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Removal efficiency of pressurized sand filters during the filtration process

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ABSTRACT

This study aims to evaluate the filtration process of a commercial sand filter operating at different filtration rates and different sand particle sizes. The second objective is to carry out sand filter efficiency evaluations and compare the standard sand filter method and the proposed method. Removal efficiency was analyzed in three filtration cycles, and determined by two methodologies: counting of particles in water at the inlet and outlet of the filtration system (standard method) and in sand bed layers (proposed method). An experimental module composed of three identical commercial sand filters was used with different sand particle sizes (G1 – 0.55 mm of sand effective diameter, G2 – 0.77 mm and G3 – 1.04 mm) and filtration rate combinations (20, 40, 60, and 75 $m^3\ m^{-2}\ h^{-1}$), repeated for three filtration cycles (C1, C2 and C3), 4 h per cycle. The removal efficiency of sand filters increases as the filtration rate increases for the water quality used, and sand particle size decreases. Between the methodologies applied to evaluate filtration systems, the method using total suspended solids retained in sand (proposed method) has shown a greater potential when compared with the standard method. The evaluation methodology proposed provides a global and accurate evaluation of the process. This form of estimation does not have the representability problem punctual water samples collected during filtration have. In addition, it is a promising methodology for farmers and technicians to carry out equipment evaluations in the field.

Keywords: Drip irrigation; Water treatment; Granular bed; Sand filter

1. Introduction

Sand filters are frequently used in drip irrigation. They are recommended for physical water treatment, have a better performance dealing with organic particles, and a better algae retention by the action of filtration bed layers. They also present a better removal efficacy than other filters (screen and disc filters) [1–4].

There are two operations that can be performed using sand filters. The first operation is filtration, where suspended solids are removed from the water by passing through a sand media [3]. This process results in an increase in filter head loss in time [5,6]. The second process is backwash, where the sand is cleaned by reversing the water flow [3,7,8].

Pizarro Cabello [9] listed the filtration process steps, namely sieving (particles larger than the porous media are retained in the surface), sedimentation (particles not retained on the surface are removed from the water by a decrease in water flow speed, causing deposition in pores), and adhesion and cohesion (retention promoted by attraction forces). The retention of particles in the filter sand bed could promote an increase in interstitial speed and detachment of particles over time.

Removal efficiency varies among filtration bed layers in function of filtration rates (ratio between filtration flow and surface area of the filtration sand bed) and sand particle sizes, according to Phillips [10]. This researcher recommends using sand filters with filtration rates between

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36 and 61.2 m^3 m^{-2} h^{-1}. According to Phillips [10], low filtration rates form preferential pathways, resulting in a low particle removal. On the other hand, high filtration rate values cause excessive fluid turbulence within the filter, causing surface movement of the filter bed, changing the hydraulic behavior of the equipment, and reducing filtration area and removal efficiency. Other literature reports for this variable do not present a correlation with particle removal efficiency [3]. A filtration rate of 60 $m^3 m^{-2} h^{-1}$ was proposed by Pizarro Cabello [9]. In a study developed by Mesquita et al. [11] on sand filters using clean water, the filtration rates from 20 to 60 $m^3 m^{-2} h^{-1}$ resulted in a lower filter head loss.

Besides filtration rates, the sand particle size in the filtration bed, which composes the porous media, is also very important. Both variables, when associated, may result in different performances in terms of hydraulic behavior and particle removal efficiency, as demonstrated by de Deus et al. [6].

In view of this, this study was developed aiming to evaluate the filtration process of a commercial sand filter at different filtration rates and sand particle sizes. Additionally, sand filter efficiency evaluations were carried out by comparing the standard sand filter method [12] with a new proposed method.

2. Methodology

2.1. Experimental setup

This research comprised three new sand filters mounted in parallel (F1, F2 and F3) connected to a fourth filter (FR), which is used to filter water for the individual cleaning (backwash) of the filters evaluated. A single water inlet was used to supply water for all filters. This prevents changes in water quality among experiments (Fig. 1).

The experimental setup was also composed of needle and gate valves to operate the tests, an electromagnetic flow rate sensor (one per filter) model 2551 (Georg Fischer Signet, São Paulo – SP, Brazil), and pressure transducers model MPX 5500DP (two per filter) (Freescale Semiconductor Brazil, Campinas – SP, Brazil) connected to integral pressure testers (two per filter – inlet and outlet). All instruments of the module were connected to a data acquisition system model USB-6341 X series (National Instruments Brazil, São Paulo – SP, Brazil) and a laptop managed by an interface developed using the software LabVIEW (National Instruments Brazil, São Paulo, Brazil).

Fig. 2a shows the evaluated sand filter model FA07 (Hidro Solo, Macéio – AL, Brazil) and the internal structure in detail (diffuser plate and underdrains). It is possible to observe the structural modifications made to the filter. Such modifications allowed sand sample collections at different depths (side openings). It also made possible the backwash process (side windows of tempered glass installed above the filter bed at 25% in four regular positions inside the filter circumference) (Fig. 2b). Table 1 shows the technical specifications of the commercial sand filter evaluated.

