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Solid build-up and consolidation within biofiltration of wastewater: A new multicretria analysis to early detect irreversible clogging

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ABSTRACT

Submerged biofiltration, using a granular medium colonised by biofilm, is indeed suitable for the treatment of urban wastewater from large cities. Unfortunately, while periodic backwashing usually controls fouling, some plants require extensive maintenance (i.e., irreversible clogging requiring declogging with soda cleaning) due to head loss development and porosity reduction that conventional backwashing cannot overcome. A new multi-criteria analysis method has been proposed and tested on a full-scale plant where irreversible clogging occured twice a year. This work first cross-analyses the on-line indirect measurements recorded over 2.2 years to explain the occurrence of irreversible clogging. We have successfully shown that excessive volumetric loading rates (in suspended solids or chemical oxygen demand) have provoked irreversible clogging. Secondly, this work proposes scenarios of formation of cohesive matter, resistant to backwashing through, a succession of three states, one for the accumulation of solids within the void volume (storage due to the partial efficiency of periodic backwashing) and two states for the transformation of the accumulated solid matter with time, starting with the initiation of consolidation (reversible) and ending with its consolidation (irreversible). Finally, this work proposes a new method based on the analysis of the magnitude of the increase of the initial relative head loss with time (ΔPi / $\Delta Pref$) to gradualy describe the clogging of a biofilter: <1.3 (no solids accumulation) for unclogged biofilters, 1.3–1.6 (solids accumulation), 1.6–2 (initiation of consolidation) and > 2 (consolidation of solids). It provides recommendations on how to process the data in a hierarchical manner to detect the transition towards irreversible clogging at an early stage, and suggests corrective actions to carry out to the operator.

1. Introduction

With some 500 medium and large facilities built worldwide, the submerged biofiltration process (also called biological aerated filter - BAF) is a biofilm-based process suitable for managing biodegradable carbon and nitrogen contained in urban wastewater [1,2]. Always located downstream of a primary clarifier, a BAF consists of a reactor filled with an immersed granular medium supporting the development of biofilm which ensures the conversion of biodegradable pollutants in addition to the filtration of particulate matter. The accumulation of matter in the pores during treatment causes fouling, reduces porosity and increases head loss [3], requiring periodic backwash (regeneration) by high hydrodynamic stresses of air and water flows for abrasion [4–6]. A number of studies have focused on bringing this technology to maturity, testing the influence of the granular medium [7–11] and its structural aging [12–14] and also optimising filtration cycles and backwash phase [5,15–18] in order to maintain long-term performance of BAF. Nevertheless, some BAF facilities are experiencing irreversible clogging events with head loss development (as represented in SPM1), occuring insidiously, rapidly, and threatening permanently their operators [15,19–21]. It leads to high operational costs (e.g. backwash water volumes, maintenance time and stoppage, granular medium loss, channeling and dead zones) and environmental impacts (e.g. degradation of the quality of the discharged effluent, use of chemicals) [22,23]. Preventing BAF from irreversible clogging requires the understanding of the fate of solids (ie transport, transformation) in submerged fixed-bed biofilm-based process, but this has so far received little attention in literature [24,25]. In addition, in-depth monitoring of clogging in a BAF is limited and no early direct observation can be made in a timely manner.

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The accumulation of filtered matter contained in wastewater and the growth of biofilm lead to the formation, at the pore scale, of a complex cohesive structure The cohesion strengthens over time due to biochemical transformation (cementing process) resulting from hydrogen bonding or van der Waals forces [4] or polymeric bridges [26] or coagulable organics coming from microbial products or extracellular polymeric substances [18] or grease [27]. Shear stress induced by physical constrains also strengthens cohesion [28,29]. Cohesive matter occupying the pores of BAF (e.g. compressed, compacted, densified matter in aggregate form) requires chemical attack (e.g. soda NaOH application) to reduce in smaller aggregates, then evacuated outside the BAF, to recover the initial void volume fraction and head loss [23].

Irreversible clogging risk of a BAF is usually anticipated at design stage by limiting the volumetric loading rate applied for a treatment cycle (load in chemical oxygen demand (COD) or in suspended solid (TSS)) and increasing the backwash frequency [30,31]. During operation, the continuous monitoring of the pressure at the bottom of a BAF, also called head loss and reflecting the resistance to flow passing through the biofilter (i.e. granular medium, biofilm and accumulated matter [32] as represented in SPM1), is monitored to track head loss development [33,34]. Unfortunately, clogging only represents a small fraction of the total head loss and occurs insidiously in some stituations (e.g. loss of sludge from the primary clarifier and incomplete backwash). An early detection method of the drift towards irreversible clogging remains definitely expected.

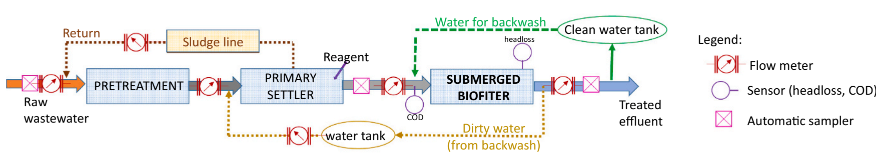
This study aims to improve the understanding of solid build-up and subsequent transformation in a biofilter to early detect irreversible clogging events. The novelty lies on the multicriteria analysis of online measurement that provides indirect access to scenarios of build-up and consolidation of solid matter in the pores, while no measurement and sampling inside the reactor is possible on a full-scale BAF plant. The experience on clogging and its causes are the result of the observations and the analysis of a plant monitored for 2.2 years and experiencing severe irreversible clogging (requiring soda cleaning) twice a year.

