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Dynamic and initial head loss in full-scale wastewater filtration and measures to prevent long-term initial head loss

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ABSTRACT

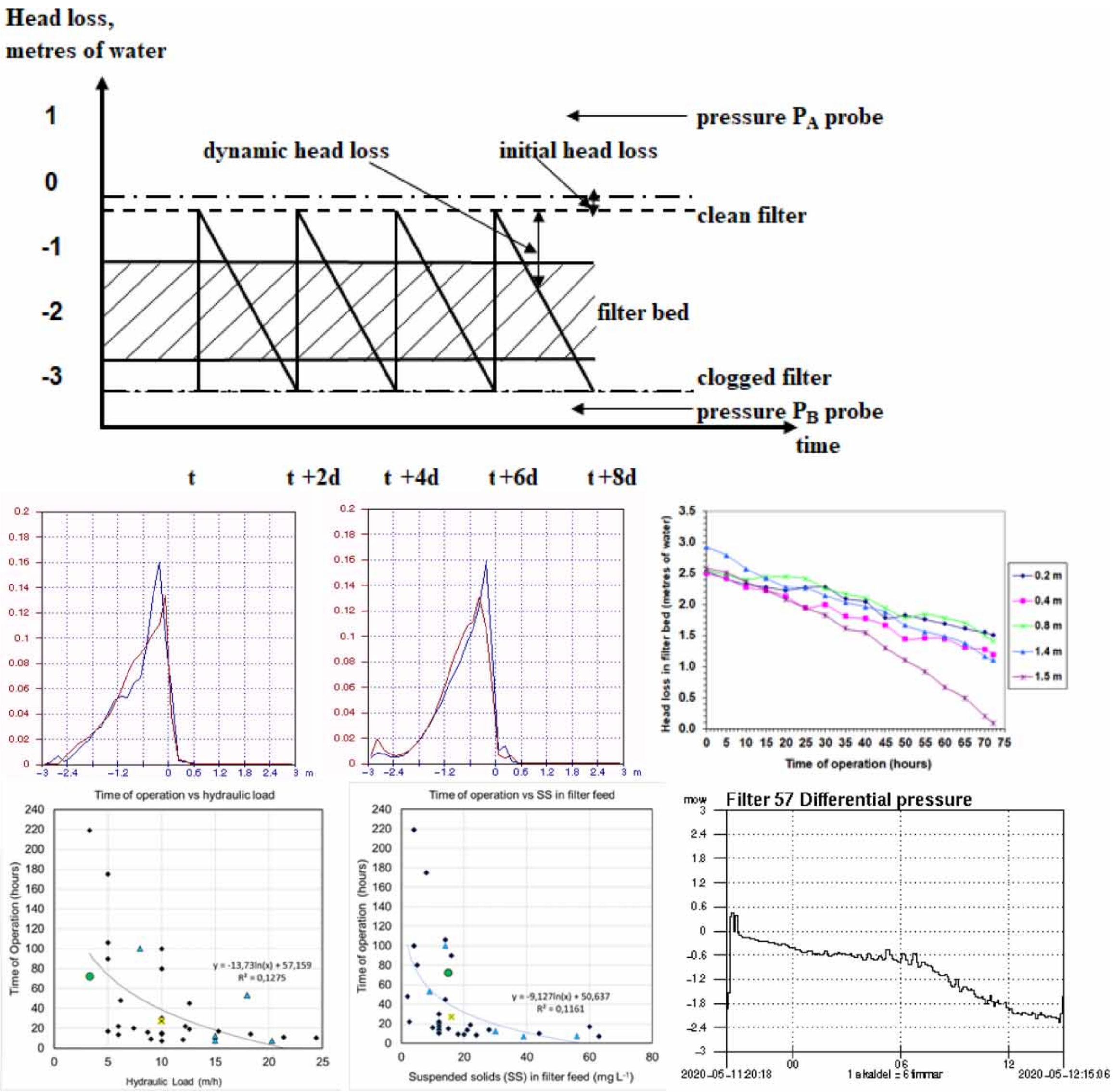
Dual media sand filters at Henriksdal WWTP began to show high head loss after five years of operation, especially during the fluidization for sorting the filter bed after backwashing. At that time, the filters were still clean and the dynamic head loss, due to clogging of the filters with suspended solids during a cycle of operation, had its lowest value. Dynamic head loss over the lower sand layer surface in the dual media sand filter was detected in some filter cycles of operation. The initial head loss in the filters has increased over the years. This type of head loss is constant during a cycle of operation and increases only slowly with time. It is due to different factors, as precipitation of ferric oxide hydroxide in the nozzle slots and on the grains in the filter bed, and accumulation of filter bed grains below the filter bottom. Different measures were tested to reduce or eliminate the initial head loss in the filters. Results from frequency diagrams showed that changing nozzles and removing of filter bed material from below the filter bottom were the most favourable actions. Backwashing more frequently and with more sequences also reduced the initial head loss.

Key words: dynamic clogging, filtration, head loss, initial clogging, sand filter, wastewater

HIGHLIGHTS

- Initial head loss from inorganic clogging developed by filtration of wastewater.
- Measures taken decreased the initial head loss by 0.10–0.31 mH_2O.
- Sand filter nozzles were changed every 12th year in average.
- Dynamic head loss developed from organic clogging during each filtration cycle.
- Initial head losses were zero–0.67 mH_2O before undertaken measures.

GRAPHICAL ABSTRACT



INTRODUCTION

Sand filters were constructed at the Henriksdal wastewater treatment plant (WWTP) in Stockholm when new effluent standards for the concentrations of nitrogen, phosphorus, and BOD_7 in the effluent of the plant were expected. Furthermore, the concentration of mixed liquor suspended solids (MLSS) in the aeration tanks was increased and three additional aeration tanks were built to increase the volume of the activated sludge step. These measures increased the nitrification and denitrification capacity of the plant, but also amplified the risk of sludge to escape from the secondary sedimentation tanks, including three new-built sedimentation tanks. The Henriksdal WWTP, with 870,700 persons connected and an average hydraulic load of 273,000 m^3/d, is the largest underground WWTP in Europe excavated into rock. The effluent standards for the mixed effluent from the two central WWTPs in Stockholm (Henriksdal and Bromma) are $\leq$10 mg total N/L as a yearly average value, and $\leq$0.3 mg total P/L and $\leq$8 mg BOD_7/L as quarterly average values.

Deep-bed two-media down-flow sand filters were built as a final particle separation step in the plant. Applications of sand filters create different operation problems connected to head loss. Following five years of operation, the head loss in the filters started to increase. After regular backwashing, there was still an extra initial head loss in the filters, which indicated that the head loss consisted of an initial part and a dynamic part. After eight years of operation, a study of the full-scale sand filters was started to find different procedures to prevent initial clogging and scaling from occurring in the filters. Several possible preventive measures were investigated, some of these during many years. The dynamic part of the head loss was also studied, and it was shown to consist of two parts; firstly, of separated and thereby accumulated suspended solids originating from the secondary sedimentation tanks transported via the influent to the filter and, secondly, from suspended solids originating from primary settled wastewater bypassing the biological step at high hydraulic loads. It is essential for an efficient functionality of the filters that a filter cycle between backwashings lasts for as long as possible, as the filter otherwise is too often taken out of operation for backwashing.

Various studies have investigated head loss in sand filters. For example, Lee *et al.* (2007) studied an up-flow fibre filter at rates of 20–80 m/h and found that the initial dynamic head loss was roughly proportional to the filtration rate. The increase of head loss during filtration was strongly dependent upon the filtration rate and the retention efficiency. This paper describes the initial and dynamic head loss at different filter bed depths and after different operational times between backwashings of the filters in the Henriksdal WWTP based on data from eight years of continuous operation.

