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Improving and upgrading an existing activated sludge with a compact MBBR – disc filters parallel line for municipal wastewater treatment in touristic alpine areas

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Abstract

Many wastewater treatment plants (WWTP) in touristic areas struggle to achieve the effluent requirements due to seasonal variations in population. In alpine areas, the climate also determines a low wastewater temperature, which implies long sludge retention time (SRT) needed for the growth of nitrifying biomass in conventional activated sludge (CAS). Moreover, combined sewers generate high flow and dilution. The present study shows how the treatment efficiency of an existing CAS plant with tertiary treatment can be upgraded by adding a compact line in parallel, consisting of a Moving Bed Biofilm Reactor (MBBR)-coagulation-flocculation-disc filtration. This allows the treatment of influent variations in the MBBR and a constant flow supply to the activated sludge. The performance of the new 2-step process was comparable to that of the improved existing one. Regardless significant variations in flow (10,000–25,000 m^3/d) and total suspended solids (TSS) (50–300 mg/L after primary treatment) the effluent quality fulfilled the discharge requirements. Based on yearly average effluent data, TSS were 11 mg/L, chemical oxygen demand (COD) 27 mg/L and total phosphorus (TP) 0.8 mg/L. After the upgrade, ammonium nitrogen (NH_4-N) dropped from 4.9 mg/L to 1.3 mg/L and the chemical consumption for phosphorus removal was reduced.

Key words: activated sludge, alpine climate, compact upgrade, microscreen, moving bed biofilm reactor (MBBR), touristic load variations

Highlights

- The treatment of municipal wastewater in touristic alpine areas presents specific additional challenges, like seasonal load variations, low water temperatures and landscape constraints.
- A compact parallel line with Moving Bed Biofilm Reactors (MBBR), coagulation, flocculation and disc filtration was an effective solution for the upgrade of an existing WWTP (primary clarification, conventional activated sludge (CAS) and tertiary filtration) in order to avoid frequent by-pass events and to fulfil the effluent requirements.
- The combination of the two treatment schemes enhanced the existing processes' performance, while minimizing civil works and footprint.
- Complete nitrification was also achieved during wintertime, when the water temperature was steadily below 10°C.
- The consumption of chemicals for phosphorus removal was optimized.

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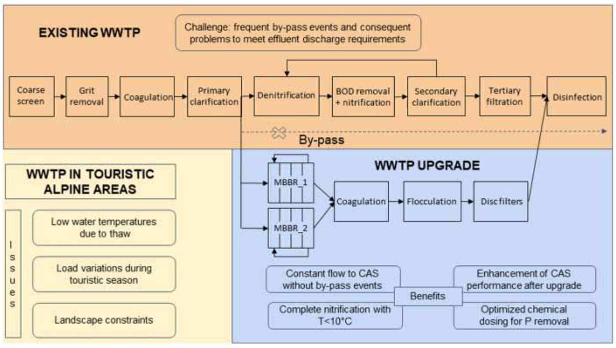
Graphical Abstract



INTRODUCTION

The importance of wastewater treatment in alpine valleys is paramount to protect the main water supply of the region. Besides fulfilling existing legal requirements, it is ecologically relevant to reduce human impacts on natural environments and water. These areas pose additional issues for wastewater treatment such as extreme seasonal load variations, low temperatures and a challenging orography (Wett *et al.* 2002; Kegebein *et al.* 2007). Moreover, the increased touristic activity and the impact of climate change on peak loads have already outdated several existing CAS plants (Weissenbacher *et al.* 2008). Most of the studies available on wastewater treatment in alpine areas refer to remote locations, where constructed wetlands are often the chosen solution (Vymazal & Březinová 2014). However, they require a high land surface to be available and struggle in removing nitrogen efficiently, a problem that is amplified at low temperatures (Vymazal 2013). Therefore, a lack of knowledge of suitable technologies for medium-sized WWTP was identified.

The Valdisotto WWTP, located near the touristic area of Bormio (Italy), was built for 43,000 population equivalent (PE, where 1 PE = 60 g BOD/d, Henze *et al.* 2015b) in 1989 using a CAS process with primary clarification and tertiary filtration. However, the increased load associated with the expansion of the sewer network, to include additional touristic areas, made the WWTP undersized. Consequently, 30% of the influent flow frequently by passed the biological treatment, causing excessive ammonia discharge. The required plant upgrade started in 2015 and was commissioned in September 2017. Given the landscape constraints and the large variations of the influent load, a compact and flexible solution for secondary treatment was needed to:

1. avoid by pass during dry weather and fulfil the effluent ammonium nitrogen requirements
2. handle the fluctuations of the influent load due to touristic seasons and the alpine climate (diluted wastewater during the thaw)
3. enhance nitrification during cold weather

The chosen solution was the combination of MBBR-disc filters to be built in parallel with the existing CAS line. The MBBR is a resilient and widely used technology (Ødegaard *et al.* 1999), where the biomass grows as a biofilm on the surface of plastic media (carriers) that are kept in suspension in the bulk liquid phase. Like other attached growth processes, no sludge recirculation is needed because the biofilm is retained in the reactor. The continuously detached biomass represents sloughing, such as the excess microorganisms to be removed in the downstream solids separation step (Ødegaard *et al.* 1999). However, an advantage of MBBRs compared to fixed bed bioreactors is that the sloughing does not cause clogging of the media. Moreover, MBBRs allow higher kinetics in a compact biological treatment, often enhanced by separate reactors in series with specialised biomass (Ødegaard *et al.*