2. Materials and methods

2.1. Biofiltration facility (equipments and operating characteristics)

The studied plant is a submerged biofiltration plant located in France that treats biodegradable carbon contained in urban wastewater (see Table 1). Wastewater is first treated by the pretreatments and a primary chemically-enhanced lamellar settler. Then, it is applied to the biofiltration stage that includes 14 individual cells of 91.5 m^2 filled with 2.9 m high spherical expanded clay material (diameter: 3.2–3.8 mm) as the filtering medium. The pressure at the bottom of each biofilter cell was continuously measured. The treatment and backwash phases were operated under co-current ascendant water and air flows. The number of biofilter cells in operation and the aeration were both determined by the controller according to the total flow rate measured at the plant inlet.

Table 1
Layout, design, operations and monitoring of the studied biofilter treatment plant.

BAF design and operations	467 000 P.E., 257 000 m^3 /d (reference flow)  <u>Design</u>: - The submerged biofilter is composed of 14 cells. Each cell (91.5 m²) is filled by 2.85-2.9 m height of spherical expanded clay material (grain size 3.2-3.8 mm, porosity 0.41) - Water flow rate during filtration: 3 - 8 $m^3/m^2/h$ - Loading rates (B_V) 6.1 kg COD /m^3 /cycle and 3.5 kg TSS /m^3 /cycle. Application of water to treat by a central distribution channel <u>Operations</u>: - Water flow rate during filtration: 3 - 8 $m^3/m^2/h$ - Air supplied by 2 compressors (plus 1 emergency) for the 14 cells. Airflow rate controled with water flow rate (periods P1 to P4) or TSS load (period P5) - Periodic backwash (100 $Nm^3/m^2/h$ for air, 20 $m^3/m^2/h$ for water, up to 530 m^3 water volume): applied at least every day. They were started when one of the 3 parameter has reached it threshold: 1) Filtration time (12 h/cycle), 2) Volume of filtered water, 3) Head-loss - Soda cleaning (0.85 kgNaOH /m^3 of material to maintain pH 12 for a night): applied at days 0, 142, 292, 544, 729
BAF Monitoring (dataset)	815 days over the years 2014 to 2016. <u>Raw data</u>: Head loss, composition of inlet/outlet/backwash waters, flowrate, motor running and valve status (every second or minute) <u>Calculated data</u>: Initial head loss and void volume (beginning of a cycle), Hydraulic and volumetric loading rates B_V (integrated for each cycle), Duration of filtration or backwash (for each phase) Five periods of time, noted as P1 to P5, defined in between soda cleaning

The backwash was applied at least every day, after a filtration time of 12 h/day (Time threshold was reached before the thresholds of volume of filtered water volume and head-loss).

Each cell of filtration stage had experienced 1 or 2 irreversible clogging events per year. De-clogging was carried out by the application of 420 L of soda (0.85 kgNaOH /m^3 of material) to maintain pH 12 for a night. After soda cleaning, wastewater was progressively applied to the cleaned cell (2 h/24 h, 4 h/24 h and 9 h/24 h) to support natural seeding of filtering medium.

Table 1 also shows the location of the sensors and sampling on the plant. Flow meters were installed at the inlet of the plant, on the backwash water line (dirty water) and the return flows from the sludge line. The flow rate applied to a cell was determined by dividing the inlet flow meter by the number of cells in operation. The flow data were recorded every second or minute for flow measurements. A probe continuously monitored the COD concentration of the primary treated effluent, and a regular check with chemical analysis was carried out on average 24-hour samples. The measurement interval was between 0.17 and 2 min according to the measured parameter. The suspended solid concentration (TSS) of primarily treated effluent was measured 3 times per week on average 24-hour samples.

This work focused on one cell of the biofiltration plant.

2.2. Parameters for detecting the transition towards clogging

Due to the discontinuous nature of a BAF operation, instantaneous valued from sensors along with motor running times, valve status, etc. were recorded in operating files of the plant controller (Table 1). Python routines were coded to determine specific descriptors of the plan operations of the BAF: instantaneous descriptor like head loss at the beginning of a filtration cycle at a given flow rate or for a period of treatment like hydraulic or volumetric loading rate Bv, the time of filtration or backwash. These descriptors, which did not exist on the BAF plant studied, have been tested off-line to detect a transition over time towards irreversible clogging.

The applied volumetric loading rate Bv [expressed in kg /m^3 material /cycle)] of a pollutant over a treatment cycle was calculated according to Eq. (1) from it concentration [g/L], the inlet water flow rate [m^3/h] averaged over the duration of the filtration cycle [h/cycle], divided by the volume of filtering media [m^3]. The volumetric loading rates for chemical oxygen demand COD [denoted $B_{V,COD}$] and total suspended solids TSS [denoted $B_{V,TSSS}$] were respectively determined with probe values and daily average composite samples.

$$\mathbf{B_{V,parameter}} = \frac{\textbf{Concentration in parameter} \bullet \textbf{Flowrate} \bullet \textbf{Duration of filtration cycle}}{\textbf{Volume of filtering material}} \tag{1}$$

The initial head loss (ΔP_i) was determined by measuring the pressure after 1 h of filtration. It was normalized by the water flow rate ΔP/Q [mbar /m^3 /d], i.e. normalized headloss. As the temperature varies between 15 and 25 °C depending on the season, the viscosity of the water was assumed to be constant and no correction was made for pressure.