METHODS

Description of the sand filter treatment step

The Henriksdal WWTP has a conventional activated sludge (CAS) step as a biological treatment step, although configured as a pre-denitrification biological nitrogen removal (BNR) step. The last separation step in the plant constitutes of deep-bed, two-media, down-flow sand filters with a total surface area of 3,600 m^2 divided into 60 filters, each with a length of 10 m and a width of 6 m, corresponding to a horizontal surface area of 60 m^2 per sand filter, Figure 1. The 60 sand filters are divided into four operational groups with 15 filters in each group. The upper layer in the filters consists of 1.0 metre of crushed ceramic grains with the size Ø 2.5–3.5 mm, d_{10}–d_{90}, and the lower layer consists of 0.5 metres of sand with the grain size Ø 1.2–1.8 mm, d_{10}–d_{90}, and the particle density ρ=2,650 kg/m^3. The particle density of the wet ceramic grains is around 1,013–1,200 kg/m^3, while the dry ceramic grains have a particle density close to the density of water. The porosity of the sand bed and the ceramic bed is 0.40 and 0.45, respectively. The nozzles in the filter bottom have slots of 1.0 mm and there are 2,880 nozzles in each filter.

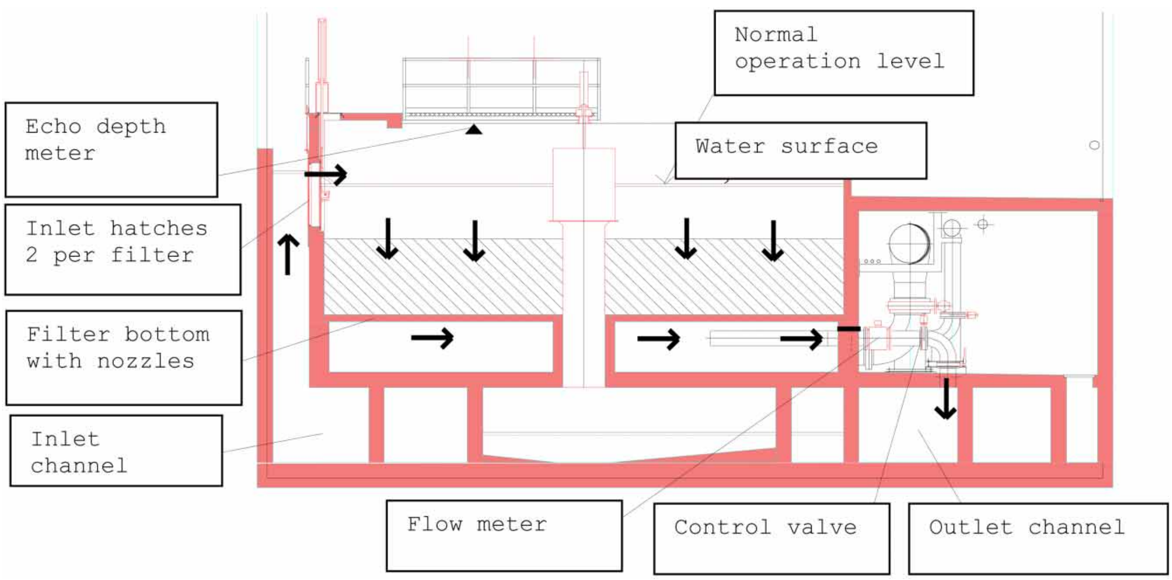


Figure 1 | One of the 60 full-scale sand filters at the Henriksdal WWTP chosen as a study object.

The cleaning of the filters occurs through up-flow backwashing with 20 m/h sand filter filtrate and 30 m/h air in two cycles, i.e. sequences, after each other. The used backwashing water is drained from the surface of the filter through a funnel in the middle of the filter after each of the two backwashing cycles. This is followed by a sorting of the grains of the filter bed material after grain size and density during fluidization, i.e. expansion of the filter bed, with 90 m/h sand filter filtrate. This water is drained through the filter and out through the nozzles in the filter bottom before a new operation cycle is started again. The inlet flow to the filters was in average 3.2 m^3/s, i.e. 3.2 m/h during daytime and dry weather. The maximum hydraulic design flow to the filter step is 10 m^3/s, i.e. 10 m/h. To remove phosphate from the wastewater, a dosage of ferrous sulphate of approximately 2 g Fe/m^3 is added to the filters in addition to approximately 13 g Fe/m^3 dosed in the pre-precipitation step.

The contribution to the dynamic head loss was studied via the pressure meters in filter No. 60, which was fed with a constant hydraulic flow of 200 m^3/h corresponding to a filtration rate of 3.3 m/h to the 60-m^2 filter. The pressure meters were first mounted at 0.20 m, 0.40 m, 0.60 m, 0.80 m, and 1.50 m, but the pressure meters at 0.60 m and 0.80 m were later moved to 0.80 m and 1.20 m, respectively. Soon after that, the pressure meter at 1.20 m was moved to 1.40 m to find the depth in the filter bed where the most dominating clogging contributing to an increased dynamic head loss occurred. In the study, the depth in the filter bed is set to zero metres at the surface of the filter bed, which is at the top of the ceramic layer. Negative values represent points in the wastewater above the filter bed and positive values are points situated down in the filter bed. The time before clogging was determined to be the time from the start of each filter cycle to the time where the head loss in the filter bed had increased enough so that the filter starts to bypass parts of the influent.

The head loss in the filters

After five years of operation, the filters began to show an excessively high head loss especially during the fluidization for material sorting of the filter bed after backwashing. At that time, the filters were fairly clean and the dynamic part of the head loss, due to clogging of the filters during an operation cycle, had its lowest value. The initial part of the head loss, however, had been increasing over the years since the filters were taken into operation. This head loss was constant during a cycle of filter operation and increased only slowly with time. It was due to different factors, e.g. precipitation of ferric oxide hydroxide in the slots of the filter nozzles and accumulation of grains leaking into the channel below the filter bottom. Head is the height of water measured in mH_2O and head loss is the pressure drop in the filter in mH_2O. Pressure, P, is the density of water times the gravity acceleration times the head. According to Figure 2, the head loss was measured as the difference of the head in the channel under the filter bottom, P_B, and the level of the water surface over the filter bed, P_A, measured with an ultrasonic level meter. The head loss in pressure units, ΔP, was calculated as

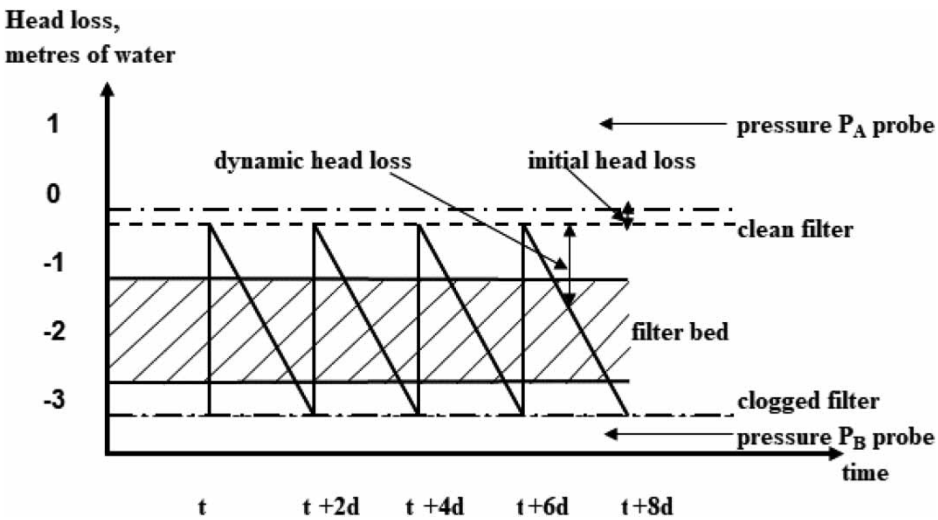


Figure 2 | Initial and dynamic head loss in a sand filter during four filter cycles.

$$\Delta P = P_B - P_A \quad (1)$$

The total head loss had its lowest value when the filters were newly built and when a filter has just been taken into operation after a backwashing. The difference value between the initial value of the head at time t0 and the value at a specific time t1, still measured directly after a backwashing, is defined as the initial head loss in the filter, $P_{initial}$, and will only be noticeable after a relative long time of operation, Equation (2).

$$P_{initial} = \Delta P_{t0} - \Delta P_{t1} \tag{2}$$

The head loss that increases during the time of operation of one filter cycle is the dynamic head loss. When that head loss is equal to the head that existed at the beginning of the filter cycle, at the Henriksdal WWTP around 3.3 mH_2O, part of the wastewater can no longer pass through the filter. The flow then starts to decrease while part of the flow bypasses the filter until the flow reaches zero and the filter is completely clogged. The head in the filter is then zero, and the filter must be backwashed. In reality, the filter is backwashed before it starts to bypass parts of the flow, due to settings in the control system allowing somewhere between 60 and 80% filter valve opening before backwashing.