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1994). Therefore, they can achieve good COD and nitrogen (N) removals regardless of low temperatures and sudden loading variations (Rusten & Ødegaard 2007). The treatment efficiency is independent from the retention time and the downstream biomass separation method. Among the biofilm separation methods, microscreens maximize the process compactness (Ødegaard *et al.* 2010). Although the TSS separation by microscreens with woven media has been studied for a decade (Persson *et al.* 2006; Mattsson *et al.* 2009; Rossi *et al.* 2013), chemical pre-treatment is a more recent development (Kängsepp *et al.* 2016; Väänänen *et al.* 2016; Langer *et al.* 2017). Coagulation and flocculation before disc filters allow TSS and phosphorus removal above 90%, while keeping a high filtration flux and having limited footprint requirements.

This paper presents the results of the full-scale implementation of the combination of MBBR followed by coagulation-flocculation-disc filtration in parallel with the existing treatment line. The aim of the paper is to follow up the overall WWTP performance and its long-term reliability for TSS, COD, N and TP removal. The focus is on the effectiveness of the compact solution towards load fluctuations and nitrification efficiency, which has the benefit of improving the CAS operation by allowing a more constant volumetric load.

METHODS

Valdisotto WWTP

The upgraded Valdisotto WWTP is designed for 63,000 PE and receives combined wastewater and rainwater from the villages of Valdisotto, Bormio, Valdidentro and Valfurva. Even though the permanent population during low season is only 22,700 PE, the historical peak load is 43,000 PE during the touristic season.

The wastewater is pumped to the WWTP, where it undergoes coarse screening (6 mm opening), centrifugal grit removal, pre-precipitation with ferric chloride and primary clarification (Figure 1). In the primary effluent channel, a level sensor controls the new pumps that feed the compact line, to keep a constant gravitational flow of 6,300 m^3/d towards the CAS. The COD and N removal in the CAS occurs in a reactor with fine bubble aeration preceded by anoxic pre-denitrification. The nitrates are recirculated together with the return sludge from the secondary clarifiers. Their effluent undergoes tertiary treatment with three submerged filters with pile cloth media (OptiFiber® Mecana, Switzerland).

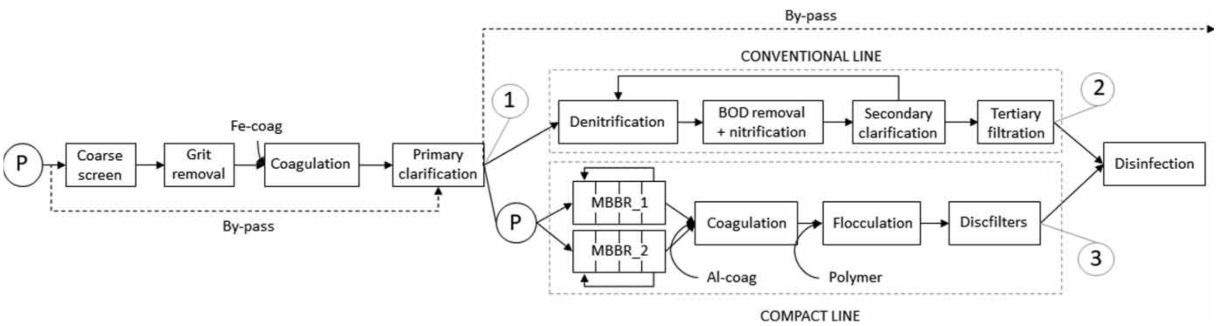

Figure 1 | Valdisotto WWTP schematic layout after the upgrade, with numbered sampling points (P represents a pumping station).

The flow above 6,300 m^3/d is directed to the compact line (designed for 13,000 m^3/d), which consists of two parallel lines (MBBR_1 and MBBR_2) with four stages each. The first anoxic pre-denitrification is filled with 59% carriers (AnoxK™5X, AnoxKaldnes, Sweden) kept in suspension

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by vertical mixers, while the following carbon removal stage has 57% AnoxK™5 and coarse bubble aeration. Finally, two identical nitrification steps in series at 55% filling degree (AnoxK™ChipM) are equipped with an extractable fine bubble ceramic aeration system. An internal recirculation system operates flow-proportionally with the influent to the MBBRs, with a design ratio of 1:1. The MBBR effluent undergoes coagulation and flocculation before disc filtration. Four units (HSF2216-2F, Hydrotech, Sweden) with 40 μm pore opening woven media (total filtration area 358 m^2) separate the biomass. The produced sludge, coming from the backwash of the disc filters, accumulates in a buffer tank, from where it is pumped together with the waste activated sludge to an aerobic digester. The sludge treatment ends with static thickening and centrifuging.

Dosed chemicals

Chemicals are dosed at three points in the WWTP (Figure 1). Ferric chloride (40% $FeCl_3$) (HIDROFLOC CF40, Hidrodepur S.p.A, Italy), is added at a constant flow (corresponding to 3 mg Fe^{3+}/L during dry weather) for pre-precipitation before primary clarification. In the compact line, chemicals are added flow proportionally instead. While about 1 mg/L of cationic emulsion polymer (HIDROFLOC CL2001RC) is added throughout the year upstream of the disc filters, poly-aluminium chloride (HIDROFLOC PAC180) is only added during the peak season for phosphorous removal. Consequently, Scenario 1 (October – November 2018) and Scenario 2 (December 2018–February 2019) were defined as shown in Table 1.