2.2. Water resource

The water used in the experiment came from a tank close to the experiment area belonging to a micro-watershed. The soil is predominantly dystroferric Red Latosol. The water inside this soil is used for irrigated agriculture. The water contains suspended solids of organic and inorganic origin.

For the characterization of water, total suspended solids (TSS) evaluations were performed based on the "Standard Methods for Examination of Water and Wastewater" [13]. The methods were used for experimental evaluations. The volume percentages of different diameters of particles contained in water ($\%V_{DP}$) were also calculated. For this, the equipment Mastersizer 2000 was used (Malvern Instruments Inc., Worcestershire, United Kingdom) (range 0.02–2,000 μm). The information generated by the equipment was divided into the following known ranges: clay (<2 μm), silt (2–60 μm), fine sand (60–200 μm), medium sand (200–600 μm) and coarse sand (600–2,000 μm).

2.3. Sand particle size

The filter material used was silica sand. There were three different particle sizes: fine (G1: effective diameter

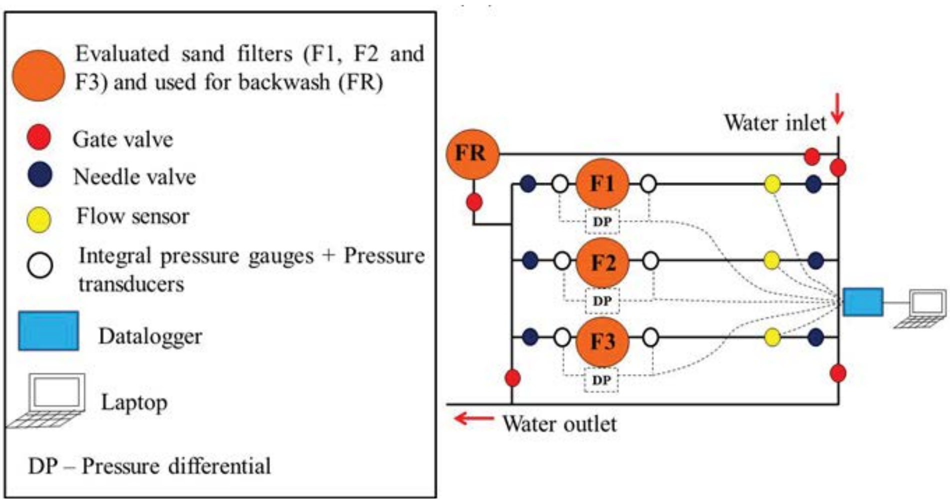

Fig. 1. Experimental setup and monitoring devices.

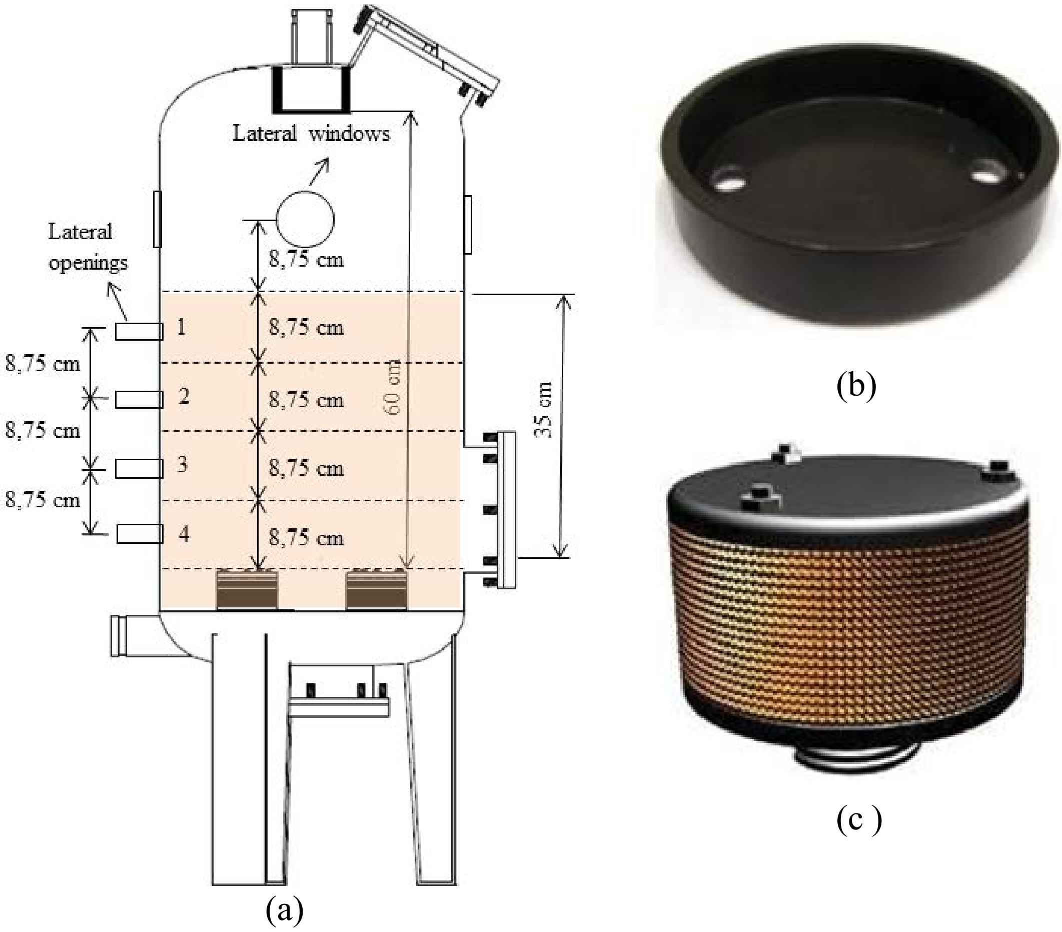

Fig. 2. Evaluated sand filter. Detail of the structural modification (side openings and windows) and their locations (a); diffuser plate with lid (b) and underdrains (c).