The initial porosity (ε) of the filter was calculated at the beginning of each cycle by solving Eq. (2) (Kozeny-Karman equation for porous media) by means of the reduced gradient method (Excel solver).

$$\frac{\Delta P}{Q} = h_k \bullet A_S^2 \bullet \frac{(1-\varepsilon)^2}{\varepsilon^3} \bullet \eta \bullet \frac{Z}{S} \tag{2}$$

with: head loss ΔP [Pa], water flow rate Q [m^3/s], ΔP/Q normalized headloss (mbar /m^3 /d), dynamic viscosity of water η [Pa.s], Kozeny constant h_k [−], specific grain area A_S [m^{-1}], porosity ε, filter height Z [m], and free cross-section without granular media S [mm^2].

The initial void volume [m^3], that is to say the space available for filtered solids and biomass produced during, was determined at the beginning of each filtration cycle with Eq. (3) using the total volume of the filter bed [m^3] and the fraction of available void or porosity ε [−].

$$\textbf{Void volume} = \varepsilon \bullet \mathbf{V} \tag{3}$$

2.3. Threshold limits / reference values

To limit the risk of irreversible clogging, the volumetric loading rates should not exceed thresholds values of 5.8 kg COD /m^3 material / filtration cycle, and 2.1 kg TSS /m^3 material /cycle [31]. These thresholds are lower for effluents rich in soluble biodegradable organic matter that produces biomass with a higher clogging capacity compared to suspended solids (e.g. estimated at 1.1 kg TSS /m^3 material /cycle for COD:TSS > 3.2). Such values were used to determine the periods of time when the BAF plant was overloaded.

Reference values in initial head loss and initial void volume were used. They were determined by selecting the lowest value of head loss after cleaning with soda (measured upon several operating cycles), or derived from a period of operations when the biofilter was not affected by clogging.

3. Results and discussion

The period of operations of the biofilters was divided into five periods of time, denoted P1 to P5 (lengths: 143 d (P1), 151 d (P2), 253 d (P3), 186 d (P4) and 87 d (P5)) which were delimited by the day of application of soda cleaning (see Table 1). Part 3.1 presents the results of the cross-analysis of the head loss, the occurrence of clogging, and the time evolution of the operating parameters of the biofilter. These observations are used to conceptualize different scenario of solids matter build-up and consolidation in a granular medium submitted to hydraulic constraints. Part 3.2 ultimately led to a method to detect the drift towards irreversible clogging at an early stage.

3.1. Cross-analysis of the operating parameters and proposed scenarios of build-up and consolidation of matter in the pores

The Fig. 1 shows the evolution over time of the operating parameters, namely the initial normalized head loss after backwash, the estimated initial void volume, the applied volumetric loading rates for chemical oxygen demand COD ($B_{V,COD}$) and suspended solids TSS ($B_{V,TSSS}$). It provides possible scenario of behaviour of solids in the pores, from no-accumulation from one cycle to another S1 (solids removed by backwash), to scenario of accumulation of solids, with storage S2, initiation of consolidation S3 and consolidation S4 (irreversible clogging). Table 2 gives detailed time informations if needed. Additional graphs are proposed in SPM2.

3.1.1. Reference values

First, it can be observed that after few days of each application of soda cleaning (beginning of period P1 to P5), the initial normalized head

