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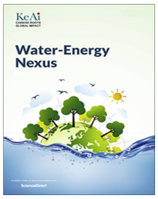

Optimization of water use in a rapid filtration system: A case study

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ABSTRACT

The objective of this research was to reduce water use during the operation of anthracite-sand filters used for treating drinking water. The variables that affect the saturation of the filter bed were evaluated, using procedures proposed by the Pan American Center for Sanitary Engineering and Environmental Sciences (CEPIS). The following were evaluated: filtration velocity, initial filtration quality, filtration runs duration, filter bed expansion, duration of the washing process, washing velocity, granulometry, and mud balls. The results obtained were compared with the design parameters recommended by CEPIS. Maximum turbidity of 0.5 NTU was obtained. Filtration runs were in the lower limit of the range indicated by CEPIS. The filter medium expansion in five of the eight filters was lower than recommended by CEPIS. The optimal washing time was 18 min. The washing velocity was low producing little filter bed expansion. The granulometric result indicated that the effective size and the anthracite uniformity coefficient were different between filters. The results also presented significant improvements in the filtration process and the amount of water saved once the filter washing process was optimized. The results also demonstrated that measuring filters performance could improve the filtration system efficiency and ensure the drinking water quality.

1. Introduction

Filtration is the removal of suspended and colloidal particles present in an aqueous suspension that drains through a porous medium (Kim and Lawler, 2011). It is the final operation of the clarification process that is carried out in a drinking water treatment plant (Brandt et al., 2017). It constitutes one of the last barriers in the safe water production for human consumption allowing water to obtain the least turbidity possible for subsequent efficient disinfection (Yi et al., 2019). Currently, water forecasting is used as a tool that allows adequate management and planning for efficient use of the water resource (Ali, 2018).

During the filtration process, the filter medium retains the particles until they obstruct the flow passage, so the filters need to be washed periodically (Mitrouli et al., 2009). The filtered water turbidity should not be greater than 1 NTU, preferably less than 0.5 NTU (WHO, 2003). Upton et al. (2017) recommend a value of 0.1 NTU. While EPA (1995) recommends a value of 0.5 NTU. North American legislation, on the other hand, recommends a value of less than 0.3 NTU in 95% of the time and never exceeding 1 NTU for systems that use rapid filtration (Kim, 2015).

The main factors that influence the filtration process are suspension characteristics (type, size, density, hardness or suspended particles resistance; water temperature, and suspended particles concentration); filter medium characteristics (type, granulometry, filter material-specific weight and filter layer thickness); hydraulic characteristics (filtration rate, available hydraulic load and effluent quality) (Brandt et al., 2017; Mahanna et al., 2015; CEPIS, 2005). During a rapid filtration process, water can pass through the filter bed at velocities between 6 and 20 $m^3/h.m^2$ (Brandt et al., 2017; Logsdon et al., 2002). At these velocities, the biological processes will be insignificant (CEPIS, 2005).

Once the solids are retained in the filter bed, the filter ends up clogging (Semsayun et al., 2015). The filter is washed, when the

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clogging reaches a maximum value (maximum load loss), or when the quality of the filtrate has deteriorated (Logsdon et al., 2002). The filtration run is the operating time of a filter between two consecutive washes (Ncube et al., 2016).

The original filter conditions are restored by backwashing, otherwise, the filter bed would deteriorate, being necessary to replace it at some point (Logsdon et al., 2002). For a better filtration process and to extend the useful life of the filters, it is necessary to keep the characteristics of the filter medium in optimal conditions (Mahanna et al., 2018). An ideal filter medium is that of a grain size and grains of a specific weight, which requires a minimum amount of water to be washed and is capable of removing as much suspended particles as possible, and producing a good quality effluent (Kim and Lawler, 2011; Bilardi et al., 2013).

Common types of media used in granular bed filters are silica sand, anthracite carbon and garnet or ilmenite (Gholikandi et al., 2012). In declining-rate rapid filtration, the water flow is distributed continuously or variably. The water entering the filters is located below the minimum level of operation, it is conducted through a common channel or tube, operating as communicating vessels so that each filter operates at a variable rate related to the filter dirt level (Di Bernardo and Sabogal-Paz, 2009; Dabrowski, 2011). In declining rate and mutual washing filtration systems, there is a minimum number of filtration units. The number is determined by the need that the wash flow required by a filter must be supplied by the other filters in the system (CEPIS, 2005).

These filters are always washed in strict consecutive order. The last one to be washed is the one that is taking the highest flow and has the highest velocity. In the previous washes, both the flow rate and the velocity decrease and the one with the longest operating time. The dirtiest is the one with the minimum flow and velocity conditions (CEPIS, 2005; Mohammed and Shakir, 2012; Segismundo et al., 2017).

Water treatment plants generally consume a lot of energy (Tatinclaux et al., 2018). Filters are the most complex units of a water treatment plant. They require energy for backwashing when not designed to use gravitational potential energy. The evaluations carried out in these units throughout Latin America indicate that there are notable deficiencies in their conception (CEPIS, 2005).

Due to previously mentioned, this study aimed to evaluate the operating efficiency of the rapid gravity filters of the "Mahuarcay" water treatment plant. This plant supplies water to more than 60% of the population of the Azogues city, Ecuador. Tests were run to determine operating conditions and filtration performance under real operating conditions in eight filters. The results provided information on the useful life of the filters and the turbidity removal efficiency. This allowed for improving the understanding of the factors that influenced the filter operation and identified opportunities for improvement.

2. Materials and methods

2.1. Description of the study area

The rapid filters used for this study were implemented in the Treatment Plant of the Azogues city, Bayas parish, in the southern part of the Republic of Ecuador. The average altitude of the city is 2518 m above sea level. The city has a population of 70,064 habitants. This plant is of conventional type with gravity operation, composed of coagulation, flocculation, sedimentation, rapid filtration and disinfection (García-Avila et al., 2018). The plant has two filter systems (batteries), each battery has 4 filters, in total 8 filters (Fig. 1).