Table 1
Technical specifications of the commercial sand filter model

Specification	Value
Filter diameter (cm)	40.00
Filter height[a] (cm)	60.00
Filtration rate recommended by the manufacturer ($m^3 m^{-2} h^{-1}$)	23.90–167.10
Number of underdrains	4.00
Mean slot width (mm)	0.30
Number of slots by underdrains	2,286.00
Drain opening area per underdrain unit (cm^2)	19.30
Drain total opening area (cm^2)	77.20
Ratio between drain opening and filter surface area	0.06

[a]Distance between diffuser plate bases and the drain level.

D_{10} = 0.55 mm and coefficient of uniformity CU = 1.34), medium (G2: D_{10} = 0.77 and CU = 1.28), and coarse (G3: D_{10} = 1.04 mm and CU = 1.36). The sand bed height was 0.35 m (Fig. 2a), according to the filter's manufacturer recommendations (approximately 0.044 m^3 of media volume).

2.4. Experimental procedure

Filtration rates followed the reviews of Testezlaf [3]. They were 20, 40, 60 and 75 $m^3 m^{-2} h^{-1}$, respectively, called FR20, FR40, FR60 and FR75.

The tests were performed at the same time on all filters (F1, F2 and F3), for each sand particle size (G1, G2 and G3) and filtration rate (FR20, FR40, FR60 and FR75) during three filtration cycles (C1, C2 and C3). The filtration cycle had a continuous interval of filtration, which lasted 4 h. After each filtration cycle, a backwash process was carried out by expanding the filtration bed by 25% (8.75 cm) for 15 min. This procedure was monitored at the equipment side window (Fig. 2a). The same sand types were used for all filtration cycles to evaluate influences on the subsequent filtration processes.

2.5. Assessment of filter efficiency

The evaluation of the filtration process was performed by calculating TSS removal efficiency. It was estimated by two different methods. One considers the difference of TSS from the water in the filter inlet and outlet, according to the standard for sand filter evaluations [12] (standard method); the other method considers the TSS retained in the filtration bed (proposed method).

2.5.1. Standard method

Water samples were collected from the inlet and outlet of each filter at three specific times (0, 120 and 240 min) (three samples per filtration cycle). The samplings were performed after the system stabilization. The objective was to improve information representativeness because the standard [12] does not specify the quantity and the time of sample collection. According to Di Bernardo and Dantas [14], and as proven by de Deus et al. [6], the detachment of particles adhered to the filter bed is common in sand filters. It affects the temporal variability in the removal efficiency of the equipment. In this sense, only one water collection during the filtration process is not enough to assess filter removal capacity.

The removal efficiency of TSS from the water (RE) was determined by the general equation (Eq. (1)). An index was determined for each experimental combination (sand filter, filtration rate, sand particle sizes and filtration cycle) (RE_{TSS}). Using all TSS for all times and filtration cycles (average value), the general removal efficiency was determined for all experimental combinations (RE_G).

$$\mathrm{RE} = \left(1 - \frac{\mathrm{TSS_{out}}}{\mathrm{TSS_{in}}}\right) \times 100 \tag{1}$$

where RE: removal efficiency of total suspended solids from the water (%); TSS_{out}: outlet concentration of total suspended solids (mg L^{-1}); TSS_{in}: inlet concentration of total suspended solids (mg L^{-1}).

2.5.2. Proposed method (removal efficiency using sand samples)

To determine TSS in the sand bed, the procedure developed by Staden and Haarhoff [15], called "cylinder inversion method", was used. This method was selected because of its accuracy and operational and equipment easiness for field applications.

The analyses were conducted in different sand layer depths, as shown by Fig. 2a, before and after each filtration cycle (that is, all experimental combinations). This methodology consisted of the following steps:

- Extract, at each depth, from sand filters a sand sample. The sample comprised equipment diameter extension before and after the filtration process. Fig. 2a shows the depths at which the samples were collected. The samples were taken from the side of the equipment (side openings) using a grain auger. The layers where the sand was collected were divided into 1 (surface – 0 to 8.75 cm), 2 (8.75 to 17.50 cm), 3 (17.50 to 26.25 cm) and 4 (26.25 to 35.00 cm). For each depth, the sample collected comprised a composition of the three sand filters. In this case, the objective was to reduce the number of samples in order to respect the maximum sample conditioning time (24 h) for TSS analyses.
- Separate 60 mL of the composite sand sample for each depth. Due to the small amount of sand collected compared with the total volume in the filter (0.044 m^3), it did not affect sand bed retention capacity in subsequent filtration cycles.
- Place the sand sample (60 mL) in a beaker (250 mL volume) containing 100 mL of treated water from common supply.
- Seal the beaker and perform 20 inversions, pausing between intervals to allow the sand to settle into the beaker bottom.
- Drain the resulting liquid from the inversion into a clean recipient (500 mL volume).
- Repeat the procedure using the same sand sample four times, resulting in 500 mL of water with TSS from the filter bed.
- Separate 100 mL from the solution volume to determine the concentration of TSS in a sand sample of 60 mL [13].