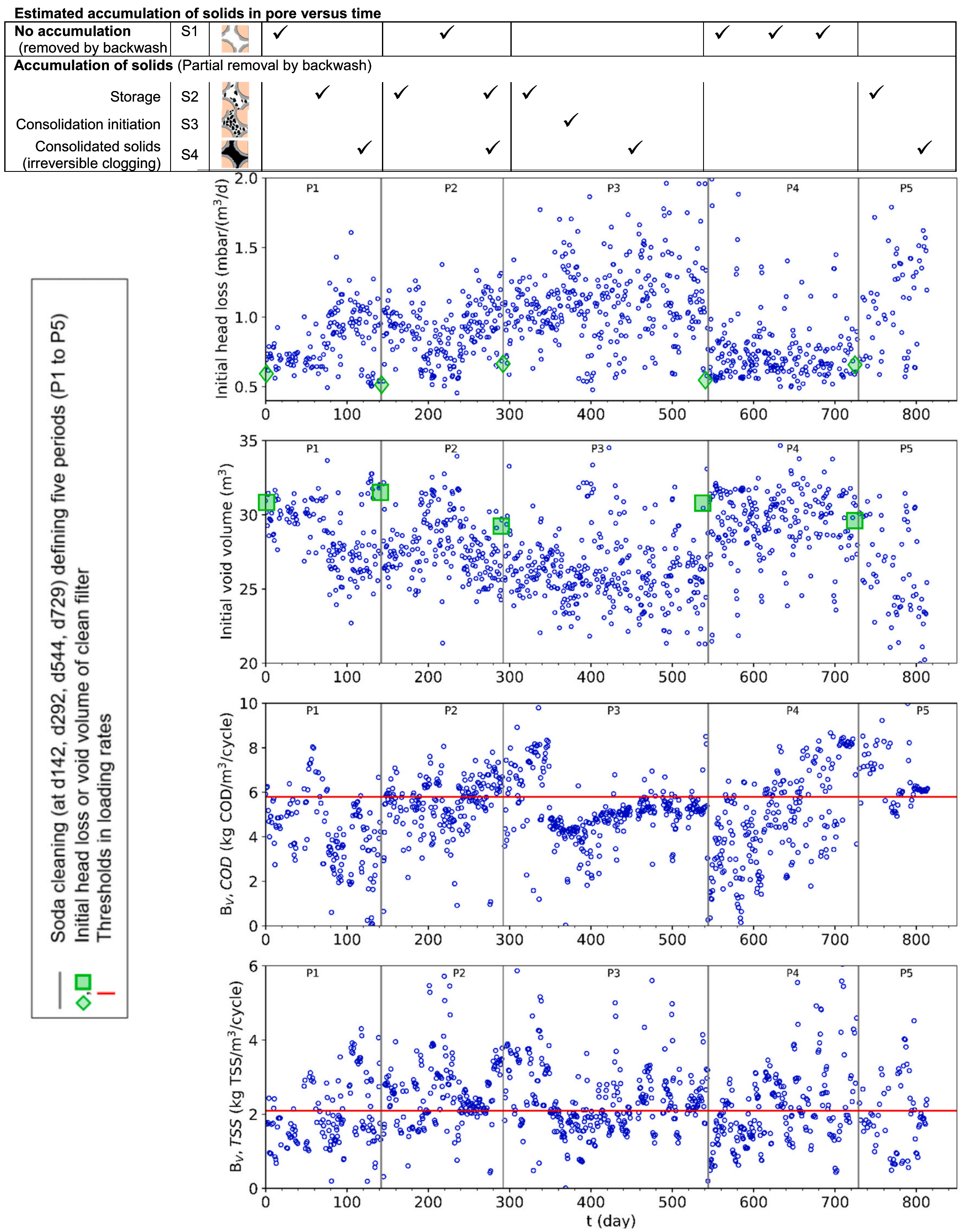


Fig. 1. Estimated content of pore by solid materials, and time evolution of operational parameters (initial head loss, initial void volume of biofilter, volumetric loading rates in COD and TSS). Additionnal deviation info in Table 2.

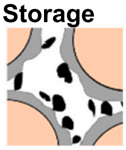
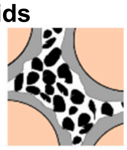
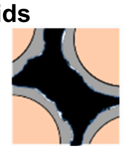
loss was low with 0.6 mbar /m^3 /d (green symbols in Fig. 1) and nearly stable. Simultaneously the initial void volume of the biofilter reached 30 $\pm$ 2 m^3. These are reference values for the biofilter, i.e. with no accumulation of persistent residual material after backwash.

In the following sections, the initial normalized head loss and void volume values are compared to these references so as to comment on the occurrence of clogging and detect the drift towards clogging.

3.1.2. No solid accumulation (S1) vs. build-up or consolidation (S2, S3, S4)

During Period P4, 86 % of the cycles have reached an initial normalized head loss from 0.7 to 0.8 mbar /m^3 /.d on average (excluding the 15 filtration cycles during which the head loss has exceeded 1 mbar /m^3 /d). The void volume was estimated at around 30 $\pm$ 2 m^3 and remained nearly constant. The volumetric loading rates for the most part remained below the clogging risk thresholds. Therefore, the backwash has regularly removed the solids built up during the treatment phase. It can be concluded that during period P4, the

Table 2
Days of operation of the studied biofilter cell for each different states of void volume occupancy (S1 to S4).

Condition after backwash and illustration	Days of deviation to the initial head loss $\Delta P_i/\Delta P_{ref}$	Days of excessive volumetric loading rate B_v	Days of high COD:TSS (nature of applied influent)
No accumulation of solids from on cycle to another			
S1. Solids removed by backwash 	**<1.3** d0-d75 (P1) d190-d240 (P2) d544-d729 (P4)	**> 5.8 kg COD /m^3 /cycle** d52-d75 (P1) d195-d220 (P2) d614-d729 (P4) some non-consecutive cycles $B_{V,TSS}$ > 2.1 kg TSS /m^3 /cycle d47-d65 (P1) d195-d240 (P2) d565-d573 & d620-d645 & d667-d729 (P4)	> 3.2 d0-d45 (P1) d690-d725 (P4)
Solid build-up and consolidation from on cycle to another			
S2. Storage 	**1.3 - 1.6** d75-d90 (P1) d143-d190 & d240-d280 (P2) d293-d350 (P3) d729-d770 (P5)	**5.8 kg COD /m^3 /cycle** d240-d350 (P2) d729-d770 (P5) **> 2.1 kg TSS /m^3 /cycle** d148-d190 & d240-d280 (P2) d293-d350 (P3) d713-d729 (P4) d750-d755 (P5)	> 3.2 d70-d80 (P1) d170-d190 & d270-d280 (P2) d305-d340 (P3) d729-d770 (P5)
S3. Initiation of consolidation of accumulated solids 	**1.6 - 2 for several cycles** d90-d110 (P1) d350-d390 (P3)	**> 2.1 kg SS /m^3 /cycle** d90-d110 (P1)	> 3.2 d385-d390 (P3)
S4. Consolidated accumulated solids  **(irreversible clogging)**	**>2 for a significant period of time, and stable (if load decreases)** d110-d142 (P1) d280-d292 (P2) d390-d544 (P3) d770-d820 (P5)	**> 2.1 kg SS /m^3 /cycle** d100-d115 (P1) d280-d350 (P2) d785-d792 (P5)	>,3.2 d425-d440 & d500-d510 (P3) d770-d820 (P5)

biofiltration cell had been operated with no solid build-up within the void volume (State S1: no accumulation of solids / no clogging). We deduce that the chemical cleaning at the end of Period P4 was preventive in nature (i.e filter unclogged) without any early indicators (such may be the case when the operator detects clogging in other cells and proceeds to clean all of them as a precaution).