Table 1 | Chemical dosing during the follow-up study

Type of chemical	Scenario 1 (mg/L)	Scenario 2 (mg/L)
Fe^{3+} [a]	3.0	3.0
Al^{3+} [b]	0	2.1
Polymer [b]	0.9	1.1

[a]constant dosing mode.
[b]flow proportional dosing mode.

Monitoring

Online instruments were used to monitor the WWTP performance with data logging every 5 min from October 2018 to March 2019 to cover daily and seasonal variations. TP was analysed by Phosphax Sigma (Hach Lange GmbH, Germany) while turbidity was measured by SOLITAX SC probes (Hach Lange GmbH), both connected to SC 1000 controller units (Hach Lange GmbH). To convert turbidity data to TSS, a correlation factor was calculated, using a linear interpolation of the data from 12 daily composite samples. Due to the different particle size distribution, the values of the mentioned correlation factors differ for each location in the WWTP (Table 2). The low coefficient of determination for the conventional line ($R^2 = 0.68$) is due to the TSS after tertiary filtration being below the detection level of the used analytical method.

Table 2 | Correlation between total suspended solids and measured turbidity

Wastewater type	TSS/Turbidity ratio (mg TSS/L/FNU)	Coefficient of determination (R^2)
Primary effluent	1.30	0.98
MBBR effluent	1.60	0.94
Conventional line effluent	1.28	0.68
Compact line effluent	2.13	0.86

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Daily composite samples were collected by three auto-samplers (Bühler 1027, Hach Lange GmbH, Figure 1) during three dry weather days per month from October 2018 until January 2019, when the supply to both lines was comparable. During Scenario 1 ($N = 6$), the average flow treated by each line was about 5,700 m^3/d with a standard deviation (SD) of 16% for the compact line and 8% for the conventional one. During Scenario 2 ($N = 6$), the average flow per line was about 6,500 m^3/d with SD below 5% for both lines. Given the flow stability, the WWTP performance was evaluated through concentrations instead of loads.

Water quality analyses

The TSS were determined according to Standard Methods (APHA 2005). Turbidity in daily composite samples was measured with a turbidimeter (2100P, Hach Lange GmbH). Spectrophotometer-based cuvette tests (Hach Lange GmbH) were used to measure COD (LCK 314, LCK 114), TP and orthophosphates, Ortho-P, (LCK 348, LCK 349), total N (TN) (LCK 238), NH_4-N (LCK 304, LCK 305), nitrites (LCK 342) and nitrates (LCK 339, LCK 340) in the composite samples. A DR 1800 spectrophotometer (Hach Lange GmbH) was used. Since nitrites were consistently below the detection limit, the organic N (N_{org}) was calculated as given below:

$$N_{org} = TN - NH_4 - N - NO_3 - N$$

RESULTS AND DISCUSSION

Flow fluctuations

The average influent flow (from January 2017 to August 2019) was 15,000 m^3/d, with long periods with less than 12,000 m^3/d and peaks above 25,000 m^3/d (Figure 2). Due to the mixed sewer, the contribution of rainwater and melted snow is evident in spring and summer. Prior to the commissioning of the compact line in September 2017, 30% of the influent flow by passed the secondary treatment. After the compact line start-up, by pass events occurred only during heavy rains and the feed of the

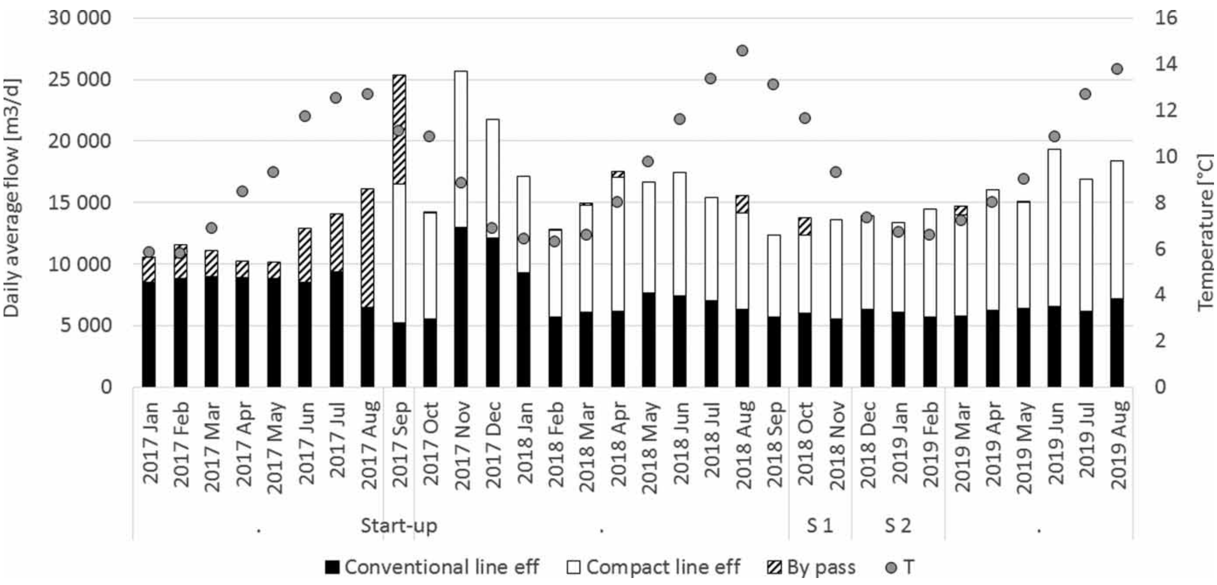

Figure 2 | WWTP daily average flow fractions treated by the conventional line, the compact line and by-pass (S 1 and S 2 represent the evaluated scenarios), together with average wastewater temperature.

