 160 mg/L. Determination of the sludge volume index (SVI) showed that the sludge of the BW water offers very good settling properties (SVI << 50 mL/g). The supernatant after 30 min of settling contained 24–27 mg/L SS, 2.8–4.3 mg/L Al and 0.3–0.6 mg/L TP. Thus, the BW water can

most probably be treated via recycling to the primary clarifiers at a full-scale installation.

Energy demand

The estimations for a full-scale application of the given process for the total energy demand amounts to 30 Wh per m³ of treated water. 18 Wh/m³ would be needed solely for the BW, including pressurization of the water and disc rotation (manufacturer information). For dosing the chemicals, mixing and a power supply of 3 Wh/m³ are estimated. The energy demand for lifting the wastewater is site-specific. In the present case, 9 Wh/m³ was assessed as the requirement for lifting the water (2 m) and pumping the disposed BW water.

Chemical cleaning

Chemical cleaning of the filter panels was applied every 6–8 weeks. At these occasions, the filter panels were soaked with 10% hydrochloric acid and with 4% sodium hypochlorite. Before, in between and after the application of the chemicals, the panels were cleaned with pressurized tap

water. For large scale installations, cleaning cycles of 6 weeks are reported (Kängsepp et al. 2016).

CONCLUSIONS

The pilot trial proved that the microsieve technology achieves good and reliable TP removal with effluent values $<80 \mu\text{g/L}$. Better phosphorus removal, less coagulant residuals in the effluent and a lower BW time were achieved with PACl in comparison with FeCl_3 . The dose of cationic polymer had a significant impact on water quality and BW time. With the initial process configuration, 1.5–2 mg/L cationic polymer was recommended for safe and stable operation. After constructional changes to the stirring tanks, polymer doses of 0.6 mg/L were possible without losses in water quality and filtration performance. The operational regime of the chemical treatment prior to the microsieve filtration is a trade-off between the energy demand for mixing and the polymer consumption. The microsieve, in combination with dosing of coagulant and polymer, is a robust technology with small amounts of BW water (1.6%) and low energy demand of about 21 Wh/m^3 (plus site-specific energy demand for water lifting). Microsieving, together with UV disinfection, is an alternative to low pressure membrane filtration or dual media filtration for applications targeting phosphorus removal and disinfection, such as effluent polishing for sensitive areas or landscape irrigation.

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