The difference between the TSS found in the samples collected after (TSS_A) and before (TSS_B) the filtration process was estimated by the volume of particle mass removed per layer (MS_{layer}) and per sand bed (MS_{bed}). Below, the mathematical development used to determine the solids removed from the sand is described.

- Particle mass removed from a sand sample of 60 mL, according to Staden and Haarhoff [15], collected for each filter bed layer (MS_{60}) (Eq. (2)).

$$\mathrm{MS_{60}} = \left(\mathrm{TSS_A} - \mathrm{TSS_B}\right) \times V \tag{2}$$

where MS_{60}: particle mass removed from a sand sample of 60 mL for each filter bed layer (mg); TSS_A: total suspended solids after the filtration process (mg L^{-1}); TSS_B: total suspended solids before the filtration process (mg L^{-1}); V: sample volume used to determine total suspended solids (L).

100 mL (0.1 L) of the sample volume were used to determine TSS in 60 mL of sand.

- 60 mL of sand represents a portion of a volume fraction (VF) (Eq. (3)).

$$\mathrm{VF} = \left(\frac{A \times H}{4}\right) \times 10^6 \tag{3}$$

where VF: fraction of representative volume (mL), A: filter cross-sectional area (m^2); H: filter bed height (m).

The sand filter evaluated has a diameter of 0.4 m (filter cross-sectional surface of 0.1256 m^2). A filter bed, 0.35 m height, was used according to the manufacturer's recommendations. It was divided into four layers (Fig. 2a). Based on the information cited, the volume fraction was 10,995.57 mL.

- Particle mass removed per layer (MS_{layer}) (Eq. (4)).

$$\mathrm{MS_{layer}} = \frac{\mathrm{VF} \times \mathrm{MS_{60}}}{60{,}000} \tag{4}$$

where MS_{layer}: particle mass removed per layer (g).

By replacing the values in the above equation, Eq. (5) is obtained:

$$\mathrm{MS_{layer}} = 0.183 \times \mathrm{MS_{60}} \tag{5}$$

- Total particle mass removed per sand bed (MS_{bed}) (Eq. (6)).

$$MS_{bed} = \sum_{i=1}^{n} MS_{layer_i} \tag{6}$$

where MS_{bed} – total particle mass removed per sand bed (g).

The removal efficiency, using the sand samples (RE_{sand}), was estimated by the ratio between total particle mass removed per sand bed (MS_{bed}) and TSS caught by the filter (TSS_{total}) (Eq. (7)).

$$RE_{sand} = \left(\frac{MS_{bed}}{TSS_{total}}\right) \times 100 \tag{7}$$

where RE_{sand}: removal efficiency using sand samples (%); MS_{bed}: total particle mass removed per sand bed (g); TSS_{total}: total suspended solids that entered through the filter during one filtration cycle (g).

The TSS caught by the filter (TSS_{total}) was estimated by Eq. (8) as follows:

$$TSS_{total} = FR \times A \times t \times \overline{TSS} \tag{8}$$

where FR: filtration rate ($m^3\,m^{-2}\,h^{-1}$); A: filter cross-sectional area (m^2); t: duration of the filtration process (h); $\overline{TSS}$: average values of TSS that entered during the filtration process (mg L^{-1}).

$\overline{TSS}$ refers to the average relative to the three specific collection times of the TSS that entered during the filtration process.

2.6. Assessment of filter head loss

To obtain one more parameter evidencing the behavior of solid removal by the filter, the filter head loss was monitored in function of filtration time. The data collection rate was one average information per second, resulting in 14.400 data per evaluation.

The increase in filter head loss was determined in function of evaluation time weighted by TSS caught at each evaluation (Eq. (9)). This is another indication of removal capacity of the evaluated equipment for each experimental combination.

$$\Delta hf = \left(\frac{hf_f - hf_i}{TSS_{total}}\right) \times 1{,}000 \tag{9}$$

where Δhf: increase in filter head loss weighted by TSS caught at each evaluation (kPa kg^{-1}); hf_f: filter head loss at the end of the evaluation (kPa); hf_i: filter head loss at the start of the evaluation (kPa); TSS_{total}: TSS caught by the filter during one filtration cycle (g).

2.7. Data analysis

Sand filters were not considered as experimental replications due to the significant data variability (the explanation is in section 3). They were analyzed independently. It was not possible to apply conventional statistics to the data generated. In this sense, the values for removal efficiency for both sampling methodologies and the behavior of filter head loss were analyzed graphically.