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conventional line was stabilized around 6,300 m^3/d. The compact line treated the flows above that value.

Footprint

The lack of flat land surface was a limiting factor for the upgrade. Since both biological treatments are designed for COD and N removal, their footprint can be compared. One separation step was considered for both cases: secondary clarification and coagulation-flocculation-disc filtration for the conventional and compact line respectively. Referring the results to a standard capacity of 10,000 PE, the compact line requires only 114 m^2 instead of 270 m^2 for the conventional line. Kängsepp *et al.* (2020) calculated 132 m^2/10,000 PE for the MBBR-disc filter bundle for carbon removal and nitrification without primary treatment.

WWTP performance improvements

The WWTP performance is monitored by the regional environmental protection agency (ARPA) through the analysis of 16 daily composite samples per year (Table 3). The influent wastewater could be defined as of very low strength due to the dilution effect of thaw and infiltration (Henze *et al.* 2015a). Before the compact line commissioning, the WWTP influent sampling point was located downstream from the sludge supernatants recirculation points, which makes the 2015 influent data not representative of the real load.

Table 3 | WWTP influent and effluent average concentration for the main parameters (when not available, n.a. is reported), before (year 2015 and January–May 2017) and after (year 2018) the compact line commissioning (data from the regional environmental protection agency database SIRE acque), compared to the effluent requirement

	WWTP influent (mg/L)			WWTP effluent (mg/L)			
	2015	Jan-May 2017	2018	2015	Jan-May 2017	2018	Effluent requirement (mg/L)
TSS	95	51	52	11	13	11	35
COD	218	150	124	35	38	27	125
BOD_5	80	77	62	8	14	5	25
TN	17	n.a.	19	10	n.a.	11	15
NH_4-N	n.a.	19	n.a.	4.9	12.8	1.3	4.5
TP	3.0	2.3	2.0	0.8	0.5	0.7	1.0

Generally, the overall effluent quality after the compact line start-up is comparable to that achieved before commissioning, with the clear benefit of a more robust ammonium nitrogen removal as a yearly average. Data collected during a pre-commissioning monitoring campaign in the cold season (10 points, January-May 2017, Table 3) show a significantly higher discharged ammonium nitrogen of 12.8 $\pm$ 3.0 mg NH_4-N/L on average.

Long-term online data

The turbidity probes installed at different stages of the WWTP recorded the variations in the particulate matter for 4 months. During this period, the sensors experienced clogging and power supply issues that prevented continuous monitoring of all the streams.

Given the low hydrolysis of volatile suspended solids (VSS) in the MBBR (Connolly *et al.* 2015), the turbidity in the MBBR effluent is plotted on the same graph to balance the lack of data from the

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primary treatment effluent. The turbidity data were converted to TSS according to the correlations in Table 2 and daily averaged (Figure 3).