2.2. Operation of declining-rate rapid filters and mutual washing

The two rapid filters batteries of four units each, work with gravity, are an anthracite-sand dual bed, declining-rate, and mutual washing.

2.2.1. Declining rate filtration

The available hydraulic load was fully applied from the beginning to the end of the filtration run, which entailed, over time, a gradual decrease in the filtered flow. In the Declining-Rate filters, the bed got dirty as time goes by and therefore less water passes through it. Consequently, the filtration velocity becomes less as time goes by CEPIS (2005). Rapid filters were removed for washing according to the number of hours in the filtration operation. It is important to note that as the filter media becomes clogged (saturated) with the sediment, the passage of water through the filter medium becomes slower and more difficult. Therefore, the height of water above the bed gradually rises from the minimum level (when the filter is clean) to this maximum level.

The amount of water that the filter can receive depends on the degree of dirt in each filter. This means that the filter that is cleanest in the battery is the one that will filter the most water and the dirtiest one is the one that will filter the least water. These filters at the outlet communicate through the water distribution channel.

2.2.2. Backwashing

Filter backwashing is the operation whereby water is injected through the bottom of the filter with adequate pressure, with the purpose that the filter bed expands, and retained material can be detached during the filtering operation.

Water for washing a filter is produced in the same hydraulic filtration system, constituting what is known as mutual washing or also known as self-cleaning filters. Their main advantage lies in not requiring systems of storage, pumping or other accessories and instruments dependent on external sources of energy.

The filters were washed when: (1) there was a head pressure loss; (2) the turbidity of filtered water was greater than 1 NTU, except for those special situations in which the turbidity of the filtered water was not a product of the filter but of problems in the previous stages of the process, such as when cutting the sulfate dosage; (3) there is a scheduled execution, according to a duration established by the previously washed filter (Smith et al., 2018).

In the plant under study, the filters were washed according to the first condition, when the level of sedimented water has reached 30 cm below the weir of the common channel for collecting sedimented water.

2.3. Filters performance evaluation

The tests were carried out for three months. During this time between six and seven filters were washed daily.

2.3.1. Characteristics of the filtration process

2.3.1.1. Filtration velocity and flow rate. The filtration flow rate, as well as the filtration velocity of each filter, was different in each filtration battery. To determine the filtration flow rate, the filter inlet valve was closed, and a graduated ruler was placed inside the filter. The time needed in seconds (t_f) was measured with a stopwatch, as the water level dropped from one mark, initially defined rule, to a different one. For this study, a reference distance (H) of 0.3 m was taken. The measurement was performed three times. Each time the eight filters were washed, and the values were averaged. The filtration rate was calculated, with Eq. (1) (CEPIS, 2005).

$$Q_F = \frac{86400\forall_f}{A_f t_f} \tag{1}$$

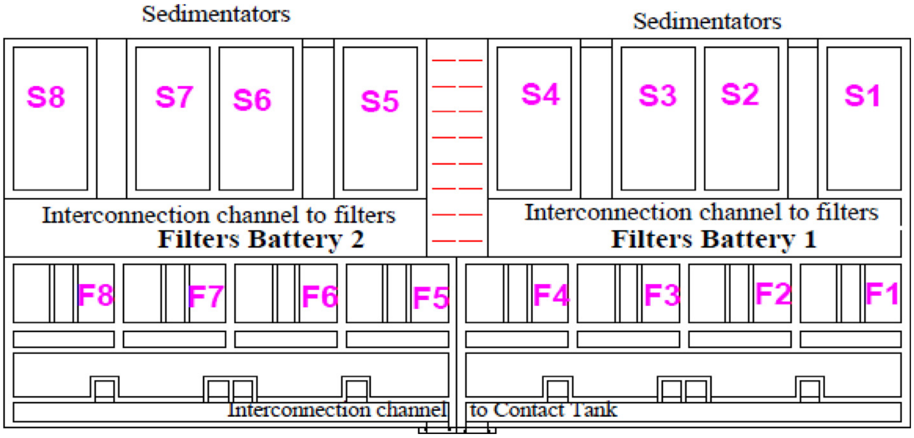

Fig. 1. Schematic diagram of rapid filters. The effluent from the four sedimentation tanks (S1–S4) is collected in an interconnection channel, in turn, this channel feeds water to four filters (F1–F4, Filter Battery 1). The effluent from the four sedimentation tanks (S5–S8) is collected in a second interconnection channel, in turn, this channel feeds water to four filters (F5–F8, Filter Battery 2).

where Q_F is the filtration rate (m^3/m^2 d), A_f is the area of the filter bed (m^2), t_f is the filtration time (s), $\forall_f$ is filtered volume (m^3), calculated as$\forall_f = A_f H$.

From the data of height (H) and time (t_f) of the previous test, the filtration velocity could be determined by Eq. (2) (CEPIS, 2005).

$$V_F = \frac{H}{t_f} \tag{2}$$

where V_F is the filtration velocity (m^3/d).

2.3.1.2. Initial filtering quality. The first washing effluent that produced turbidity greater than that of the rest of the filtration run, because a part of the particles that detached during the wash remained in the filter. The, however, leave when the filter comes back into service after backwashing. The more careless the filter operation is, the more turbid is the first effluent produced by the filter. To estimate the water quality at the start of the filtration run and determine the time in reaching normal turbidity, the turbidity was measured every minute for 30 min once the filter went into operation. Turbidity versus time was plotted semi-logarithmic paper (CEPIS, 2005).

2.3.1.3. Duration of filter runs. The duration of the filtration run (FR) generally ranges from approximately 24 to 60 h. Long times, help save on backwashing water but encourage the growth of bacteria in the filter bed. Therefore, it was desirable to restrict maximum operating lengths to 48 h in warm water temperatures and 60 h in cold water temperatures (Brandt et al., 2017). To estimate the FR, the operation records of the filters of the last two years available in the treatment plant were analyzed. In the end, an average FR was obtained for each of the filters.