3. Results and discussion

3.1. Characterization of the water used

The water used for the experiment showed average values of 5.20 ± 3.09 mg L^{-1} (variation coefficient of 59.42%) for TSS. It has, according to Bucks et al. [16], a low physical risk of drip obstruction (<50 mg L^{-1}). This information results from the 324 samples collected during the experiment (combination of four filtration rates, three sand particle sizes, three filtration cycles, three sand filters and three sampling times during each filtration cycle).

Fig. 3 shows the volume percentage average of different particle diameters contained in inlet water for the samples collected at the beginning of the filtration process (first sampling).

The water used in the experiment had around 7.79% of particles with a size within the range of the clay fraction, 83.44% within the silt fraction, 7.71% within the fine sand fraction, 0.95% within the medium sand fraction and 0.09% within the coarse sand fraction.

The hydraulic installation proposed (parallel installation) aimed to provide the lowest solid variability among filters. However, a coefficient of variation (59.42%) was observed. Therefore, for this reason, and others that will be presented, each sand filter was considered as independent evaluations.

3.2. Removal efficiency of the filtration process considering TSS from water (standard method)

Figs. 4–6 show the RE_{TSS} behavior for the evaluated filters in different experimental combinations, that is, for samples collected at the beginning (0 min), after the system stabilizes, at the middle (120 min) and at the end (240 min) of the process, respectively.

There is an evident variability in information on the filtration times. This was also reported by Puig-Bargués et al. [4,174]. This result demonstrates the need to improve the standard sand filter evaluation [12] by creating a methodology in which the sample represents the real removal behavior of the equipment. Such temporal variability of removal times can be explained by the observations of Di Bernardo and Dantas [14]. The researchers reported that the particle removal mechanisms in sand filters are complex, and can be divided into three stages: "transportation", "adhesion" and "detachment". Transportation is the stage of conduction of suspended particles near the filter bed surface, and they can be removed by the surface. The adhesion stage is particle retention force due to the existence of a force, such as electric power. However, depending on the water speed in the filter bed pores (interstitial velocity), there may be a detachment of particles previously retained by the filter bed. In summary, depending on sampling time, the efficiency value will not represent the actual removal capacity because of the dynamics of sand filter removal efficiency. In this sense, some values are not shown in the graphs in some treatments (Figs. 4–6).

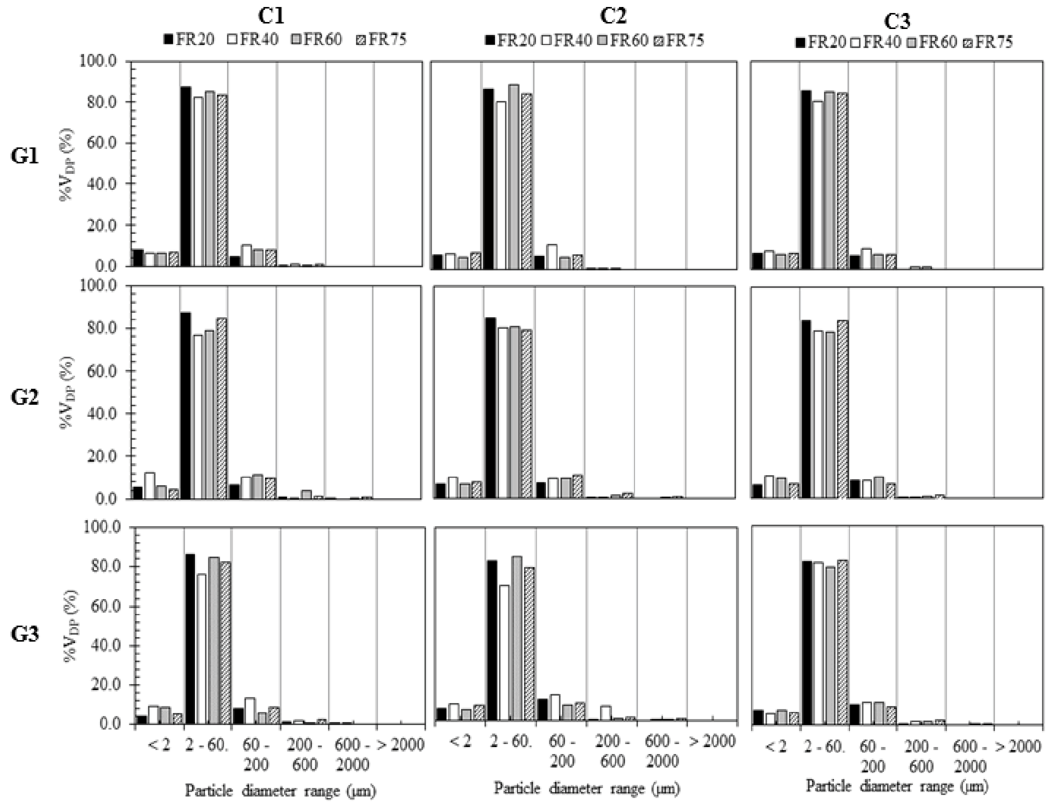

Fig. 3. Volume average percentage of different particle diameters contained in inlet water.