The development of head loss during filter operation

During operation of a sand filter, the head loss varies. $\Delta P = P_B - P_A$ (Equation (1)). $\Delta P < 0$ when $P_B < P_A$ during normal operation. $\Delta P \geq 0$ when $P_B \geq P_A$ at backwashing and subsequent fluidization of the filter bed. $\Delta P \approx 0$ at the start of a new filter cycle, if the initial head loss is zero or minus some mm or cm corresponding to the initial head loss. P_A is more or less constant while the head loss is not included in the value. P_B is decreasing during a filter cycle, when the head loss increases, and ΔP is thereby decreasing and the value becomes more and more negative. It measures the pressure over the probes including both the level of water and the head loss in the filter bed above the probe. P_B increases during a backwashing at which ΔP increases and the value becomes less negative. Backwashing decreases the dynamic head loss towards zero. P_B is increasing at changes in the filter, for example when the nozzles are cleaned, and ΔP is increasing and becomes less negative, i.e. the initial head loss becomes lower. The head loss is presented in Figure 2.

Two different types of head losses

A small initial head loss gives a possibility to handle a higher dynamic head loss and thereby prolong the time of filter operation before backwashing. A smaller initial head loss is thus essential for the operation of the filters. This is represented in Figure 2 by the upper dash-dotted line. A filter with an initial head loss at the beginning of a cycle is represented in Figure 2 by the dashed line. At the beginning of a new filter cycle, the head has its highest value, i.e. the zero water level minus the accumulated initial head loss. When the filter is close to clogging, the head loss is reaching −3.0 mH_2O. The curve in the figure represents four filter cycles with its smallest head loss after a backwashing when the dynamic clogging of the filter with the accumulated suspended solids has just been removed and the lowest value, around −3 mH_2O, represents a filter clogged with suspended solids. A decrease in initial head loss corresponds to an increase from the dashed line to the dash-dotted line and a higher head at the beginning of a filter cycle, Figure 2.

The results from the experiments are calculated from frequency diagrams with the frequency at the y-axis and the head loss in mH_2O at the x-axis. + before the value refers to decreased initial head loss and – refers to increased initial head loss. As an example, the head loss in the filter before any measures were done is shown in the frequency diagram as the value from zero to the top of the reference peak, in Figure 3(a) approximately 0.2 mH_2O. The reference curve and the experiment curve coincide, which shows that the experiment did not gave any change in head. A gain in the head from a measure taken is shown in Figure 3(b) as 0.2–0.05=+0.15 mH_2O. In Figure 3(c), the measure taken gave instead a deterioration with a head loss of 0.2–0.3=−0.1 mH_2O. In this study, diagrams showed values for the initial head loss before any measures were done between zero and −0.67 mH_2O, where minus in −0.67 shows that it is a loss of the head. Most of the values point to initial head losses of 0.1–0.2 mH_2O. In a pilot filter, Al-Jadhai (2003) found initial head losses of 0.035, 0.10, and 0.30 mH_2O at the beginning of three different experiments. In a down-flow one-media filter with a bed height of 2.0 m presented by Boller *et al.* (1997), the initial head loss was approximately 0.02–0.07 mH_2O. The head loss in an empty down-flow filter tank was calculated and compared to the head loss in a tank filled with sand (Mesquita *et al.* 2012). In our study, it will correspond mainly to the possibility to calculate the head loss in the nozzles and filter bottom.

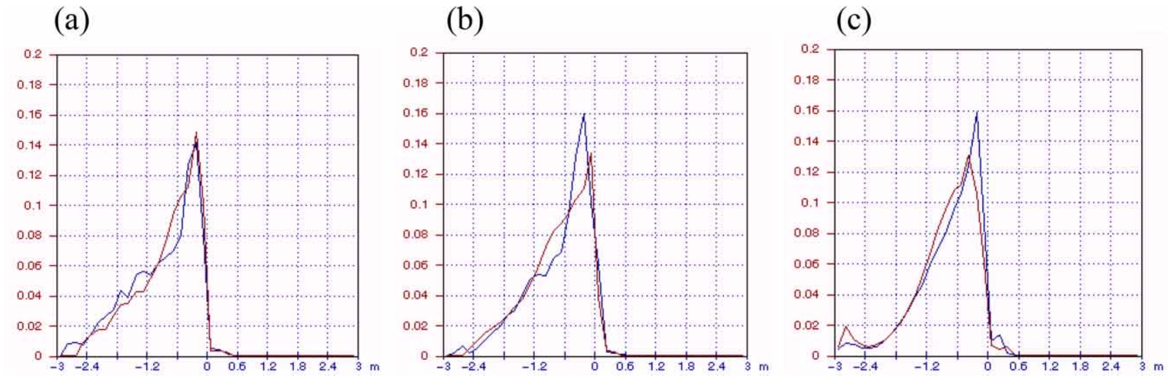


Figure 3 | Frequency curves for the initial head loss in mH_2O. (a): Filter No. 16. No change in initial head loss. (b): Filter No. 17. Decreased initial head loss after removing of filter bed material. Reference curve peaks at 0.16. (c): Filter No. 13. Increased initial head loss with a lower ferrous sulphate dosage controlled from the effluent phosphate phosphorus meter. Reference curve peaks at 0.16.

RESULTS AND DISCUSSION

In the full-scale filters of Henriksdal WWTP, simultaneous separation of suspended solids, denitrification, and phosphorus precipitation occur. In this study, an evaluation of head loss measurements was done from periods without denitrification to identify the initial and the dynamic part to the total head loss. Different measures to decrease and counteract the initial head loss were investigated.

Cleaning of the material in the filters with chemicals

Laboratory tests with cleaning of the grains in the filter bed were done with different types of acids and cleaning agents. Precipitates on the grains were expected to be dissolved with the chosen chemicals. The precipitates were found to be 70% inorganic and 30% organic. The inorganic part consisted of different ferric oxide hydroxides. Different concentrations of nitric acid, citric acid, lactic acid, oxalic acid, soft soap, Neodisher (a cleaning agent), and Decon 90 (a cleaning agent) were tested as solvents. Second-best result was achieved with treatment in oxalic acid. The precipitation was removed by 25 and 19%, respectively, by the leaching in nitric or oxalic acid. The time of leaching affected the cleaning to a low extent. When increasing the cleaning time from 0.5 to 24 hours, the removal of precipitate increased from 9.5 to 11.6%. Treating the grains with acids at a higher concentration increased the result of the cleaning, for oxalic acid linearly, e.g. 2 and 8% solution of oxalic acid removed 1.9 and 17.9%, respectively, of the precipitates on the grains. The 10% solution of oxalic acid gave the best cleaning result of grains. In the selection of cleaning method for the sand filter material, it is a risk that oxalic acid and citric acid inhibits the nitrification in the biological stage at the plant if no countermeasures are taken. The inhibition can be as high as 40–74% (Stockholm Water Co. 2003a). In one sand filter (No. 52) in Henriksdal WWTP, a full-scale study was performed with soaking the grains in 10% citric acid for 33 days. The initial head loss after the backwashing, calculated from the frequency curves, was not lower after the leaching in the citric acid compared to before the leaching. Although the initial head loss becomes slightly lower 22 months later, it becomes higher after 15, 29 and 42 months. After 8 months, the initial head loss was $+0.03\ mH_2O$ lower than before the citric acid leaching, i.e. a small not statistically significant improvement. The conclusion from the full-scale study is that the citric acid leaching will not give any long-lasting effect on the initial head loss in the sand filter.