2.3.2. Backwash system characteristics

2.3.2.1. Filter bed expansion. The filter bed expansion depends on the washing flow and the weight of the sand and anthracite grains. The latter varies according to the granular material diameter (Brandt et al., 2017). To determine the percentage increase in the filter bed thickness (sand + anthracite) during the washing operation, a metal rod was used that had 100 ml cuvettes welded at a distance of 5 centimeters between the edges of each cuvette. At the end of the rod, a metal plate was placed to prevent it from entering the surface of the filter material (CEPIS, 2005). Before the start of the wash, the rod was placed inside the filter, placing the lower end of the rod on top of the filter bed. Washing was performed normally. After 3 min, the rod was gently removed, verifying how many cuvettes were filled with the filtering material and the distance (Δh) between the highest bucket containing material and the lower end of the rod was measured. The height of the filter bed (h) was determined. To determine the filter bed expansion percentage (E), the Eq. (3) was used (CEPIS, 2005; Anderson and Chescattie 2003).

$$E = \frac{\Delta h}{h} * 100 \tag{3}$$

where h is the height of the filter bed. This measurement was made at several points of the filter bed to determine if the expansion is uniform throughout the filter area. Especially in points opposite to the outlet of the wash water and the immediate. When there is a faulty distribution of the wash water, these are the points where there was greater or less expansion (Anderson and Chescattie, 2003).

2.3.2.2. Duration of the backwashing process. During the filter washing, the turbidity of the washing water increases rapidly during the first 2–3 min and can reach values close to or greater than 1000 NTU (CEPIS, 2005; Mahanna et al., 2018). Then, as the filter bed is cleaned, the turbidity decreases. By analyzing the NTU vs. time curve, the most convenient backwashing time can be determined (Dabrowski, 2011). Backwashing time also varies with raw water quality. In the rainy season, when the turbidity is high, the washing time required is usually longer than in the clear water season.

Once the filter wash was started, a sample was collected every minute and the turbidity of the samples was measured. Subsequently, turbidity versus time was plotted on logarithmic-arithmetic paper. On the curve, the lower inflection point was identified where it tends to be asymptotic to the horizontal axis. The optimal washing time corresponded to the coincidence with the inflection point. From this moment on, nothing was gained by prolonging the process. It was desirable that at this point, the water had a turbidity of no more than 5 UNT (CEPIS, 2005).

2.3.2.3. Filter wash velocity. The flow rate and washing velocity with which the filters were operating was determined. A graduated ruler was attached to one of the filter walls. The water inlet valve to the filter was then closed until the water level dropped to the minimum level in the filter. Then, the wash water inlet valve was opened. The time (t_w) it took to raise a certain height of water in the filter box (H_w) was measured. The velocity washing (V_w) and the washing flow rate (Q_w) were determined with the Eqs. (4) and (5) (CEPIS, 2005):

$$V_w = \frac{H_w}{t_w} \tag{4}$$

$$Q_w = \frac{A_f H_w}{t_w} \tag{5}$$

2.3.3. Filter medium characteristics

The filter medium was the most important part of the filter, as it constituted the filter itself, and the characteristics that influence the filter efficiency were the size and grains shape, filter medium porosity and its height.

2.3.3.1. Filter media granulometry. Once the filter was washed, a representative sample of the entire depth of the filter bed was obtained. It was allowed to dry and the sample of filter material was weighed. To determine the granulometry of the filter medium, a set of Tyler series meshes was used. The whole was agitated manually until the grains passed through as many meshes as their sizes allowed (Logsdon et al., 2002). They were plotted on a logarithmic probability paper. Placing the percentages in cumulative weight on the axis of the ordinates (logarithmic scale) and the grains size in millimeters on the axis of the abscissa (probability scale) (CEPIS, 2005).

2.3.3.2. Mud balls. When poor washing of the filter (lack of expansion) occurs or there is an inadequate frequency of backwashing, sludge accumulates inside the filter bed. This degree of deterioration of the filter bed was visualized through the presence of mud balls. After washing the filter and draining the water up to 20 cm below the level of the surface of the filter bed, the volume of the mud ball was determined: (1) four samples of material were extracted from each filter, approximately 25 kg, (2) The samples were spread on a table leaving them to dry, (3) the dried filter medium was passed through a sieve with an opening size of 6 mm, (4) the mud balls were retained in the sieve, (5) the mud balls were placed in a test tube, in which a certain volume of water had been placed (Haarhoff and Van Staden, 2013). The mud balls volume was equivalent to the increase in volume contained in the test tube. The result was expressed as a percentage to the sample volume (Eq. (6)) (CEPIS, 2005).

$$\text{Mudballs} = \frac{\text{Volume increase}}{\text{Sample volume}}\ 100 \tag{6}$$

3. Results and discussion

The results determined that the factors that had the greatest influence on the filter's performance were: the duration of the washing process, filter medium expansion and washing velocity since most filters failed to comply with the provisions of CEPIS (2005). The performance of the filters was better by closing the dump gate corresponding to the output of the interconnection channel every time a filter is washed. So, that the water volume produced by the three remaining filters that do up each of the batteries was temporarily stored to provide a better wash flow to the filter being washed. This creates a better medium expansion and therefore the washing velocity was increased, reducing the washing duration. This was intended that the filtering medium after washing be as clean as possible and thereby lengthen the filtration runs.

After filters washing with this method for one month, the following tests were re-determined: initial filtering quality, filtration runs, optimum washing time, washing velocity and filter medium expansion.