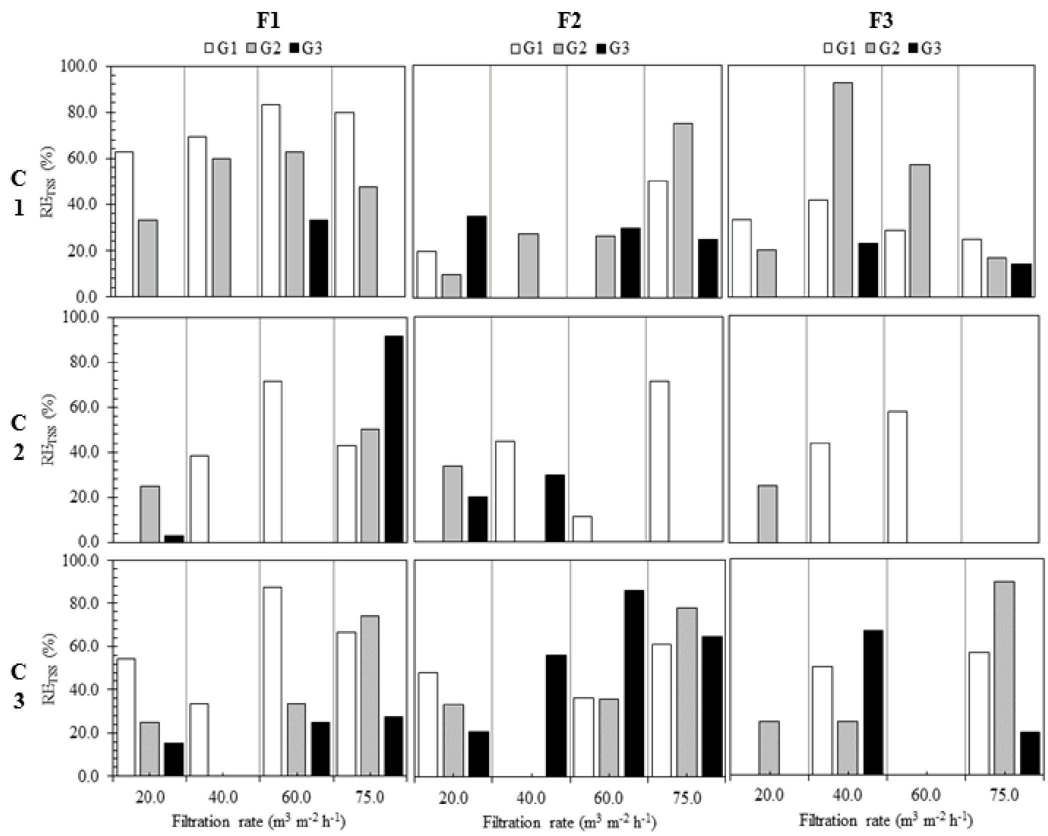

Fig. 4. Filtration removal efficiency using TSS from water samples (RE_{TSS}) (%) considering the first sampling (0 min) calculated for different sand particle size and filtration rate combinations for the filtration cycles C1, C2 and C3.

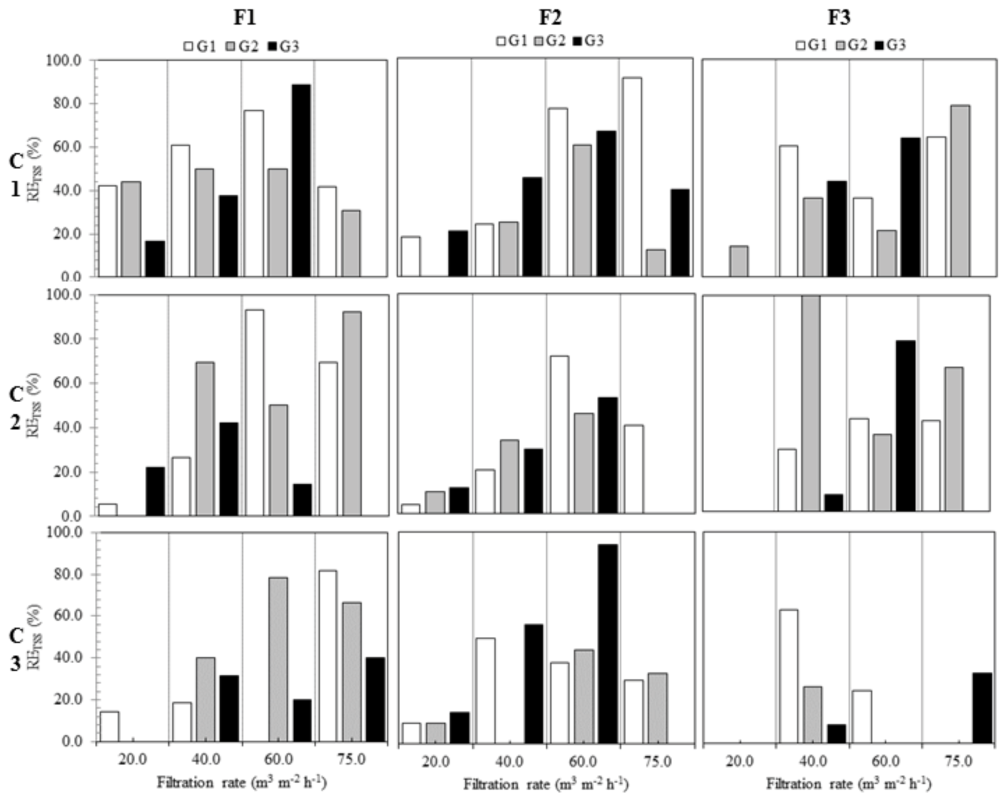

Fig. 5. Filtration removal efficiency using TSS from water samples (RE_{TSS}) (%) considering the second sampling (120 min) for different sand particle size and filtration rate combinations for the filtration cycles C1, C2 and C3.