Cleaning of the nozzles in the filters with chemicals

An investigation showed that the 2,880 nozzles in one sand filter (No. 52) were clogged to an extent of around 50%. Therefore, a laboratory study with cleaning the nozzles by leaching in different acids and cleaning agents for 16 hours was performed. The precipitate in the slots of the nozzles was expected to be dissolved or at least be more vulnerable to mechanical sharing forces to be removed. Oxide remover, general-purpose cleaner, industrial-strength cleaner, formic acid, oxalic acid, and ammonium oxalate were tested (Stockholm Water Co. 2003b). The best result, with the cleanest nozzles and with the most easily removable precipitate that was still attached on the surface of the nozzles, was obtained by the oxalic acid followed by the ammonium oxalate. After the leaching with 5% solution of oxalic acid and 5% solution of ammonium oxalate, 7.4 and 2.8%, respectively, of the precipitate in the nozzle slots were removed. If this were going to be performed continuously in the full-scale filters, the oxalic acid would be chosen as a cleaning agent, which also cleaned the grains of the filter bed effectively.

Exchange of the nozzles

The nozzles in filters were exchanged or treated with cleaning agents and brushed to remove precipitates during nearly seven years. The nozzle slots were clogged and this inorganic clogging or scaling generated a high head loss in the filter that caused the pump motor protective circuit breaker to release during fluidization, which resulted in poorer sorting of the grains after backwashing. The cost for cleaning the nozzles was approximately the same as buying new nozzles. Therefore, only new nozzles were installed in the filters after some years. The effect of cleaning or exchange of the nozzles was evaluated by comparing the initial head loss before and after cleaning. Nearly half of the filters, 20 of 41 filters, did not show any difference in initial head loss after the nozzles had been exchanged. A positive effect with an average decreased initial head loss of +0.26 mH_2O (min +0.13, max +0.45) was noticed in 17 of 41 filters, while 4 of 41 filters showed a negative result with an increase in the initial head loss to an average value of −0.12 mH_2O (min −0.02, max −0.16). Overall, the 41 filters showed a decreased initial head loss of +0.10 mH_2O.

In one filter (No. 1), an increased initial head loss was measured 32 month after the nozzle exchange. The initial head loss can then possibly has first decreased but later, when 32 month have passed, the filter clogged again and passed below the reference curve, showing an increased initial head loss. In the cases where no evident change in initial head loss was detected, it was nevertheless observed that the head loss during the fluidization of the filter bed had decreased from 7 to 5.5 mH_2O. The filters in the other WWTP in Stockholm were earlier operated with 0.8 mm nozzle slots, but the head loss became too high and at exchange of nozzles new with 1.0 mm slots were chosen. Both plants are now operated with 1.0 mm nozzle slots. The nozzles have been exchanged approximately every 12th year. The conclusion is that exchanging nozzles or cleaning them thoroughly has a positive effect by decreasing the initial head loss. Consequently, the present study resulted in an exchange of nozzles in 39 filters and cleaning of nozzles in 21 filters in the Henriksdal WWTP.

Hindrance of filter bed fluidization – accumulated sand below the filter bottom

The fluidization of the filter bed for sorting the grains was observed to be physically prevented after several years of operation of the sand filters, when the pump motor protective circuit breaker released at a high head loss. This was found to be an effect of accumulated filter bed grains in the channel below the filter bottom. The problem was either that the grains completely filled the distribution zone below the filter bottom with limited space for the fluidization water, or that the grains was transported by the fluidization water into the nozzles from below and clogged them. After this discovery, the filters were taken out of operation and thereafter the grains were removed manually. After the removal of accumulated sand, the pumps did not release at fluidization of the filter bed. All filters were subsequently investigated by use of a camera probe. It was estimated that accumulation of more than 0.1 m^3 of grains under a filter bottom demanded removal so as not to stop the fluidization of the filter bed.

Removing filter bed material from the sand filters

The filter bed volume of sand and ceramic grains has increased with 0.03–0.04 metres per year during six years, which has increased the initial head loss in the filters. A precipitation of ferric oxide hydroxide on the surface of the grains has been observed. The precipitate forms a stiff shell around the grains. In all filters, in total 0.10–0.15 metres of the filter material have been removed from the surface of the filter bed during three years. This measure decreased the problem with difficulties to close the two inlet hatches in each filter, as the level of grains then was kept beneath the level of the hatches. The volume of the filter bed was continuously increasing, however, as the grains of the filter bed were still increasing in size from further chemical precipitation on the surface of the grains. Samples taken from three filters showed no shell on the surface of the sand grains thus the precipitation has only occurred on the ceramic grains. In 22 of 40 filters, no obvious change in the initial head loss was observed. In 7 of 40 filters, a positive tendency could be seen, i.e. a lower initial head loss with an average value of +0.16 mH_2O (min +0.13, max +0.29). In 11 of 40 filters, a negative tendency was detected, i.e. a higher initial head loss with an average value of −0.23 mH_2O (min −0.02, max −0.61). Overall, the studied 40 filters showed an increase in the initial head loss with an average of −0.04 mH_2O, which indicated little or no change in the initial head loss after the removal of surplus filter bed material. Even though the grains increase in size, the pores between the grains are also increasing in size giving the same value of porosity, and the water could easily pass through the pores i.e.

an increased grain size do not had to imply an increase in the initial head loss in the filter bed. The conclusion is that removing filter bed material has little or no effect on the initial head loss in the filters. Instead, the great benefit is that the inlet hatches can be easily closed.

Enhanced backwashing with air

A lower initial head loss in the filter might be performed by an improved backwashing, which gives a cleaner filter bed and possibly less precipitation in the slots of the nozzles. The filters were normally backwashed with 20 m/h water (filtrate) and 30 m/h air in two subsequent sequences. In backwashing with filtrate solely, the captured suspended solids were not transported from the filter bed. Backwashing with a mix of filtrate and air was essential to clean the filter from accumulated particles. The introduced air fluidized and thereby shook the filter bed introducing shearing forces, and the suspended solids were released and washed away to a much higher extent than without air, which resulted in a higher head at the start of each operational filter cycle. The airflow at backwashing was increased in filter group 4 from 30 m/h to 50 m/h air through the filter. The effect on the initial head loss in the sand filters of the increased airflow was studied during three years. The values varied between individual filters. In 10 of the studied 14 filters, there were no difference in initial head loss after the increased airflow at the backwashing had been introduced. In 4 filters of 14, a decrease of the initial head loss was seen with a higher airflow during backwashing, average value +0.15 mH_2O (min +0.13, max +0.21). The total average value of the 14 filters was +0.04 mH_2O, which is a small improvement, resulting in a lower initial head loss. However, it might be too small to be statistically significant.

Prolonged backwashing time

Cleaner filters with less inorganic precipitates in the nozzle slots and thus a lower initial head loss may also be achieved by backwashing the filters during a longer time with water. A backwashing continues until the level of water, registered by an on-line level meter, has reached a pre-set level just below the upper edge of the pipe shaped draining funnel for used backwashing water. It was not possible to prolong the standard time in the control system for backwashing of the filters. In this study, performed for 1.5 years, the outlet signal to the backwashing pump was decreased by 10%, which corresponded to a decrease of the backwashing velocity from 20 m/h to 15 m/h through a filter. With a backwashing velocity of 15 m/h, it took longer time to backwashing a filter, since the pump is controlled by the water level in the sand filter. In 8 of 13 filters, no change in the initial head loss in the filter could be detected after the prolongation of backwashing time with water. In 3 of 13 filters, an improvement was seen, i.e. a decrease in the initial head loss with an average of +0.22 mH_2O (min +0.13, max +0.28). In 2 of 13 filters, a deterioration with an increase in the initial head loss was recorded, average value −0.14 mH_2O (min −0.12, max −0.16). The total average value for the 13 filters was +0.03 mH_2O. The conclusion is that no statistically significant change in the initial head loss with prolonged time of backwashing was achieved with decreased backwashing flow rate.