3.1. Filtration velocity and flow rate

The average values of V_F and Q_F of each filter before implementing any improvements are presented in Fig. 2. When adding the flows, a total of 104.72 L/s was obtained, which was very close to the average flow rate that the treatment plant operated, which was 105.83 L/s. In Fig. 2(a), the variation of V_F and Q_F can be observed in the eight filters before implementing the improvement. Meanwhile, in Fig. 2(b), the variation of V_F and Q_F in the eight filters was observed after the improvement.

In Fig. 2(a) only filter 4 had a filtration rate higher than the design value of the plant (250 m^3/m^2 d). While the other filters had filtration rates lower than the design. The lowest average filtration rate was presented in F1 and F5, this is since these filters were the first to be washed in each battery. So, when washing F1 it is known that the remaining filters that make up this battery that (F2, F3, and F4) were also close to washing, so they did not provide a sufficient flow for washing the F1. The same was happening with F5 in the other battery. After making modifications to the operation and maintenance of the filters, in Fig. 2(b) it was demonstrated that the filtration rate could be increased in all filters.

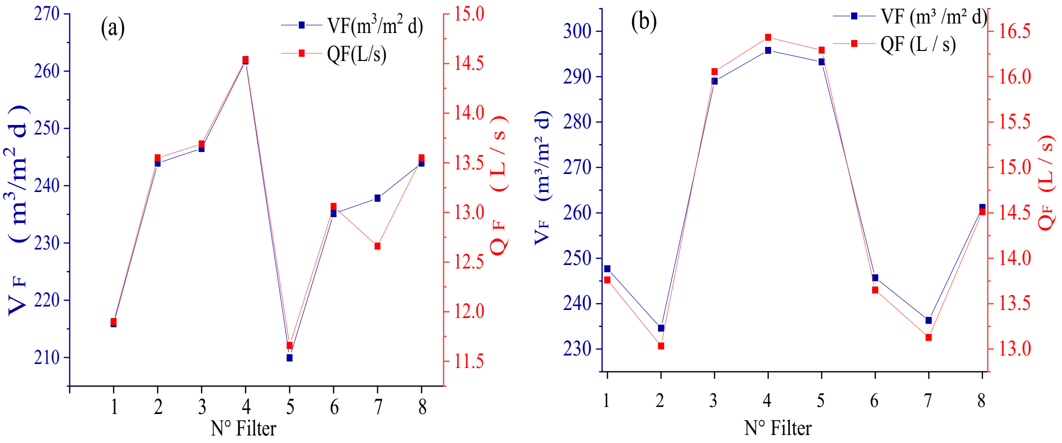

Fig. 2. Filtration rate and flow rate of the eight filters. (a) Filters F1 and F5 had the lowest filtration rate and flow rate, while filter F4 had the highest filtration rate, higher than the design filtration rate (250 m^3/m^2d). (b) Filters F2 and F7 had a filtration rate slightly lower than the design, while the other filters had a filtration rate higher than the design (250 m^3/m^2d).

3.2. Initial filtering quality

In Fig. 3, the turbidity data were determined before implementing the improvements. This turbidity was measured in the filters immediately after they were washed. Average turbidity of 0.4 NTU was obtained, which is well below 1 NTU recommended by CEPIS (2005) and did not exceed the 0.5 NTU determined by (Gholikandi et al., 2012). Therefore, it can be said that the initial filtering quality of the eight filtration units complies with that recommended by (CEPIS, 2005; Gholikandi et al., 2012).

The initial filtering quality improved when implementing the changes in the operation of the filters. Comparing Fig. 3(a), before the improvement, the turbidity at the beginning of the filtering process was between 0.38 and 0.90; while, in Fig. 3(b), after the improvement, the turbidity at the beginning of the filtering process was between 0.35 and 0.58.

3.3. Duration of filtration runs

Before implementing improvements, the operation records of the Potabilization Plant filters were reviewed and the values are shown in Fig. 4(blue bar). Operation these filters were producing filtration runs that varied between 29 and 31.5 h. These filtration runs are within the recommended by CEPIS (2005) (30–50 h) and also are between 24 and 60 h recommended by Brandt et al. (2017). However, the filtration runs are at the limits recommended by the references. It should be noted that the F1 and F5 had the lowest filtration runs, which corroborated the lowest filtration rates obtained.

After implementing the changes in the operation and maintenance of the filters, the results presented in Fig. 4(red bar) were obtained. The filtration run was increasing as the filters were repeatedly backwashed, this was since in each wash more and more accumulated sediment was discarded in the filter medium. It is expected that a certain number of filter washings will be reached so that almost all the sediment has been removed. It is evident that the filtration run of all filters improved.

3.4. Filter bed expansion

This technique was used to predict the expansion of the filter bed, as well as to determine the possible loss of sand and anthracite during backwash. In Fig. 5 (blue red) the results of the measurements made in the eight filters are included. The expansion values obtained in filters F1, F2, F3, F5 and F6 are below the range of between 20 and 30%, which are the design parameters recommended by CEPIS (2005). Logsdon et al. (2002) recommend 20% expansion values, while Brandt et al. (2017) indicate a maximum