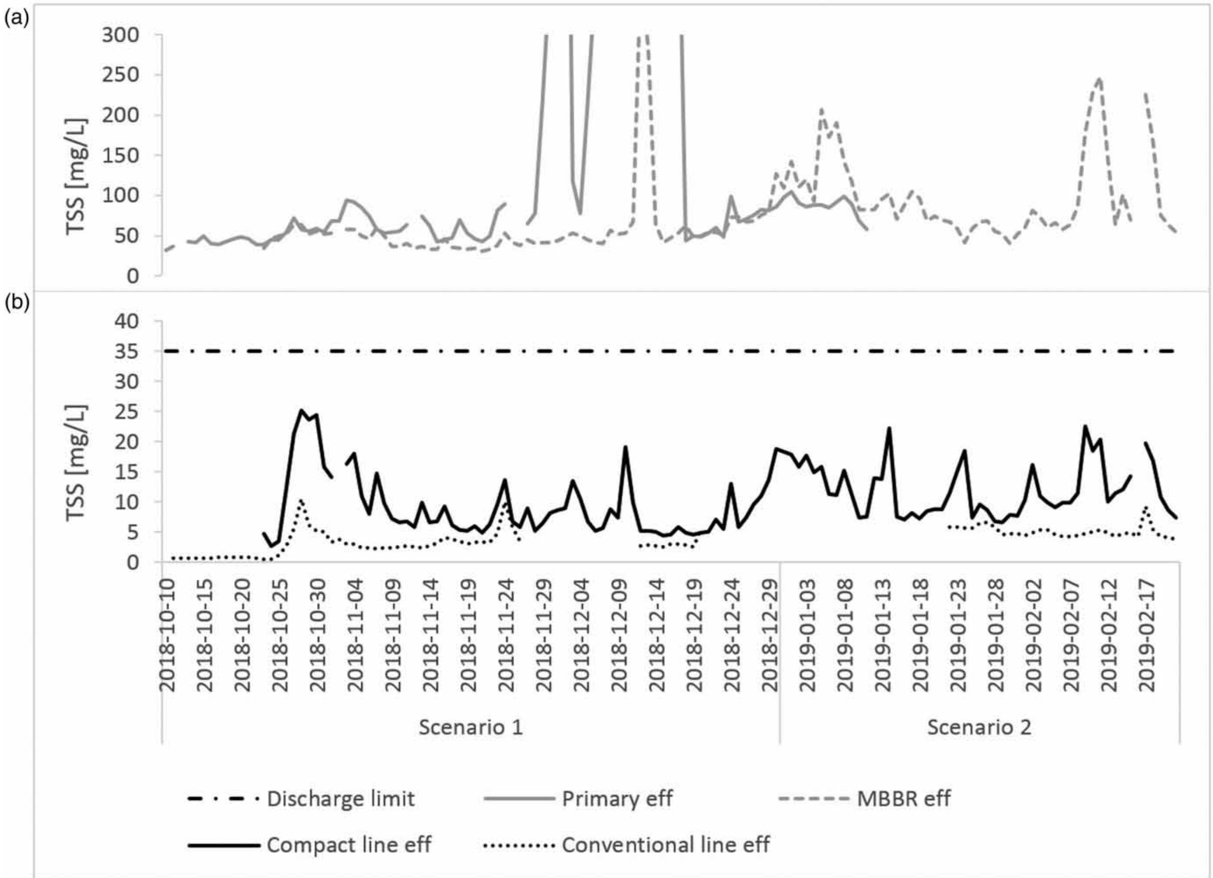

Figure 3 | Daily average turbidity for primary and MBBR effluents (a) and lines effluents, compared with the discharge limit (b).

The primary effluent TSS fluctuations were significant, with peaks from four to five times higher than the average due to sludge escape events. Although the trends of both lines are similar, the TSS in the effluent of the compact line were higher than in the conventional line due to the more open mesh installed in the disc filter and larger flow variations (average effluent of 10 mg/L vs 4 mg/L). Overall, the effluent quality consistently remained below the discharge limit of 35 mg TSS/L.

The compact line TSS effluent concentration could be reduced by increasing the polymer dosing, as shown in previous studies (Väänänen *et al.* 2016). The specific polymer dosing was 0.014 mg poly/mg TSS during Scenario 1 (average TSS in the MBBR effluent was 62 mg/L) and decreased to 0.008 mg poly/mg TSS during scenario 2 (average TSS in the MBBR effluent was = 114 mg/L).

TP was evaluated for the compact line only (Figure 4) for one month during Scenario 1.

Although the online primary effluent average recorded (2.7 mg TP/L) is similar to the average of the collected daily composite samples, spikes up to 10 mg/L were detected, probably due to sludge escape during rain events. To evaluate their effect on the compact line performance, an additional analyser monitored the MBBR effluent for a shorter period. The average effluent concentration was 1.6 mg/L (40% removal), suggesting that the MBBR biofilm acted like a phosphorus buffer, levelling down the influent peaks. This TP uptake was higher than expected and it could be due to the integration of phosphorus in extracellular polymeric substances (EPS) (Cloete & Oosthuizen 2001). The disc filter had a good performance even without coagulant dosing upstream with average effluent

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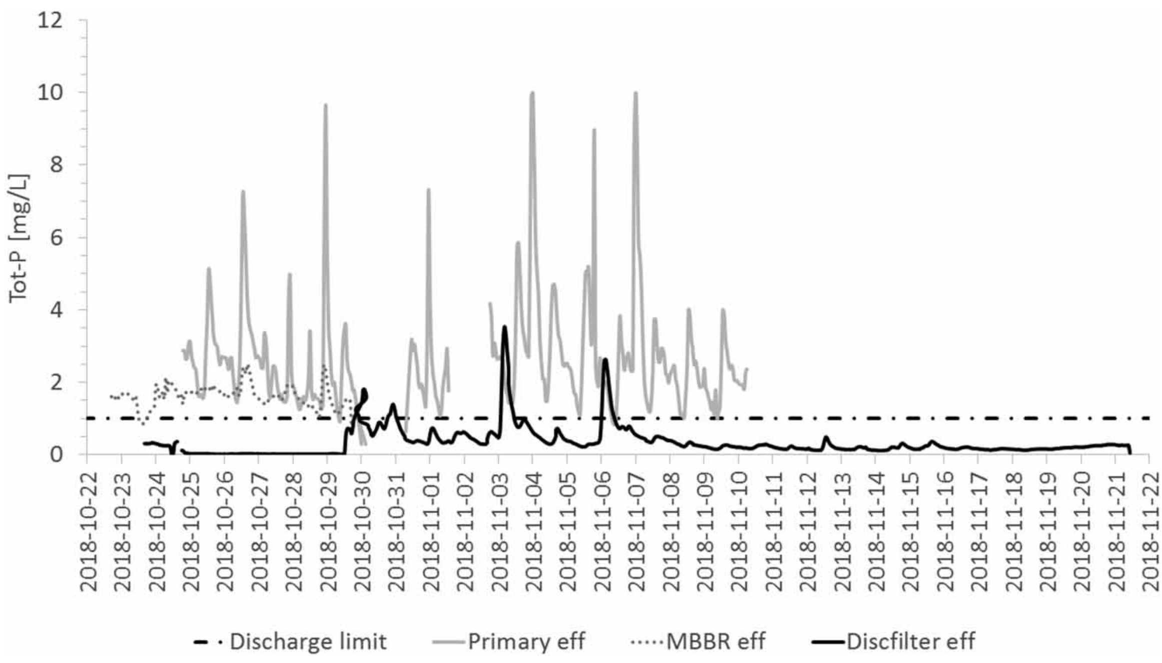