Backwashing more frequently

Cleaner filters with less inorganic precipitates in the slots of the nozzles and thus a lower initial head loss might also be achieved if the filters were backwashed more frequently. Generally, the initial head loss only decreases if more frequently backwashing results in less precipitation in the slots of the nozzles. The filters were normally backwashed after 48 hours of operation if critical dynamic clogging has not occurred earlier. In filter No. 23 and filter No. 25, the frequency of backwashing was changed from 48 hours to 12 hours. Generally, the filters turned out to be cleaner, which decreased the dynamic head loss, but this does not imply that the initial head loss developed from clogging the slots of the nozzles with inorganic precipitates was decreased. The study was performed for three years. The meter in filter No. 23 did not show correct values. A visible decrease in the initial head loss with +0.13 mH_2O could be detected in filter No. 25 during the periods when the filter was backwashed after 12 hours. Unfortunately, only one filter could be interpreted. The initial head loss increased when the filter was backwashed after 48 hours again. A cautious conclusion is that backwashing more often might decrease the initial head loss. The conclusion is far from statistically significant since only one filter could be interpreted.

Number of backwashing sequences during backwashing

Cleaner filters with less inorganic precipitates in the nozzle slots may also be possible to obtain if the number of backwashing sequences during a backwashing cycle was increased. The precipitates would hopefully be eroded from the nozzles by the repeated backwashing leaving the slots free from inorganic precipitates and thus decreasing the initial head loss. Normally, two backwashings after each other are performed followed by the fluidization for the separation and sorting of the grains in the filter bed. In filter No. 12 and filter No. 14, a study with three backwashings after each other was done for in total 20 months. The study showed light yellow backwash water after three sequences and fairly clear backwash water after four sequences. After two sequences, the concentration of suspended solids was still considered too high in the backwashing water.

At heavily dynamic clogging, when larger amounts of suspended solids are present in the secondary sedimentated water, even more backwashing sequences were needed, up to five subsequent backwashings to remove most of the biological sludge from the filters. In filter No. 11 and filter No. 14, a study with five subsequent sequences every second Monday was performed during 7.5 months. In filter No. 14, this was combined with three subsequent sequences at every backwashing during the time of the study, i.e. the investigation in filter No. 14 was a combination of the investigations in filter No. 11 and filter No. 12. The initial head loss in filter No. 12 was somewhat lower during, as well as after, the period with three backwashing sequences with an improvement of $+0.29$ mH_2O.

The curves after two and six months of operation with five extra sequences in filter No. 11 corresponded to lower initial head loss than the reference periods, i.e. an improvement. However, the value after four months of operation equalled the value during the reference period. As an average, this gave an improvement of $+0.31$ mH_2O. Finally, the measurements from filter No. 14 showed a value from the experiment with three backwashing sequences and five extra backwashings that coincided nearly completely with the value corresponding to two sequences, i.e. no change. The results from filter No. 11 and filter No. 12 but not from filter No. 14 might indicate that an extended number of backwashings either through the automatic control with five sequences every second week or through the operation with three sequences at every backwashing could result in a decrease in the initial head loss from clogging in the filters. The conclusion, however, is not statistically significant as only three filters were investigated.

Decreased dosage of ferrous sulphate to the sand filters

A water solution of ferrous sulphate is added to the filters to remove phosphate from the wastewater. The dosage of the ferrous sulphate solution to the filters was previously controlled from the inlet flow meter. It was changed to be controlled from the effluent phosphate phosphorus on-line meter instead to, presumably with a lower dosage of ferrous sulphate, decrease the amount of unprecipitated iron in the filters and thus decrease the precipitation risk of iron oxide hydroxides in the nozzle slots and on the grains in the filters. The time of operation might be prolonged, in this case from twelve to fifteen years or more, before an exchange or cleaning of the nozzles would be necessary. In this study, seven periods with different ferrous sulphate doses were investigated and corresponding water samples were analysed, Table 1.

Table 1 | Dosage of ferrous sulphate to the filters at Henriksdal WWTP, the corresponding average set point value, and the concentrations of total phosphorus and phosphate phosphorus in the filtrate

Period	Dosage, g Fe/m^3	Set point, g Fe/m^3	Set point, mg PO_4-P/L	Control meter	Total P, mg P/L	PO_4-P, mg P/L
1	2.1	2.5		flow	0.13	0.06
2	1.4	1.5		flow	0.12	0.07
3	1.7		0.05	P meter	0.13	0.08
4	1.3	1.5		flow	0.14	0.08
5	0.6		0.11	P meter	0.12	0.07
6	0.7		0.13	P meter	0.18	0.10
7	2.0		0.075	P meter	0.17	0.06

With a decreased ferrous sulphate dosage to the filters, the concentration of phosphorus had to be thoroughly supervised to discover and prevent increasing phosphate concentration in the sand filter filtrate. Fortunately, the average concentration of phosphate phosphorus did not show any increased values during the time of phosphate phosphorus meter (P meter)-controlled dosage of ferrous sulphate compared to reference periods near in time with flow-steered dosage. This was also valid for the average concentration of total phosphorus. The average concentrations in the effluent were 0.14 mg total P/L and 0.07 mg PO_4-P/L for the seven periods.

The initial head loss in the filters during period 4, when the dosage of 1.3 g Fe/m^3 was controlled from the flow with a set point of 1.5 g Fe/m^3, was compared to period 5, when the dosage of 0.6 g Fe/m^3 was controlled from the phosphate phosphorus meter in the outlet, set point around 0.11 mg PO_4-P/L. Only 0.6 g Fe/m^3 was interpreted as no overdosage. Comparing periods 4 and 5, showed that in 44 of 54 filters, no change in the initial head loss occurred. In 1 of 54 filters, an improvement with a lower initial head loss was seen for period 5, +0.16 mH_2O. In 9 of 54 filters, a deterioration was found, i.e. a higher initial head loss was detected for period 5, average value −0.19 mH_2O (min −0.12, max −0.30). The total average value for the 54 filters was −0.03 mH_2O, i.e. almost no change in the initial head loss during compared to before the period with phosphate phosphorus meter-controlled ferrous sulphate dosage. The conclusion is that lower iron dosages do not decrease the initial head loss in the filters.

Summary of measures to counteract initial head loss

The measures to maintain or improve the capacity of the sand filters in Henriksdal WWTP by decreasing the initial head loss showed different results (Table 2). The study showed that an increase in the initial head loss in the filter could be suppressed by some measures while other measures had little or no influence on the initial head loss.

Table 2 | Results from the study at different measures taken to decrease the initial head loss in the filters

Measure taken	Change of initial head loss, mH_2O
Citric acid leaching of the filter bed	+0.03
Exchange of nozzles	+0.10
Removing of bed material from the bed surface	−0.04
Increased airflow at backwashing	+0.04
Prolonged time for backwashing of water	+0.03
Backwashing after 12 hours of operation i.e. more frequently	+0.13
Three (3) backwashing sequences instead of two (2)	+0.29
Five (5) backwashing sequences every second Monday	+0.31
Three (3) backwashing sequences, and five (5) every second Monday	±0.00
Phosphate phosphorus meter-controlled $FeSO_4$ dosage	−0.03

Values in the interval from −0.04 to +0.04 mH_2O are considered not to be statistically significant.+corresponds to improvement and – to deterioration.