The four other periods of operations P1, P2, P3 and P5 have revealed a biofiltration cell functioning with solid build-up within the porosity, despite the periodic backwash. These periods were characterized by continuously increasing trends in the initial normalized head loss, from 0.6 to 1.2 mbar /m^3 /d (P1& P2), and even up to 1.65 mbar /m^3 /d (P3 & P5). These increases were very rapid, equal to 20 % from one cycle to the next over several consecutive days. The initial void volume decreased from 31 to 25 m^3 (P1 & P2), and even dropping to 22 m^3 (P3 & P5). It was deduced that the backwash was unsufficiently efficient at withdrawing the stored materials, thus causing a solid build-up in the pores from one cycle to another. Consequently, in each of these four periods, the biofilter cell gradually evolved towards State S4 (consolidation of accumulated solids / clogging), in which soda cleaning was necessary to remove the consolidated solid matter built-up in the biofilter. Indeed, the applied COD and TSS volumetric loading rates exceeded by 1.5 and 2.5 times respectively the threshold values corresponding to a high risk of irreversible clogging, for at least 90 and 40 days /year for COD and TSS respectively.

By comparing P1, P2, P3 and P5 to P4, we conclude that the increase in the initial head loss and the decrease in initial void volume both occurred when the COD and TSS loading rates were applied in excess in this BAF. This observation suggests that a backwash may contain a given capacity of solid mass withdrawal, resulting in an accumulation of solids in the biofilter when the applied load exceeds the treshold capacity.

3.1.3. Reversible solid build-up (S2)

At the beginning of Period P2, the initial normalized head loss has reached 0.9 mbar /m^3 /d (i.e. 30 % above the reference value), and the available void volume was on average around 25 m^3 (i.e. 12 % below the reference value). These values are explained by the high volumetric loading rates applied: 7–8 kg COD /m^3 /cycle and 3.5 kg TSS /m^3 /cycle, i.e. 1.5 to 2 times greater than the recommended values. The biofilter reached an onset of clogging defined as State S2, caracterized by non-cohesive solids. When the COD and TSS volumetric loading rates decreased (between days d180 and d230) from 6.0 to 3.8 kg COD /m^3 /cycle and from 3.0 to 1.5 kg TSS /m^3 /cycle, it was observed that the initial head loss have reached the reference value in only about ten cycles of treatment/backwash (Fig. 1), returning to State S1 (no clogging). We deduce that, between days d180 and d230, the solids stored in the pores were not cohesive enough compared to the energy of backwash, and they were gradually removed by the backwash. These observations suggest that regular operations of a BAF can evacuate a temporary accumulation of non-cohesive and non-consolidated solids (S2).

3.1.4. Consolidation of solids (S3) and drift to irreversible clogging (S4)

The beginning of Period P3 was characterized by an high initial normalized head loss of 0.9 mbar /m^3 /d (i.e. 30 % higher than the reference value) maintained for nearly the entire period (only 12 % of the cycles in P3 had an initial normalized head loss below 0.8 mbar /m^3 /d). The average available void volume was 26 m^3 throughout Period P3, which is 12 % lower than the reference value. For the beginning of Period P3 and up to d330, high volumetric loading rates were applied with 7–8 kg COD /m^3 /cycle and 3.5 kg TSS /m^3 /cycle (1.5 to 2 times the recommended thresholds). Hence, the biofilter was operated under State S2 (with accumulation of solid inside the pores) due to insufficient withdrawal of solids for several cycles. Despite the application of energetic backwash twice a week, the BAF was unable to return to state S1, suggesting that cohesion started, moving BAF towards state S3 (initiation of consolidation). From Day d330 until the end of Period P3, the COD and TSS volumetric loading rates were reduced to 4.5–5 kg COD /m^3 /cycle and 2 kg TSS /m^3 /cycle, respectively. Nevertheless, the initial normalized head loss remained high (between 1.2 and 1.5 mbar /m^3 /d), and the initial void volume remained low (24–25 m^3). This behaviour means that the solid material stored in the pores had not decreased with backwash during this time frame. It can be deduced that solids stored in the filter became cohesive (consolidation) and could not be withdrawn by the energy applied during backwash. In other words, the BAF cell had drifted towards State S3 (initiation of consolidation) between d350 and d390, and then reached State S4 (confirmed consolidation / clogging) between d390 and d544. These observations confirm that despite the capacity of solid mass withdrawal of a backwash, the consolidation opposes a physical resistance to the elimination of solids, and leads in the long-term to irreversible clogging (S4).