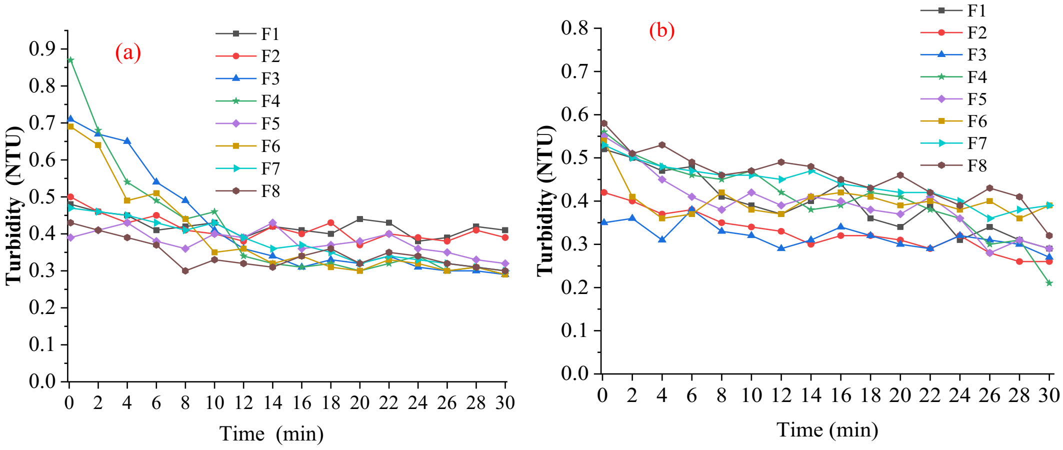

Fig. 3. Initial filter turbidity. (a) Before implementing changes in the operation of the filters. (b) After implementing changes in the operation of the filters. In (a) the average turbidity was 0.40 NTU, in (b) the average turbidity was 0.39 NTU.

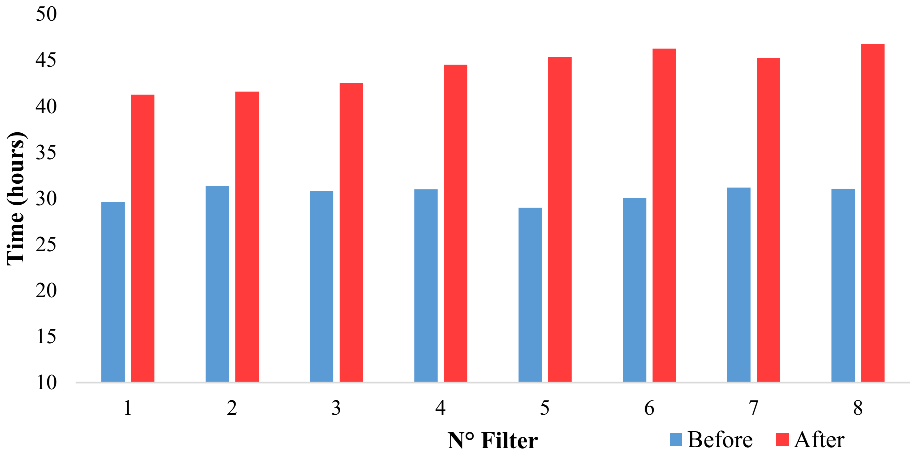

Fig. 4. Filtration runs duration. (Blue bar) Before implementing changes in the operation of the filters. (Red bar) After implementing changes in the operation of the filters, it was possible to show a notable increase in the filtration run in all filters.

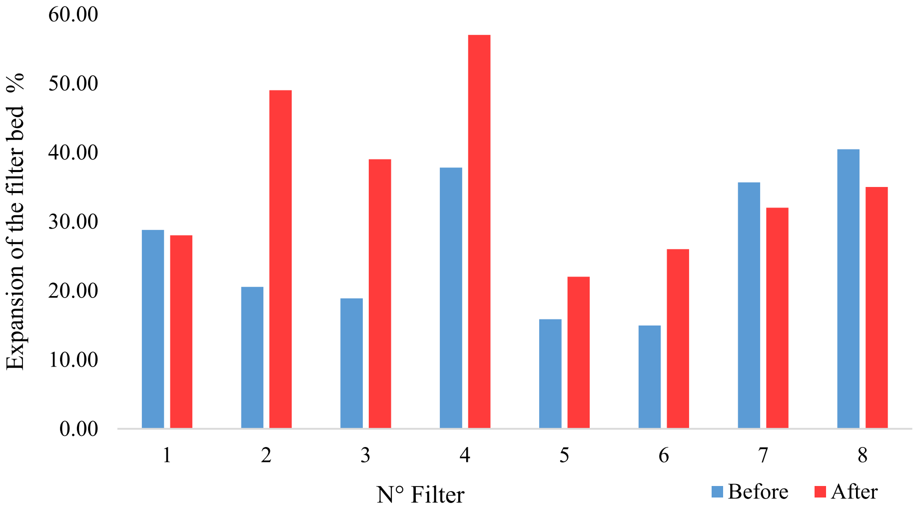

Fig. 5. Filter bed expansion. (Blue bar) Before implementing changes in the operation of the filters. (Red bar) After implementing changes in the operation of the filters. There was a notable increase in the expansion of the filter bed in all filters.

expansion of 30%; therefore filters F4, F7 and F8 comply with the aforementioned.

When the changes in the operation of the filters were implemented, it can be seen that all filters had an expansion equal to or greater than that recommended by CEPIS (2005), including filter F5 that had a low expansion when the washing was done with the normal procedure, increased the value of the expansion notably, reaching the recommended (Fig. 5(red red)). On the other hand, filters F2 and F4 markedly increased the filter bed expansion, so there might have been a leak of filter material. To resolve this issue, the valve that allows the entry of the wash water to these filters was regulated. For efficient filter backwashing, an optimal filter bed expansion must be ensured, which prevents an accumulation of suspended solids in the filter after a period of filter operation (Quaye, 1987; Clements and Haarhoff, 2004).

3.5. Duration of the backwashing process

The turbidity data obtained at the time of backwashing of the eight filters as well as the respective times at which the samples were taken are shown in Fig. 6(a). When the washing of the filters began, the turbidity of the wash water increased rapidly at the beginning, reaching values between 150 and 220 NTU. As the bed was washed, the turbidity decreased to reach values lower than 20 turbidity units. This slowly decreased despite the prolonged washing time. Adequate washing time was between 15 and 18 minutes. From this time forward, a considerable decrease in wash water turbidity was not obtained. Service water would be wasted on longer wash times.