- Exchange of the nozzles or thorough cleaning and brushing the nozzles decreased the initial head loss by 0.10 mH_2O. In addition, the head loss during fluidization of the filter bed decreased from 7 to 5.5 mH_2O.
- Backwashing more frequently e.g. every 12 hours instead of every 48 hours gave a decrease in the initial head loss of 0.13 mH_2O.
- Increasing the number of sequences during a backwashing gave a decrease in the initial head loss of zero to 0.31 mH_2O.
- Increasing the airflow during backwashing decreased the initial head loss by 0.04 mH_2O.
- Removing of leaked filter bed material from the distribution channel below the filter bottom decreased the head loss during fluidization of the filter bed considerably, which solved the problem with the water pump that released during sorting, but it did not change the initial head loss in the filter bed during operation of the filter.
- Leaching of the filter bed grains and nozzles with citric acid decreased the initial head loss by 0.03 mH_2O.
- Prolonged time of backwashing gave a decrease of 0.03 mH_2O in the initial head loss.
- Decreased dosage of ferrous sulphate to the filters controlled by the effluent phosphate phosphorus meter instead of controlled by the flow to the plant increased the initial head loss by 0.03 mH_2O.
- Removing of 0.10–0.15 m of filter bed material from the surface of the filter bed increased the initial head loss with 0.04 mH_2O. The great advantage was instead that it was possible to shut the inlet hatches to the filters. A continuous removing of filter bed material, however, is not a permanent solution to the problem.

If a measure gave a change in initial head loss from −0.04 to +0.04 mH_2O, the influence was probably not statistically significant, although increased airflow during backwashing might give a small decrease in initial head loss. The initial head loss in the filters before any measures were done varied between zero and −0.67 mH_2O but mostly between −0.1 and −0.2 mH_2O.

Dynamic head loss

The dynamic component of the total head loss in the sand filters was studied during different periods. The concentration of PO_4-P in the outlet from the secondary sedimentation tanks at Henriksdal WWTP is occasionally high. Ferrous sulphate is thus dosed to the filters. Previous investigations showed that the time of operation between backwashings increased if ferrous sulphate dosage to the filters was terminated. Then the dynamic head loss increased slower (Jonsson 1997). Consequently, one strategy was suggested to stop the iron dosage, when the filters were most sensitive to increased dynamic head loss and accordingly too short operation times between backwashings.

The grains from a filter were sifted and it was discovered that a significant part of the ceramic grains had received grain sizes far below the declared diameters in virgin filter material. This implies that the influent water with the highest concentration of suspended solids meets the small ceramic grains and thus gives the filter greater risk of clogging, i.e. the dynamic head loss increases rapidly during operation of the filter. Small grains probably derive from eroded larger grains or, less probable, grains that have been crushed and divided into two parts or more. As a consequence, the Henriksdal WWTP bought new filter bed material and changed it in all filters.

Sludge storage capacity in the filter bed and influence of bypassed primary wastewater

A sand filter bed is designed to accumulate a significant amount of particles in the cavities or pores in the bed material without clogging the filter completely. This deep filtration capacity is important, since it implies that the sand filters do not have to be backwashed so frequently. The influent wastewater to the filter step is normally mechanically, chemically, and biologically cleaned. At a high influent flow to the plant, often during heavy rain or snow melting, part of the primary settled wastewater (PW) bypasses the biological step. The maximum flow that enters the biological step is cogitated and set manually in the control system of the Henriksdal WWTP. It is usually set to 4, 4.5, 5 or 5.5 m^3/s. The remaining flow is bypassed directly from the primary sedimentation step to the filters. PW contain high concentrations of suspended solids, which further increase the clogging with increased dynamic head loss and, consequently, decreased time of operation. PW also consists of a greasy organic liquid-like wastewater fraction that passes the filter, since filters cannot remove liquids. The organic liquid in PW might contain high concentrations of organic phosphorus and nitrogen compounds.

At high flows, the level of biological sludge might reach the water surface and effluent weirs of the secondary sedimentation tanks. Already settled sludge might also leave the sludge layer at the bottom of the tanks by erosion, move upward and leave the tanks with the effluent. Biological sludge might also not have the retention time needed to settle and leaves with the effluent of the secondary sedimentation tanks. These three scenarios all lead to sludge escape. The biological sludge clogs the filters more rapidly than the greasy sludge in the PW. The particle phase of PW was only partly separated by the filters in contrast to suspended solids from the biological step, which was separated to a high degree by the filters. During a period of six months, when large amounts of floating sludge from the surface of the secondary sedimentation tanks were flushed to the filters, the filters clogged rapidly with solid fat, and the influent flow to the biological step was limited to 3 or 3.5 m^3/s. In April, hydraulic flows exceeding 2.7 m^3/s were bypassed the biological treatment.

The average concentration of suspended solids in the influent to the filters has increased from around 13 mg suspended solids (SS)/L in 1997 to around 51 mg SS/L in 2020. The concentration of suspended solids in the filtrate has increased during the same period from around 1.5 mg SS/L to 3.5 mg SS/L. The separated amount of SS has thereby increased from around 2.5 tonnes SS/day to 14 tonnes SS/day during the same period. This means that the sludge storage capacity corresponds to 2,500 kg SS per day/3,600 m^2 surface area or 0.69 kg SS/(m^2·d) and 14,000 kg SS per day/3,600 m^2 or 3.9 kg SS/(m^2·d), respectively. The filters in Henriksdal were designed with a calculated sludge storage capacity of 5 kg SS/m^2 that conform with internationally reported filter sludge storage capacities of 4–6 kg SS/m^2. Boller *et al.* (1997) accumulated 4.65 kg SS/m^2 in.their study, and with SS left from the former filter cycle, 8.25 kg SS/m^2 were kept in the filter. During 1997, the filters would have had the possibility to operate 5.8–8.6 days during one filter cycle (e.g. 4 kg SS/m^2/0.69 kg SS/(m^2·d) equals 5.8 days), and during 2020 for 1.0–1.5 days.

In filter No. 60 in the Henriksdal WWTP, the dynamic head loss in the filter bed during a cycle of operation was evaluated, Figure 4(a) and 4(b). The curve at 1.5 m down in the filter bed corresponds to the total filter bed. The dynamic head loss corresponds in the figures to the decrease from around 2.5 mH_2O at the start of the filter cycle to approximately 0.1 mH_2O at the end of the operation cycle. At that time, the filter was put by the SCADA system into the queue for backwashing of filters. In this full-scale study, the hydraulic load was kept at 3.3 m/h.

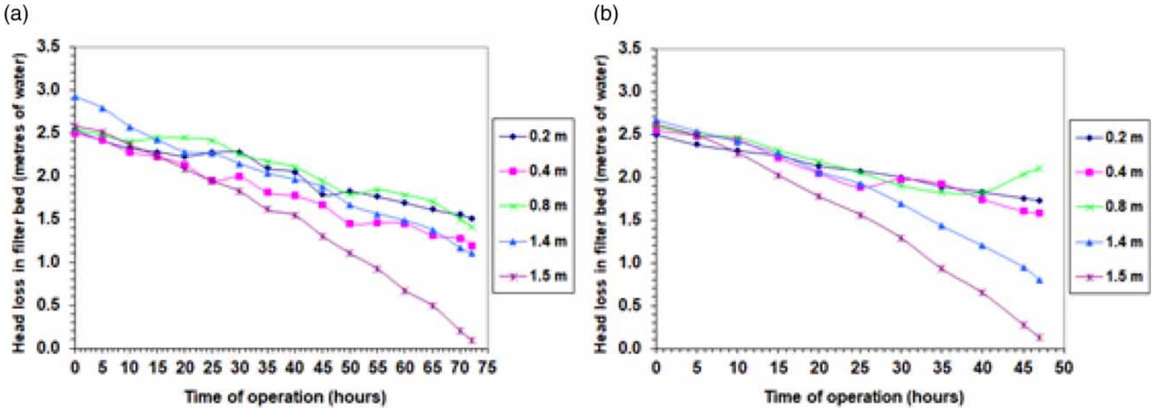


Figure 4 | The total head in the filter bed during two different filter cycles (a) and (b), respectively. Time of filter cycle operation from start to the clogging in filter No. 60 at 3.3 m/h.