We also noted that the consolidation of matter was influenced by the nature of the wastewater to be treated. Indeed, the increase in the initial normalized head loss up to 1.2 mbar /m^3 /d (i.e. >100 % higher than the

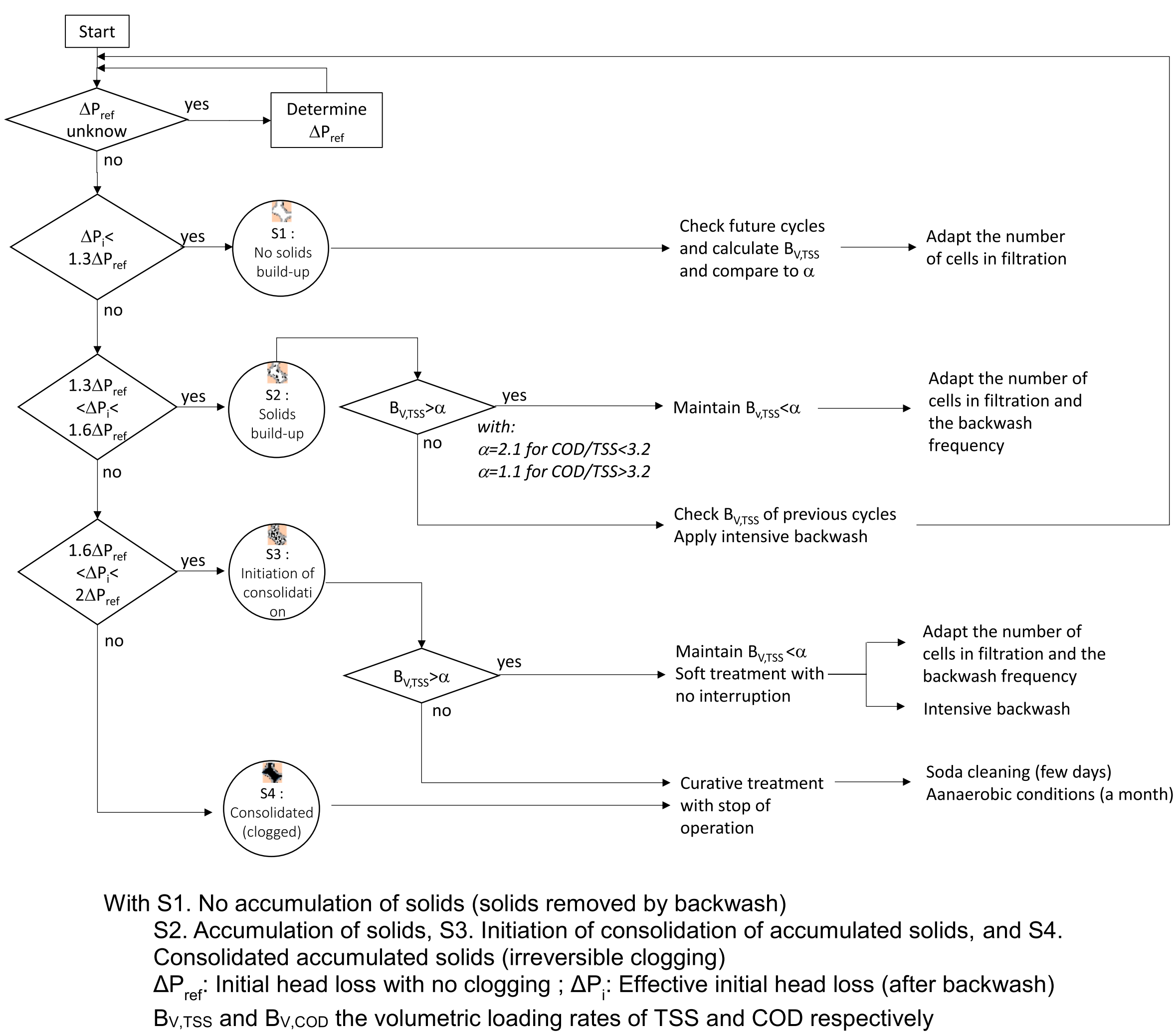


Fig. 2. A multicriteria cross-analysis method to early detect a drift towards irreversible clogging of a biofilter.

reference value) was observed in two time frames during Period P3. This increase was concomitant with a high biodegradability of wastewater that reached COD:TSS ratio of 6 between Days 320 and 380, and 9 between Days 504 and 543, with no increase in the loading rate. These values are 2 to 3 times higher than a typical value of 3.2. This condition generates more biomass (due to biodegradable COD), which in turn has a higher clogging capacity compared to suspended solids. Moreover, this observation would suggest that the hypothesis on increase of the cohesion of the material entrapped in the pores (to be verified with sampling when possible). It can be deduced that besides the applied volumetric loading rates, the nature of the organic matter contained in the wastewater to be treated may influence the drift towards irreversible clogging. As a result, in this time frame, the BAF gradually evolved from State S3 towards State S4 (consolidation of accumulated solids / clogging), whereby soda cleaning was necessary to remove the consolidated solid material build-up in the biofilter.

In summary, the dynamic of head loss has been correlated with different scenarios of consolidation level of the solid materials in the pores (i.e. physical resistance), considering that the consolidation of solid material is the consequence of a cohesion due to the biochemical composition of matter (e.g. hydrogen bonds, Van der Waals forces [4], polymeric bridges [26]) and/or a compaction (densification) due to increased shear stress [28]). Further investigations by direct measurement would be interesting to confirm the scenarios, but the sampling of such materials remain a key issue in full-scale BAF.