When washing the filters by closing the gate of the interconnection channel, the wash water turbidity was increased during the first minutes, with which more sediment was released. As seen in Fig. 6(b), the turbidity of the washing water in most of them exceeded 450 NTU, and even up to 500 NTU in the first three minutes. After, it went down to values below 10 NTU. Fig. 6 clearly shows how the optimal time for filters F4, F7 and F8 was only 10 min; for filters F2, F3, and F6 it was 12 min and for filters F1 and F5 15 min. Comparing Fig. 6(b) with Fig. 6(a), wash times decreased, this demonstrates that the sediment percentage accumulating in the filter bed was already removed, which was shortening wash time.

3.6. Filter wash velocity

The results of the washing velocity for each of the filtration units are presented in Fig. 7(blue bar). The washing velocity recom-

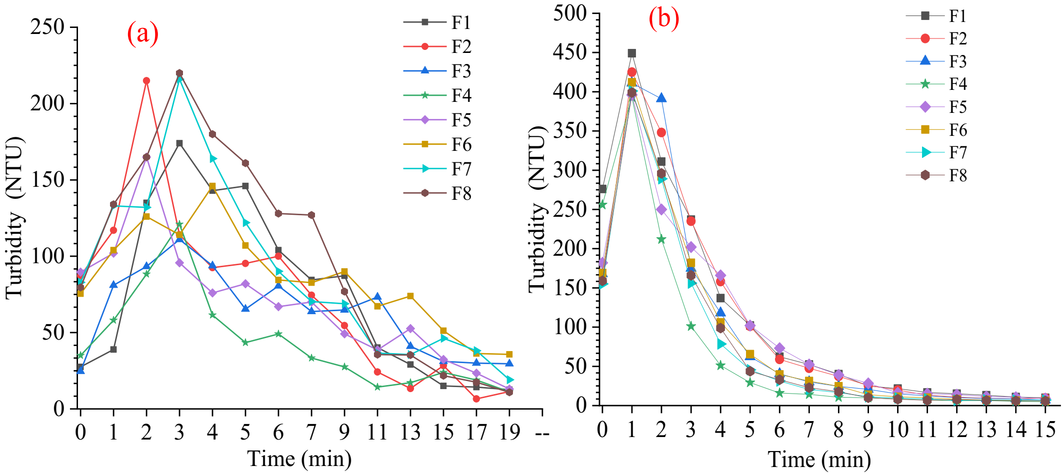

Fig. 6. Filters washing time. (a) Before implementing changes in the operation of the filters. (b) After implementing changes in the operation of the filters the washing time of the filter bed was reduced from 15 to 10 min.

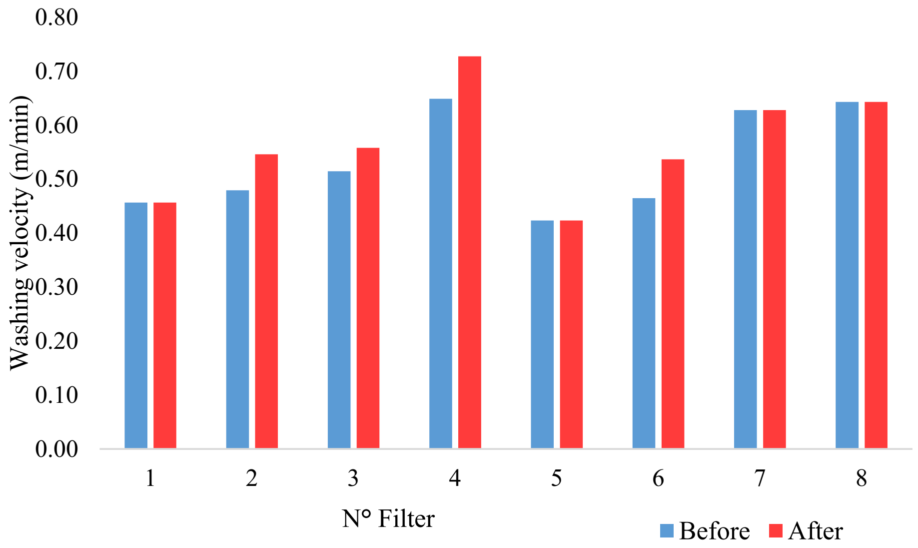

Fig. 7. Filter wash velocity. (Blue red) Before implementing improvements. (Red bar) After implementing improvements; there was an increase in the washing speed in all filters, except for filters F1 and F5.

mended by CEPIS (2005) is in a range of 0.6–0.8 m/min, and it can be estimated that the appropriate velocity in m/min is equal to the sand effective diameter (mm). According to design parameters, the washing velocity should be 0.625 m/min, which is within the range suggested by CEPIS (2005). In filters F4, F7 and F8 the highest washing velocity was obtained and they are within what is recommended by CEPIS (2005); meanwhile, the other filters showed a lower washing velocity and were below the recommended by CEPIS (2005). No filter had extremely high washing rates and this prevents an exaggerated filter bed expansion, which in turn prevents the filter material loss.

Similarly, for this test, the same procedure was followed by closing the dump gate of the interconnection channel when turning on the backwash. By washing the filters with this procedure it is possible to increase the washing velocity in the eight filters, in almost all except filters 1 and 5 the velocity is close and in some, it slightly exceeds the recommended by CEPIS (2005). This can be seen in Fig. 7(red bar).

3.7. Filter media granulometry

As a filter was repeatedly washed, the filter medium is lost either through the washing channel or through the drains. Therefore, the particle size of the bed changes over time. The results of the anthracite granulometric analysis in the eight filters are presented in Fig. 8. These results served to compare with the granulometric parameters recommended by CEPIS (2005). Table 1 shows the anthracite granulometric characteristics measured and recommended by CEPIS (2005), the effective anthracite size of filters F1, F5 and F6 were found to be equal to the maximum value recommended by CEPIS (2005).