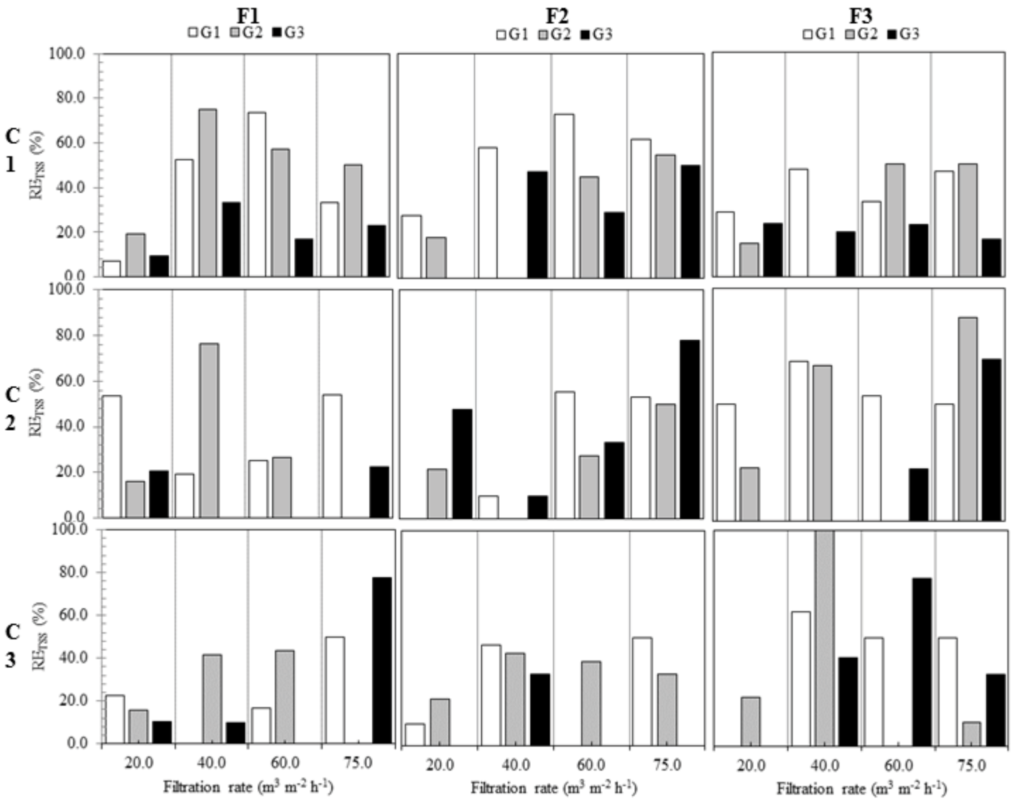

Fig. 6. Filtration removal efficiency using TSS from water samples (RE_{TSS}) (%) considering the third sampling (240 min) for different sand particle size and filtration rate combinations for the filtration cycles C1, C2 and C3.

This is because removal efficiencies were negative (there was no removal of particles).

Because of the temporal variability in the information and the limitation of the standard methodology for sand filter evaluation [12], the removal behavior was less visible due to changes in intervening variables (filtration rate, sand particle size and filtration cycle). Regarding filtration cycles, the initial hypothesis considered a decrease in filter removal capacity due to usage and backwashing inefficiency, as mentioned by de Deus et al. [8] and Mesquita et al. [11]. Due to the temporal variability of the filtration process influencing the evaluation [14], the filtration cycles influence was not conclusive. In addition, although the filters were installed in parallel to receive the same solid loads, it did not occur. There was a behavior variation among filters of the same manufacturer and model.

Considering the average TSS among time and filtration cycles, the general removal efficiency of the filtration process was calculated (RE_G) (Fig. 7).

Fig. 7 shows the influence of sand particle size and filtration rates on the removal of TSS. In general, there was an increase in RE_{TSS} as filtration rate increased, and there was a decrease in sand particle size. de Deus et al. [6], who evaluated the removal efficiency of different particle diameter ranges in water, also observed this behavior. Haman and Zazueta [18] reported that the solids removed increased as sand particle size decreased.

The best treatments were F1 (61.1%, G1FR75), F2 (53.3%, G1FR60) and F3 (71.2%, G2FR75). However, the values presented may not represent the real solid retention capacity of the equipment because of a significant temporal variability in information.