3.2. A method for detecting a drift towards irreversible clogging, and corrective actions

Based on previous observations, a method based on indirect measurements was developped to early detect a transition towards the irreversible clogging state (Fig. 2), and advice on corrective action to be taken.

The proposed method is composed of 4 steps (Fig. 2). It requires online monitoring of three operating data elements, namely: the initial cycle head loss after backwash measured at a given flow rate (ΔP_i), the applied volumetric suspended solids loading rate per filtration cycle ($B_{V,TSS}$), and the COD:TSS ratio of the water to be treated (α). This last element is mandatory to adapting the admissible load threshold according to the quality of the influent COD (adjustment between solids from either particles or biomass). The clogging dynamics is determined according to the magnitude of increase in the initial relative head loss over time (ΔPi / $\Delta Pref$ ranges: <1.3, 1.3–1.6, 1.6–2, >2). The method yields recommendations for processing the information in a hierarchical manner, and provides a set of corrective actions.

The method starts by determining the head loss reference value (ΔP_{ref}). Next, the initial head loss value of a treatment cycle (ΔP_i) is compared to this reference ΔP_{ref}, by calculating the magnitude $\Delta P_i / \Delta P_{ref}$. When the initial head loss remains near the reference ($\Delta P_i < 1.3\Delta P_{ref}$), the biofilter is operated under State S1 (No accumulation of solids): Each backwash regularly removes the solids that build-up during the treatment phase. Preventive action consists of verifying the evolution over future cycles ($B_{V,TSS}$ calculation and comparison to the maximum threshold load α, as estimated using the COD:TSS ratio of the water to be treated).

Failure to reach the initial head loss reference value ($\Delta P_i > 1.3\Delta P_{ref}$) for several cycles is a warning sign that should alert the operator about low backwash efficiency and solid build-up in the void volume. The TSS volumetric loading rates ($B_{V,TSS}$) should still be calculated and then compared to the maximum threshold load α estimated with the COD:TSS ratio of the water to be treated (2.1 kg TSS /m^3 /cycle or lower). The following cases are encountered:

- When ΔP_i lies between 1.3 and 1.6 ΔP_{ref}, the biofilter is operating under State S2 (Solids build-up). In this situation, a chemical cleaning is not necessary, but it is urgent to reduce the TSS load applied in order to withdraw solids stemming from a few cycles prior, at a state when the matter stored in the pores is neither cohesive nor consolidated (i.e. temporary build-up). If the applied $B_{V,TSS}$ lies,below the α value, it is recommended to apply an intensive backwash so as to disaggregate the solids; otherwise, the increase in ΔP_i would continue;
- When the initial head loss ΔP_i lies in the range of 1.6 to $2\Delta P_{ref}$, the cohesion of the solids entrapped in the pores has increased (State S3), and it resists to the energy applied during backwash. Since a conventional backwash is often insufficient to disaggregate the stored matter, it is recommended to apply an intensive backwash that conveys high mechanical energy (i.e. longer duration, higher water and/or air velocities compared to standard ones), and then return to State S2. Reactivity is very important at this stage to stop the drift to next state;
- If the initial head loss exceeds $2.\Delta P_{ref}$, the solids are cohesive and can no longer be removed by the given mechanical constraints (State S4: Consolidation of accumulated solids). The biofilter has reached a state of irreversible clogging. Only specific curative maintenance steps can remove the consolidated solids, for instance by applying soda cleaning which entails a short stoppage of operations yet requires time to develop a biofilm. An alternative would consist of applying anaerobic conditions to digest the organic matter but this requires a longer stoppage of operations (about one month).

The proposed procedure presumes that the operator regularly verifies the effective water and air velocities during the treatment and the backwash phases, to ensure the application of the correct mechanical constraints.

The method is based on the finding that the solids accumulate in a biofilter when the solid input exceeds the withdrawal capacity of a backwash, and on the finding that cohesion increases as solids spend time in a BAF due to chemical transformation and physical constraints. Consequently, reactivity of the operator is a key issue to struggle until cohesion and withdraw the excess of solids applied.

Measuring the initial head loss at a constant water flow rate at the beginning of a treatment cycle (i.e. rinse phase) limits the variability and increases the detection of small head loss variations linked to stored matter. Monitoring over several consecutive cycles is necessary to assess the deviation with respect to reference values. The reference values need to be checked and readjusted every year due to the possible loss of granular medium over a year (this value does influence head loss).

In the studied facility, irregular sludge withdrawal at the primary treatment and backwash applied according to a clock-triggering mode, led to COD and TSS overloading of the biofilter cells. To prevent from this problem, COD and TSS sensors at the biofilter inlet are highly recommended. Other key points to check are the non-occurrence of hydraulic shock (caused by an excessive drainage flow of backwash water), the absence of nitrates is return water from backwash and sludge line that sometimes occurs in summer (provocking natural denitrification in primary settler, and sludge loss towards BAF).