The anthracite effective size in filters F2 and F3 was within that recommended by CEPIS (2005). Meanwhile, the effective anthracite size in filters F4, F7 and F8 were outside the range recommended by CEPIS (2005), presenting a smaller effective size. Therefore, the bed tended to expand mostly causing material leakage in the washing channel, which corroborated the expansion results obtained for these filters. Regarding the uniformity coefficient, all filters had a uniformity coefficient higher than that recommended by CEPIS (2005). Thus, the uniformity coefficient of filters F1, F2, F3, F5, and F6 were slightly higher than the uniformity coefficient of design, meanwhile, F4, F7 and F8 had very high uniformity coefficient (Table 1).

The lower the uniformity coefficient, the more uniform the granular material will be. Therefore, the penetration of impurities will be deeper and the duration of the filter runs will be longer, and probably a greater washing water volume will be required to remove the particles that have penetrated very deeply into the filter medium.

3.8. Mud balls

A well-preserved filter should not contain mud balls. However, it is possible that over the years, they can be formed up to 1% without greatly affecting the operation of the unit. Above that value, efficiency is increasingly affected. Percentages greater than 5% are indicating the need to rebuild the filter bed.

The results indicated that the only filter that presented mud balls was the F5 filter at 0.1%. Since no mudballs were found in the other filters, the sediment content that the filter media contained was determined. The sediment content was determined by weight difference. The extracted sample (P) of each filter was weighed, the sample was washed until it was sediment-free and the washed sample (PA) was weighed. The sediment percentage was calculated using:

$$\%\, Sediment = \frac{(P - PA)}{P} * 100$$

The sediment percentage for the eight filters is presented in Fig. 9. In this figure, it can be seen that the F5 filter has the highest sediment content (0.77%), which corroborates the mud ball content mentioned above.

The results confirmed that with more rigorous and standardized control of the operation, the improvements can be even greater. These improvements were a direct consequence of the adequacy of the washing velocity and the washing process. In Table 2, Operation 1 represents the filter working before the improvement and operation 2 represents the filter working after the improvement (closing the interconnection channel gate). With the proposed method, after the evaluation was carried out, the water quality of the initial filtrate was increased, obtaining turbidity of 0.30 NTU, the filtration runs increased up to 56.41% (F5), the expansion increased by 428.84% (F5). When, the duration of the washing pro-

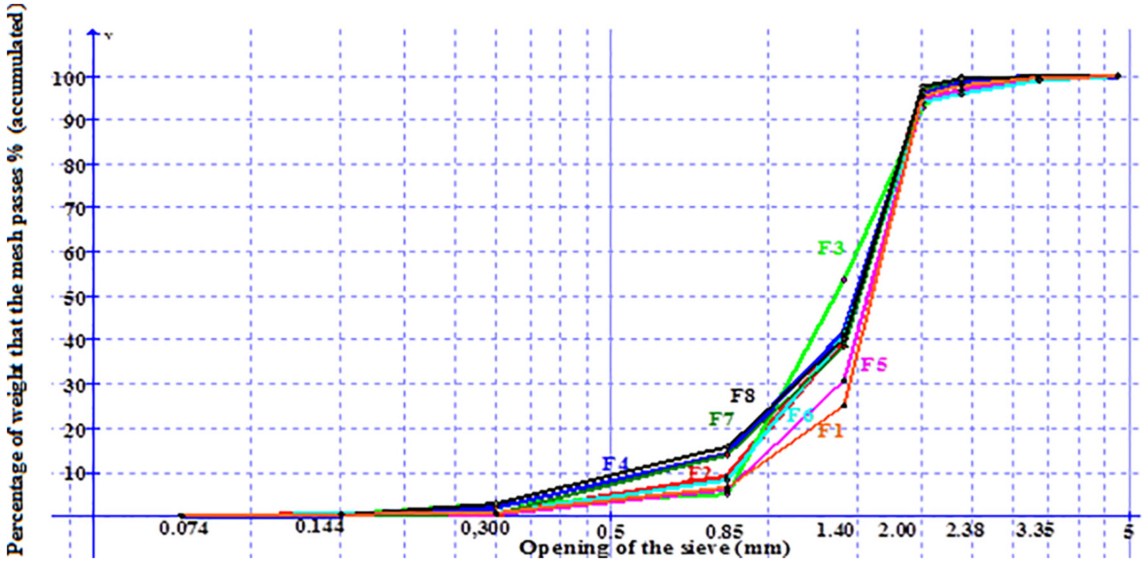

Fig. 8. The anthracite effective size of filters F1, F2, F3, F5 and F6 (0.9 mm) were within what was recommended by CEPIS (0.8–1.10 mm). The effective size in F4, F7 and F8 (0.6 mm) was slightly below the recommended by CEPIS.

Table 1
Comparative analysis of anthracite granulometry. The uniformity coefficient of F1, F2, F3, F5, and F6 (1.78–1.89) were slightly higher than the uniformity coefficient of design (1.5). Meanwhile, F4, F7, and F8 (2.46–2.50) had a very high uniformity coefficient.

N° Filter	Granulometric characteristics of anthracite			
	Effective size (mm)		Uniformity Coefficient	
	Measured	CEPIS	Measured	CEPIS
1	0.9	0.80–1.10	1.89	≤1.5
2	0.8	0.80–1.10	1.88	≤1.5
3	0.8	0.80–1.10	1.88	≤1.5
4	0.6	0.80–1.10	2.50	≤1.5
5	0.9	0.80–1.10	1.78	≤1.5
6	0.9	0.80–1.10	1.78	≤1.5
7	0.6	0.80–1.10	2.50	≤1.5
8	0.6	0.80–1.10	2.46	≤1.5

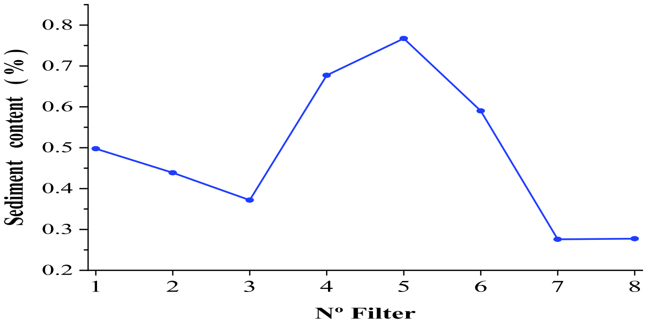

Fig. 9. Sediment content in the eight filters.

cess was reduced by up to 57.14% (F6), the washing velocity increased by 28.26% (F6), due to the shorter washing time, as well as, the lower number of filters washed monthly. This allowed the water consumed per month in the washing of the filters to be reduced by 30.1%.