Figure 4 | Total phosphorus hourly average concentration in primary, MBBR and disc filter effluents, compared to the discharge limit.

concentrations below 0.35 mg TP/L. The yearly average limit of 1 mg TP/L was exceeded only during a few days, due to primary effluent spikes. To achieve a more constant effluent concentration, a coagulant dosing control strategy based on influent TP measurements could be used. Given the target concentration, the dosing can be set as molar ratio (mol Al/mol TP), so that it increases according to the influent load.

Removal of key parameters

The TSS after primary clarification ranged between 25 and 125 mg/L, with an average of 60 mg/L. The TSS in the CAS and the two line effluents were below 15 mg/L (discharge limit 35 mg/L, Figure 5).

Since the MBBR has a limited TSS buffer capacity due to the low retention time, TSS in the compact line effluent are linearly proportional to those in the primary effluent. On the contrary, the CAS

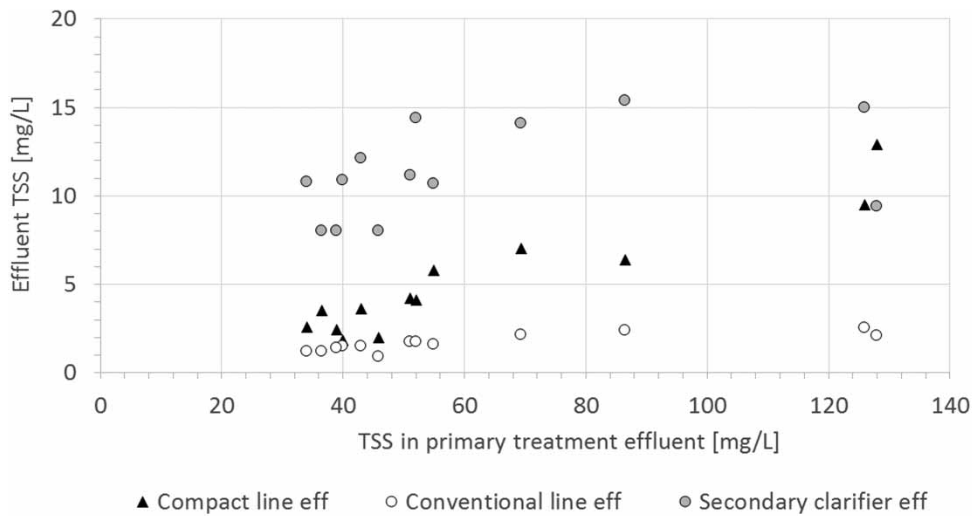

Figure 5 | TSS concentration in secondary clarifier and lines effluents in correlation with that of the primary effluent.

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works at long SRT, the influent VSS are hydrolysed and the effluent TSS concentrations are not directly affected by the influent variations. Furthermore, as the compact line receives the flow variations, the operation of the activated sludge is stabilized. Consequently, the influent load to the tertiary filters was 10 times lower than that of disc filters (MBBR effluent). Even though the conventional line has two separation steps (clarification and filtration with pile cloth media), and the compact line has one (disc filtration with 40 μm woven cloth), both achieved excellent TSS removal efficiencies, 97 ± 1% and 92 ± 2% respectively.

For both lines, the total COD discharged was below the detection limit of 15 mg/L, despite primary effluent concentrations ranging from 75 mg/L to 250 mg/L, fulfilling the discharge limits of both COD (125 mg/L) and BOD_5 (25 mg/L). Comparable COD and TSS effluent concentrations were achieved by another MBBR-coagulation-flocculation-disc filtration scheme in an alpine area in France (Kängsepp *et al.* 2020).

The discussion of total N results was divided into two scenarios (Figure 6) to highlight the change in the influent composition and the effect of low temperature, whose average was 10.5 °C during Scenario 1 and 7 °C during Scenario 2 (Figure 2).