4. Conclusion

A multicriteria cross-analysis of the operating conditions of a biofilter facing 4 irreversible clogging events over 2.2 years was carried out. This method has output that excessive volumetric loading rates in suspended solids or in chemical oxygen demand are related to the occurrence of irreversible clogging. This work also suggests the formation of cohesive matter resistant to backwash (irreversible clogging requiring soda cleaning). It defines a succession of states including one state of accumulation of solids within the void volume (storage due to partial efficiency of periodic backwash), and two states of transformation with time of this matter, with initiation of consolidation (reversible) and consolidation leading to cohesive matter (irreversible). This work finally proposes a new 4-step method based on the analysis of the magnitude of the increase in the initial relative head loss over time (ΔPi / ΔPref ranges: <1.3, 1.3–1.6, 1.6–2, >2). This method yields recommendations for processing the indirect measurements in a hierarchical manner, to early detect the transition towards an irreversible clogging.

The outlook for future work would include sampling and characterizing matter resistant to periodic backwash to better evidence the cohesion of solids generated under mechanical constraints. Modelling of irreversible clogging is also an avenue for future research.

CRediT authorship contribution statement

Beatriz González Vázquez: Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Jean-Marc Choubert:** Writing – review & editing, Validation, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jean-Pierre Canler:** Writing – review & editing, Methodology, Conceptualization. **Etienne Paul:** Writing – review & editing, Validation, Supervision, Methodology, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jwpe.2024.105796.

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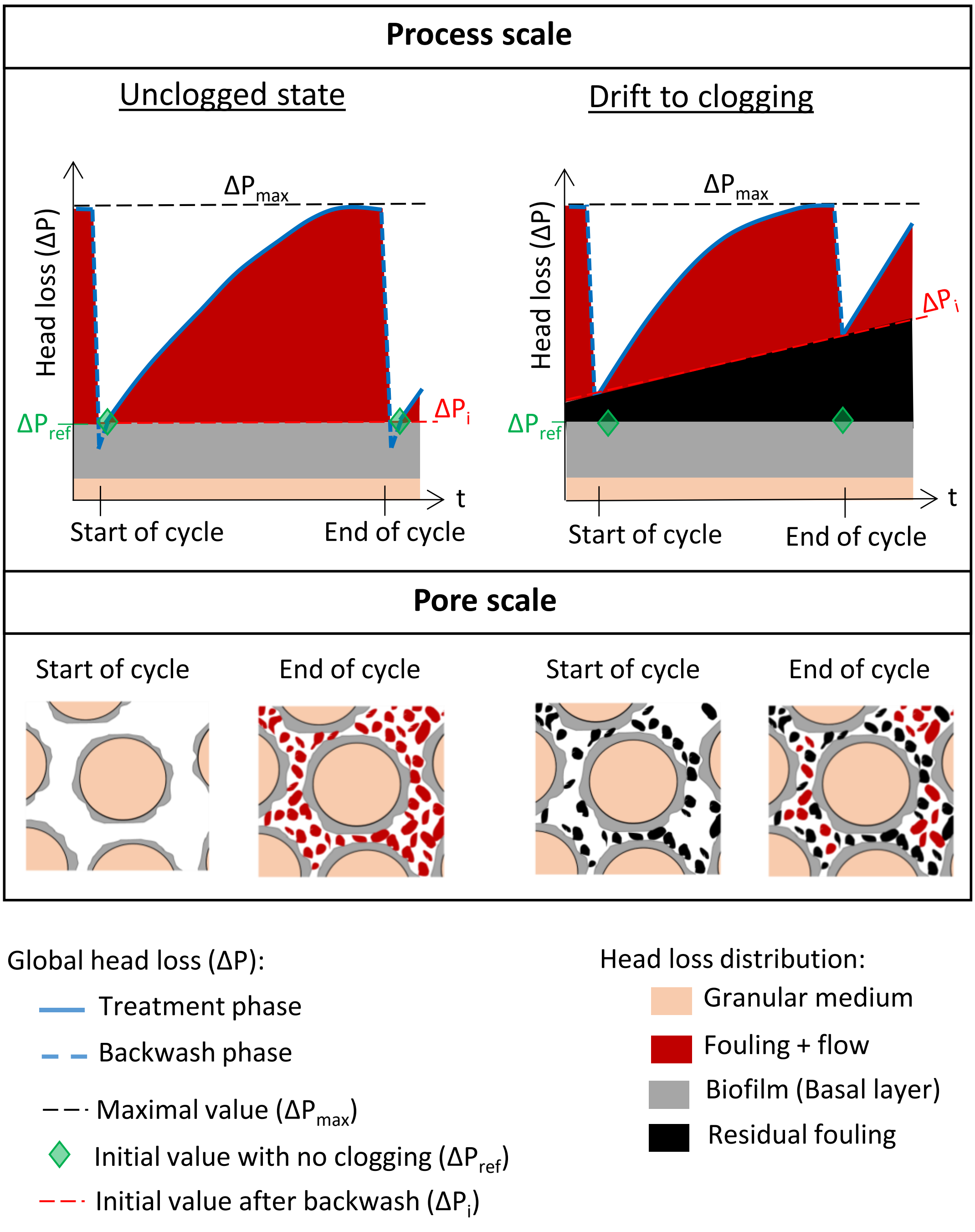
SPM 1: Schematic representation of the link between the head loss measured at the bottom of a biofilter and the presence of materials in the void volume with and without a drift towards clogging



SPM 2: Plots for the relative initial headloss vs. the cumulative loads in COD ($B_{V,\,COD}$) and TSS ($B_{V,\,TSS}$)