The objective of this evaluation was to improve and optimize the filtration operation and estimate the state of the filters. After the pertinent measures were carried out, the expansion of the filter medium was improved for bed effective cleaning, it was within the range 20–30% recommended by CEPIS (2005). However, in Anderson and Chescattie (2003) and in some filters, it exceeded this value. The wash water turbidity at the end of the backwash was achieved to be <10 NTU (Logsdon et al., 2002). This indicated that most of the dirt had been removed, maximizing filtration production and, at the same time, providing the consumer highest water quality. When the filter effluent turbidity remained low and constant, the microbial contamination risk in the filter was low and the overall water quality is high. The average recommended wash time for all filters was between 9 and 10 min.

The granulometry characterization revealed a material (sand and anthracite) with effective size within the specifications established by (CEPIS, 2005; Di Bernardo, 1993). While the uniformity coefficient was slightly higher than the recommendations, no mud balls were found in the filters, except for the filter F1.

The variables that affected the saturation of the filter bed, before and after implementing changes in the operation of the filters were compared using the t-test ($p < 0.05$), the results are presented in Table 3.

A successful evaluation program includes a thorough on-site filter assessment. Drinking water supply companies should set the goal of supplying drinking water with <0.1 NTU. In Pennsylvania, the drinking water quality has been considered acceptable when the final water is <0.2 NTU (Consonery et al., 1997). An accurate determination of the backwash time when the turbidity was less than 10 NTU was very useful for the plant's operating personnel. These backwash times were invariably used as a saving in backwash time, which means a saving in the backwash water amount, which is a very expensive product in the filtering operations.

Drinking water supply companies should continually strive to improve filter performance. This implies improvements in the operations, design, administration, and maintenance of a water system and ensuring that personnel can handle future challenges, such as unanticipated changes in the raw water quality.

This filtration system evaluation has focused on identifying low-cost improvements rather than building new filtration units. The demand for excellent drinking water quality requires a comprehensive self-assessment program to reduce the outbreaks risks of waterborne diseases.

Table 2
Hydraulic parameters of the filtration system before and after the improvement.

Parameter	F1		F2		F3		F4	
	Operation 1	Operation 2	Operation 1	Operation 2	Operation 1	Operation 2	Operation 1	Operation 2
Filtration velocity (m^3/m^2d)	215.9	247,60	243.95	234,60	246.5	289,00	261.8	295,80
Initial filtering quality (NTU)	0.39	0.30	0.42	0.34	0.39	0.31	0.39	0.30
Filtration run times (h)	29.62	41.25	31.33	41.58	30.81	42.50	30.98	44.50
Filter bed expansion (%)	12.68	29.22	11.42	50.13	5.78	40.35	33.82	57.84
Duration of the washing process (min)	14	10	18	9	20	10	16	7
Filter wash velocity (m/min)	0.46	0.47	0.46	0.55	0.51	0.56	0.65	0.73
Parameter	F5		F6		F7		F8	
	Operation 1	Operation 2	Operation 1	Operation 2	Operation 1	Operation 2	Operation 1	Operation 2
Filtration velocity (m^3/m^2d)	209.95	293,25	235.12	245,70	237.8	236,30	243.95	261,20
Initial filtering quality (NTU)	0.30	0.29	0.44	0.31	0.41	0.33	0.55	0.42
Filtration run times (h)	28.98	45.33	30.02	46.25	31.17	45.25	31.04	46.75
Filter bed expansion (%)	5.20	22.30	8.27	24.53	22.27	33.60	23.91	35.80
Duration of the washing process (min)	18	10	21	9	18	8	16	10
Filter wash velocity (m/min)	0.42	0.42	0.46	0.59	0.63	0.63	0.64	0.65

Table 3
Differences in the results of the variables that affect the saturation of the filter before and after implementing the improvements.

Variable	Results
Filtration velocity	Significant Difference ($p = 0.032$)
Initial filtering quality	Significant Difference ($p = 0.0094$)
Filtration run times	Significant Difference ($p < 0.0001$)
Filter bed expansion	Significant Difference ($p = 0.0021$)
Duration of the washing process	Significant Difference ($p < 0.0001$)
Filter wash velocity	No Significant Difference ($p = 0.3578$)

4. Conclusions

This document presents convincing evidence that performance evaluation of the filters makes it possible to identify the poor operation causes of the filters after being in service for several years. The procedure proposed by CEPIS proves to be useful for the more detailed and rational diagnosis of the cause, and possibly the rehabilitation of dirty filter media. This allows for the identification of the problems that cannot be easily eliminated through the routine operation of the filters. The proposed methods can be easily applied to inform operation and preventive maintenance decisions. The results highlight the need for a constant evaluation of the unitary treatment processes performance and, in particular, of filtration. The latter being one of the most susceptible or neglected operating processes in a water treatment plant. From the experimental results, it was observed that increasing the filter washing velocity has a significant improving impact on the filtration run, filter bed expansion, and turbidity removal efficiency. This results in gains in terms of the filtered water quality and water-saving through increasing filtration runs. In conclusion, the theoretical considerations presented here led to the verification of a rapid filter evaluation methodology that allows for identifying problems in the operation of the filters. This allowed us to find corrective solutions that not only improved the filter condition but also reduced operating costs and extended the filter infrastructure life.

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.

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