Although the influent organic N doubled during Scenario 2 due to the seasonal peak, the effluent concentrations were stable throughout the whole period. During Scenario 1, the effluent ammonium

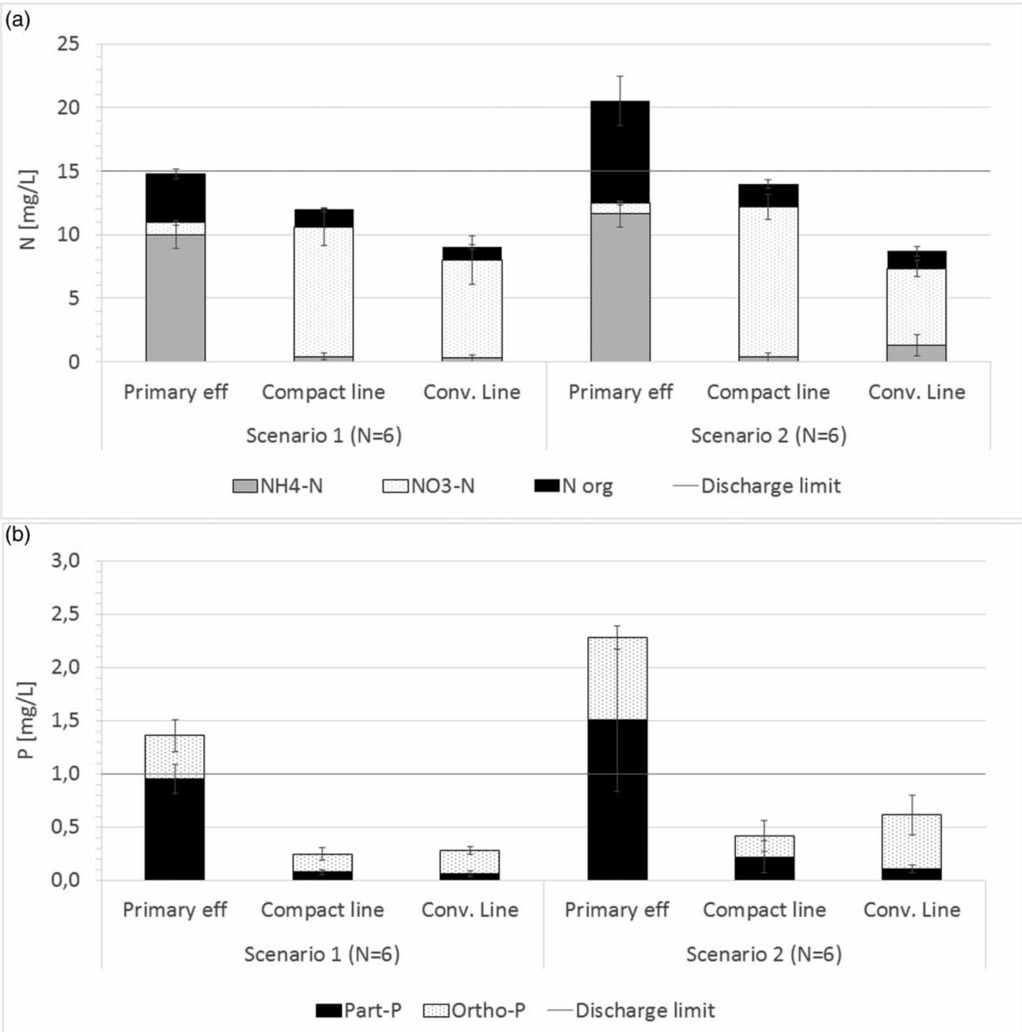

Figure 6 | Nitrogen (a) and phosphorus (b) fractions in primary, conventional and compact line effluents, compared to the discharge limit (annual average).

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nitrogen concentration was similar for the two lines (0.3 mg NH_4-N/L). However, in Scenario 2 it increased to 1.5 mg NH_4-N/L only for the conventional line. This is below the discharge limit (4.5 NH_4-N/L) and significantly lower than the average value recorded from January to May 2017 ($N =$ 10) of 12.8 ± 3.0 NH_4-N/L (Table 3). The overall ammonium nitrogen removal efficiency of the complete WWTP during cold weather improved from 33% (January–May 2017) to 89% (December 2018–February 2019, where data on primary effluent were used as WWTP influent). It is evident that temperatures below 10 °C and load variations have greater impact on the suspended nitrifying biomass than on the biofilm. On the other hand, the nitrates concentration is higher in the compact line effluent due to the breakage of the mixer motor in the denitrification stage of the MBBR_1 line. Although the internal nitrates recirculation flow of MBBR_2 line was adjusted, the limited denitrifying capacity is the main cause of the higher TN concentration in the compact line effluent. Overall, due to the reduced load and variation after the upgrade, the nitrifying performance of the CAS is enhanced, which results in a reduced overall TN effluent concentration (average 11 ± 3 mg TN/L). The discharged TN concentration reported by Kängsepp *et al.* (2020) is 28 ± 7 mg TN/L due to the absence of a denitrification step, but the nitrification is complete.

The TP results are also reported for different scenarios (Figure 6), due to the different chemical dosing described in Table 1. The P fractions in both final effluents were investigated for three days at the beginning of the study ($N = 6$). The soluble inert phosphorus was below detection limit (0.05 mg P/L). Therefore, the soluble phosphorus is mainly made of reactive Ortho-P (Henze *et al.* 2015a), 94% in the analysed samples.

The upgraded WWTP allowed a TP removal of 80%, despite a 30% decrease of $FeCl_3$ consumption, which was limited to 3 mg Fe^{3+}/L. Even though the influent wastewater strength is very low, the dosing is below the usual range of 5–20 mg Fe^{3+}/L for chemically enhanced primary treatment (Väänänen *et al.* 2016). Moreover, the dosing upstream of tertiary filters was replaced with that upstream of disc filters, which involves only a fraction of the treated flow.