Operation times of 72 hours or longer were detected, depending on the suspended solids concentration in the influent to the filters. The surface of the sand layer is situated at 1.0 m down in the filter bed. Most of the suspended solids were found on the surface of the ceramic layer. The point of having a two media filter is to catch the smallest suspended solids flocs that is not caught by the ceramic layer. In Figure 4, the surface of the sand layer should show a dynamic head loss between the meters at 0.8 m and 1.4 m if there actually are any suspended solids caught by the sand layer. In Figure 4(b) and in some other experiments, a dynamic head loss could be seen between 0.8 m and 1.4 m, but in Figure 4(a) and in some other experiments, a larger dynamic head loss on the sand layer surface could not be detected. Other experiments showed a small dynamic head loss between 0.8 m and 1.4 m, but it was smaller than e.g. between 1.4 m and 1.5 m. When suspended solids are caught by the sand layer, the flocs will be smaller than other suspended solids flocs and might not cause any pronounced larger dynamic head loss. The suspended solids concentration in the filtrate will, however, decrease.

A comparison with studies of one, two and three media filters at other sites showed that the parameters in our study (average values between brackets) were contained in the previously reported broad range of process conditions. In the comparison, the hydraulic load varied between 3.3 and 24.4 m/h (3.33 m/h), the concentration of suspended solids in filter feed varied between 2.0 and 63 mg/L (15–20 mg SS_{in}/L), and the time of operation varied between 7 and 219 h (25–72 h). Table 3 and Figure 5 present values from our study and from Boller (1984), Al-Jadhai (2003), Angermüller *et al.* (1998), Brenner *et al.* (1994), Altmann *et al.* (2016), Williams *et al.* (2007), Tchobanoglous (1970), Zenz *et al.* (1973), Oliva (1973), and Jonsson (1997).

The time of operation for one filter cycle decreased with an increase of hydraulic load. The tendency was that the time operation decreased logarithmically with an increased hydraulic load. One reason that contributed to the tendency was the amount of suspended solids in the feed to the filter, which most probably increased with a higher hydraulic load.

The length of a filter cycle decreased logarithmically with an increase of suspended solids in the feed to the filter. The sludge accumulation capacity is reached faster with a higher concentration in the feed. The tendency is that the time of operation dropped significantly in the range zero to 20 mg SS/L. The main reason assumed to be that a limit for the sludge accumulation was reached. For 20 hours of operation, Figure 5, SS_{in} was 20 mg/L, Figure 5(b), and the hydraulic load was 15 m/h, Figure 5(a). The sludge accumulation was 6 kg SS/m^2, which is the maximum value in the expected interval of 4–6 kg SS/m^2. Figure 5(b) even suggest SS_{in} to be 25 or 30 mg/L, which would result in an accumulation of 7.5 or 9 kg SS/m^2.

Table 3 | Evaluation of filter capacity between backwashings

Study	Filter type	Upper layer grain size [mm]	Lower layer grain size [mm]	Hydraulic load [m/h]	Time of operation before backwash [h]	Head loss at initiation of backwash [mH_2O]	Suspended solids in filter feed [mg/L]	Bed height [m]	Reference
Present study	Downstream, dual media	2–3.5	1.2–1.8	3.33	72	2.5	15	1.5	Present study
		2–3.5	1.2–1.8	3.33	25	2.4	20		
Chemical Optimization of Tertiary Contact Filters	Downstream, dual media	n.d.	n.d.	10	30	6	12	1.85	Boller (1984)
		n.d.	n.d.	7.4	20	6	12		
Pilot-plant study of the tertiary filtration of wastewater using local sand	Downstream, one media	2.0–3.36	–	8	100	2.25	14	0.9	Al-Jadhai (2003)
				18	53	2.25	9		
Auswirkung von konstanten Filter-geschwindigkeiten auf die simultane Denitrifikation im Sandfilter	Downstream, dual media	1.4–2.5	0.7–1.2	6	13.5	1.52	21	1.7	Angermüller *et al.* (1998)
				9	9	1.50	20		
				12	8.5	1.36	24		
				15	9.5	1.18	18		
Deep-bed filtration of SBR effluent for agriculture reuse: Pilot plant screening of advanced secondary and tertiary treatment for domestic wastewater	Downstream, one media	1.41–2.00	–	20.3	7	1.18	39	1.15	Brenner *et al.* (1994)
				15	12	0.90	30		
				15	10	0.80	44		
				15	7.5	0.91	56		
Combination of granular activated carbon adsorption and deep-bed filtration as a single advanced wastewater treatment step for organic micropollutant and phosphorus removal.	Downstream, dual media	0.6–2.4	0.7–1.1	6	22	1.7	2.6	2	Altmann *et al.* (2016)
The impact of increased loading rate on granular media, rapid depth filtration of wastewater.	Downstream, dual media	1.22–2.05	0.62–1.14	12.2	22	3.4	12	1.5	Williams *et al.* (2007)
				15.3	17	3.4	12		
				18.3	14	3.4	12		
				21.4	11	3.4	12		
				24.4	10.5	3.4	12		
Filtration techniques in tertiary treatment	Downstream, dual media	0.8–2.0	0.5–0.9	12.6	19	n.d.	22	0.61	Tchobanoglous (1970)
		1.08–1.99	0.98	12.6	48	0.13	14	0.51	
Process design manual for suspended solids removal. U.S. EPA.	Downstream, dual media	n.d.	n.d.	5	90	n.d.	16	0.9	Zenz *et al.* (1973)
		n.d.	n.d.	10	15	n.d.	15		
		n.d.	n.d.	6.2	48	n.d.	2	1.2	Oliva (1973)
		n.d.	n.d.	8.7	16	n.d.	10		
	Downstream, three media	n.d.	n.d.	5	106	n.d.	14	1.2	Zenz *et al.* (1973)
		n.d.	n.d.	10	27	n.d.	16		
Experiences of nitrogen and phosphorus removal in deep-bed filters at Henriksdal sewage works in Stockholm	Downstream, dual media	2.5–4.0	0.8–1.2	3.3	219	3	4	1.5	Jonsson (1997)
				5	175	3	8		
				5	17	3	60		
				10	100	3	4		
				10	80	3	5		
				10	14	3	28		
				10	7.3	3	63		

Literature and our data.
n.d.=no data.

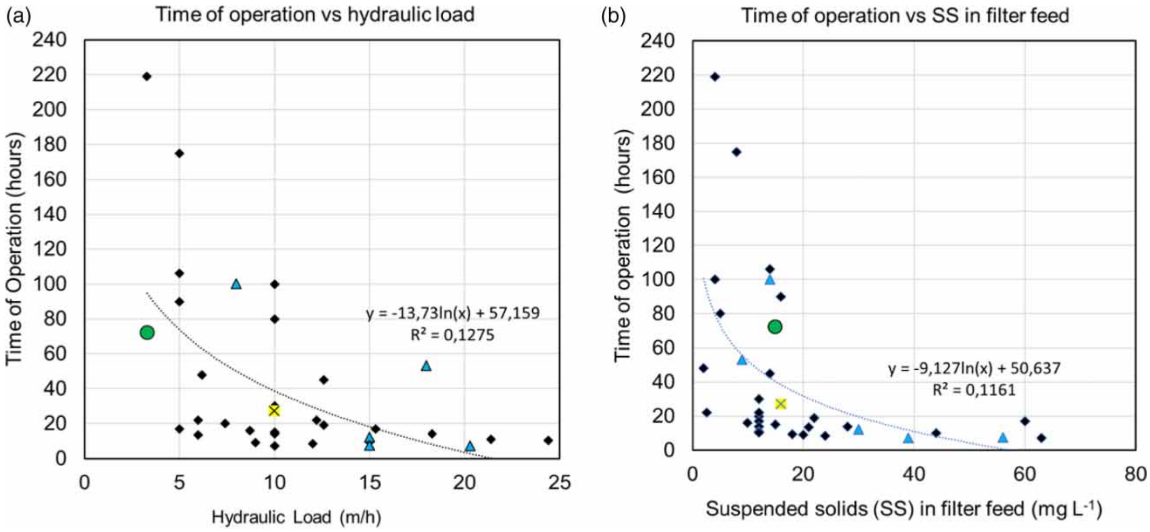


Figure 5 | (a): Time of operation in hours vs hydraulic load in m/h. (b): Time of operation in hours vs suspended solids in filter influent in mg SS/L. Literature and present study data (large round dot). Data from literature for one media filters are marked as triangles, dual media filters marked as diamonds, and ternary media filter as square with an X.