During Scenario 1, the effluent concentration was 0.25 mg TP/L for both lines, of which 70–80% was Ortho-P. This is reasonable, since there was only a common coagulant dosing point upstream and both lines achieved low TSS concentrations in the effluent (Figure 5) and consequently low particulate phosphorus (Part-P).

During Scenario 2, the primary effluent TP concentration increased significantly (50% more Part-P and 100% more Ortho-P), but the effect on the effluent concentration was larger on the conventional line (0.6 mg TP/L) than in the compact one (0.4 mg TP/L). Although its removals were comparable to Scenario 1 (82%), the performance of the compact line could have been improved if the polymer dosing had been increased accordingly to the optimal specific dosing of 0.020 mg poly/mg TSS recommended by Väänänen *et al.* (2016), closer to that of Scenario 1. Due to an insufficient polymer dosing increase (only 20%, while the TSS in the MBBR effluent were 2.3 times higher), the Part-P in the compact line effluent doubled compared to Scenario 1. The effluent Ortho-P concentration was 150% higher in the conventional line, as no coagulant was dosed there. The molar ratio between metal dosed and TP to remove was 0.75 mol Al/mol TP. Overall, the lower the required effluent TP concentration, the higher the molar ratio has to be. Kängsepp *et al.* (2020) reported a comparable TP effluent concentration (0.3 ± 0.1 mg TP/L) with a chemical dosing of 5.0 mg Al^{3+}/L and 1.9 mg/L of polymer. The corresponding metal molar ratio (1.6–2.3 mol Al/mol TP) was more than double than in this study, while the specific polymer dosing (0.018 mg poly/mg TSS) was comparable to that of Scenario 1.

Perspectives of disc filter chemical pretreatment automation

To maximize the TSS and TP removals and optimize the dosing, an automatic system for chemical dosing regulation could be developed based on turbidity measurements (Väänänen *et al.* 2017).

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Given the TSS-turbidity correlation and the average TP content of TSS (Figure 7), it would be possible to estimate the TP concentration in the biological effluent and to adjust the polymer dosing in order to fulfil the requirements while avoiding overdosing during low TSS periods.

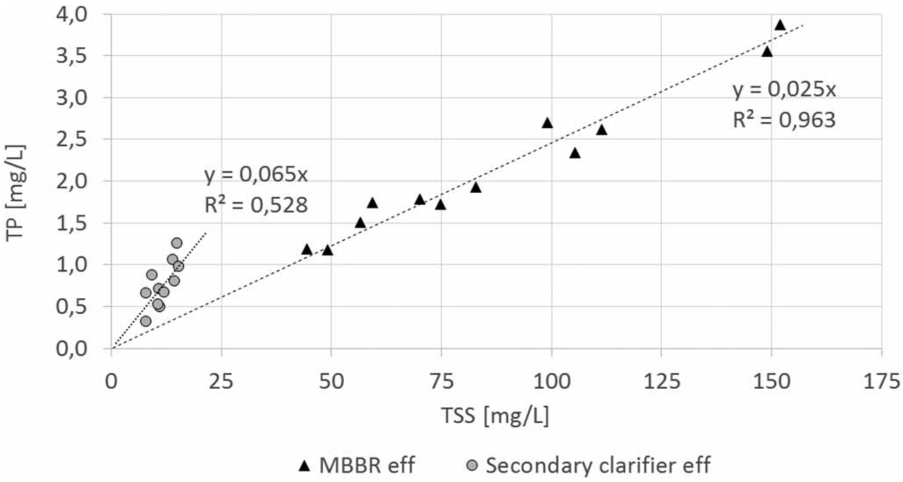

Figure 7 | TP – TSS correlation for MBBR and secondary clarifier effluents with linear interpolation equation and coefficient of determination (R^2).

The TP content of TSS is 2.5% in the MBBR effluent and 6.5% in the secondary clarifier effluent, but in the second case the coefficient of determination (R^2) is low, due to the described uncertainties in the TSS measurements (and consequently the Part-P fraction is only 47 ± 11% of TP, while it is 90 ± 5% in the MBBR effluent). A turbidity-based system could be a reliable and cost-effective TP monitoring strategy for MBBR effluents, while for CAS a TP analyser would be needed.

Benefits of an upgrade with MBBR-disc filters in parallel

Although the MBBR-coagulation-flocculation-disc filtration setup alone (Kängsepp *et al.* 2020) can handle the typical variations of a WWTP in touristic alpine areas, the Valdisotto WWTP upgraded scheme had the advantage of using the existing CAS line. By stabilizing the CAS and therefore enhancing its performance, it was possible to minimize the civil works. Moreover, the resilience of the MBBR process guaranteed a good COD, NH_4-N, and TP performance during both peak and low loading conditions.

CONCLUSIONS

The present article shows how a WWTP in an alpine touristic area featuring a CAS with frequent by pass issues causing effluent requirement violations can be upgraded by an MBBR-coagulation-flocculation-disc filtration line in parallel requiring less than half of the existing CAS footprint. This compact and flexible combination dealt efficiently with the load variations: the frequency of WWTP by-pass dropped and the flow supplied to the CAS stabilized, improving its performance. The overall WWTP ammonium nitrogen removal efficiency during cold weather (water temperature below 10°C) rose from 33% to 89%. Both lines easily fulfilled the TSS, COD, BOD_5, TN and TP discharge requirements, while reducing the chemical consumption for TP removal by 30%.

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