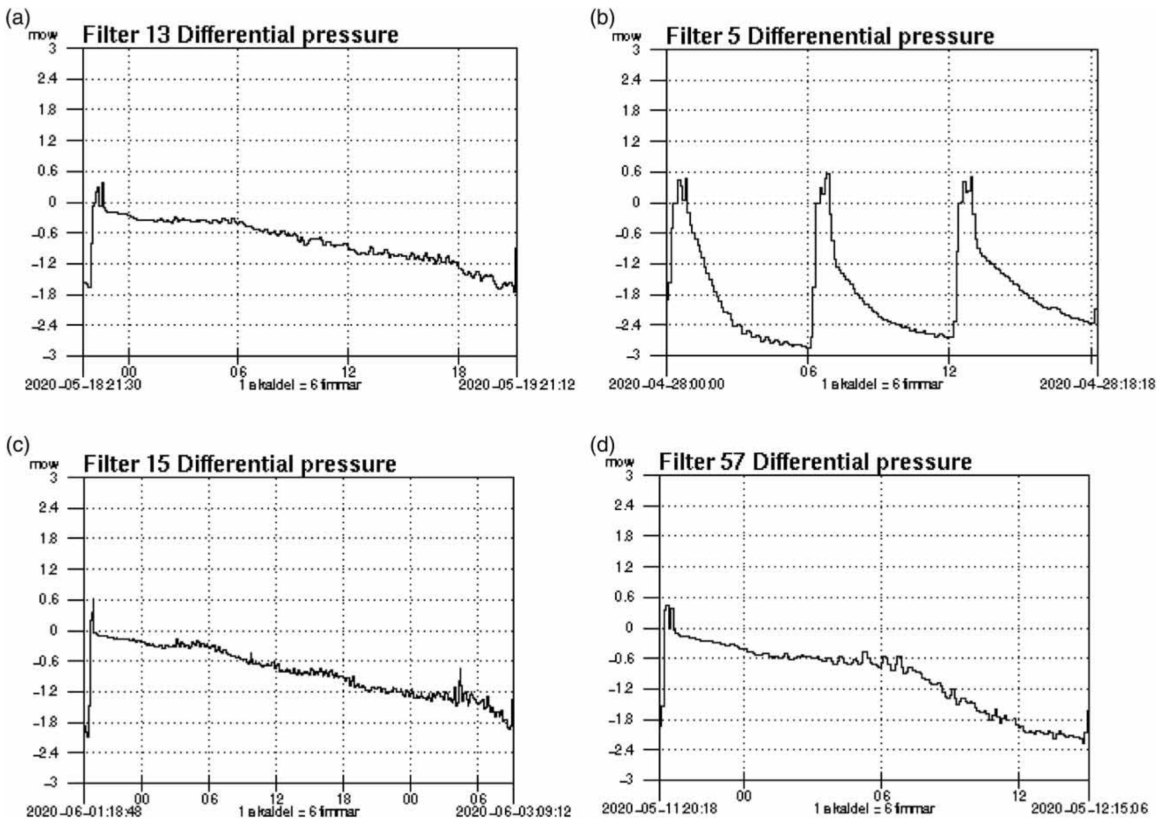


Figure 6 | The total head loss in mH_2O. (a): In filter No. 13 at 3.1 m/h during one cycle of operation of 22.5 h. 32 mg SS_{in}/L, 1.8 mg SS_{out}/L. (b): In filter No. 5 at 8.1 m/h during the second cycle of operation. Time 5.1 h, 5.3 h, and 5.2 h. 160 mg SS_{in}/L, 11 mg SS_{out}/L. (c): In filter No. 15 at 2.8 m/h during one cycle of operation of 37.4 h. 17 mg SS_{in}/L, 1.0 mg SS_{out}/L. (d): In filter No. 57 at 3.1 m/h during one cycle of operation of 18.1 h. 31 mg SS_{in}/L, 2.3 mg SS_{out}/L. (mow=metres of water). +0.6 mH_2O is recorded as small peaks corresponding to a higher water level during backwashing before each filter cycle.

The dynamic head loss, from little less than zero mH_2O (initial head loss) to approximately −2 mH_2O (−1.8/−2.4), in the filter bed for four filters in full-scale operation, versus hydraulic loads (time and flows) in the Henriksdal WWTP is presented in Figure 6. Ferrous sulphate was dosed to the filters as a precipitation agent. The suspended solids load to one of four studied filters was little less than four times higher than to the other filters but the time of operation was four to five times shorter, which implied that the time of operation was approximately inversely proportional to the suspended solids load but only under otherwise similar conditions and in the span investigated. The time of operation differed depending upon the load on the filter and varied in the examples between 5.3 h and 37.4 h, Figure 6. All four filters in Figure 6 had a reduction of SS of 93–94%, although the concentration in the filter influent varied between 17 and 160 mg SS/L. When comparing filter 15, Figure 6(c), with filter 57, Figure 6(d), it was shown that filter 15 reduced in total 101 kg suspended solids while filter 57 reduced 97 kg suspended solids during one cycle. This was close to the same value despite that filter 15 separated 16 mg SS/L during 37.4 h at 2.8 m/h but filter 57 separated 28.7 mg SS/L during 18.1 h at 3.1 m/h, which suggests that the capacity for these two filters was rather equal regarding the removal of suspended solids. Figure 6(b) corresponds to a day with rain.

Summary of dynamic clogging

Dynamic head loss was shown to be caused by suspended solids from the biological step and primary settled wastewater.

- The tendency was that the time of operation decreased logarithmically with an increased hydraulic load. One reason that contributed to the tendency was the amount of suspended solids in the feed to the filter, which most probably increased with a higher hydraulic load.
- With Fe dosage but without a carbon source, the time of operation for a filter cycle could be 72 hours or longer before clogging with a hydraulic load of 3.3 m/h.
- The time of operation was approximately inversely proportional to the suspended solids load but only under otherwise similar conditions and in the span investigated. Else, the relation was logarithmic.
- A part of the ceramic grains was discovered to have eroded and fine grains with sizes far below the declared diameters in virgin filter material were found in the filter bed. This implies that the influent water with the highest concentration of suspended solids meets the small ceramic grains and thus gives the filter greater risk of dynamic clogging.

CONCLUSIONS

The general conclusion from this study is that head loss in a sand filter bed consists of an initial component and a dynamic component. Studies performed at Henriksdal WWTP show that initial head loss has its origin in inorganic clogging, which can be reduced by different measures.

The different measures taken to recover filtration capacity by decreasing the initial head loss in the filters had variable results. The effective measures for decreasing the initial head loss were in declining order: increased number of subsequent backwashings, shorter interval between backwashings, exchange of nozzles that may have partly clogged slots, increased airflow during backwashings, prolonged time of backwashing with water, and cleaning the filter bed with citric acid leaching. The initial head loss increased slightly when bed material was removed from the surface of the filter bed but also unexpected when the dosing of ferrous sulphate was controlled from a phosphate meter instead of from the hydraulic flow meter.

Dynamic head loss is caused by clogging by suspended solids from the biological treatment and from bypassed pre-settled wastewater. The measures taken to decrease the dynamic head loss involved stopping the dose of ferrous sulphate on the filters during bypassing of high flows of pre-settled wastewater to the sand filter to prolong the time of filter operation. Another measure was to exchange the filter bed material when the ceramic grains became too small.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICTS OF INTEREST STATEMENT

The authors declare there is no conflict.

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