The lowest filtration rate values around (20 and 40 $m^3\,m^{-2}\,h^{-1}$), which provided the worst results, converged with Phillips [10] explanations. According to the researcher, low filtration rates (less than 36 $m^3\,m^{-2}\,h^{-1}$) cause the formation of preferential pathways, resulting in a low particle removal. On the other hand, filtration rate values around 60 and 75 $m^3\,m^{-2}\,h^{-1}$, which provided the best results, diverged with Phillips [10] explanations. According to the researcher, high filtration rate values (greater than 61.2 $m^3\,m^{-2}\,h^{-1}$) cause an excessive fluid turbulence within the filter, leading to surface movement of the filter bed, changing the hydraulic behavior of the equipment, and reducing the filtration area and the removal efficiency. Burt [19], Mesquita et al. [11] and de Deus et al. [20] also proved this fact.

Fig. 8 shows the behavior of RE_G as a function of the filtration rate for the three sand particle sizes, considering the average between sand filters despite the variability between them.

3.3. Particle mass removed per layer and per sand bed

The particle mass removed from different layers of the sand bed (MS_{layer}) can be observed in Fig. 9.

It is possible to observe a decrease in the volume of solids removed as the sand particle size increased at a given filtration rate in filter bed layers evaluated. These results corroborate previous observations.

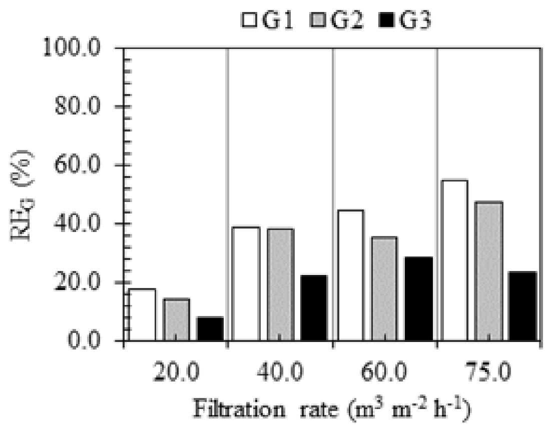

Fig. 8. Filtration removal efficiency calculated considering TSS from water samples and data collected for times and filtration cycles (RE_G) (%) for different sand particle sizes and filtration rates ($m^3\,m^{-2}\,h^{-1}$) according to the average value between sand filters.

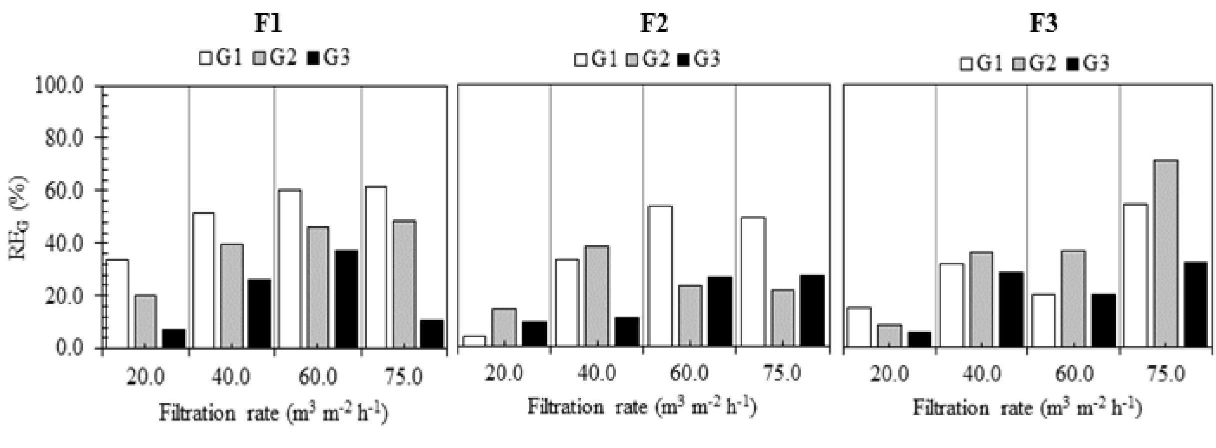

Fig. 7. Filtration removal efficiency using TSS from water samples considering all data collected for time and filtration cycles (RE_G) (%) for different sand particle sizes and filtration rates ($m^3\,m^{-2}\,h^{-1}$).

There was an increase in solids removal for all filter bed layers evaluated as filtration rates increased. This is more evident in G1 and less evident in G3.

In the FR20, combined with G2 and G3, no solid removal was observed in all layers evaluated. There may have been particle detachment [14].

Comparing the volume of solids removed from the different filter bed layers, the surface layer (1) presented a greater solid retention in the filtration process. Pizarro Cabello [9] called this process “sieving”, and Di Bernardo and Dantas [14] called it “transport”. The differentiation between layers becomes more evident with the increase in filtration rate for certain sand particle sizes. The higher filtration rate (FR75) allowed particles to be removed by collision with the surface layer. The result is in agreement with Phillips’ [10] observations.

There are no values reported for some layers because particles contained in the sand moved to other layers or out of the equipment (particle detachment) [14].

By comparing the results among filtration cycles, there was an excessive variability of results. However, there was a decreased tendency in removal for the subsequent filtration cycles.

Fig. 10 shows the particle mass removed during the filtration process for all sand bed layers (MS_{bed}).

The same behavior as the analysis performed per filter bed layer, with the exception of the TF40 treatment, where the G2 removed a smaller quantity of solids in comparison

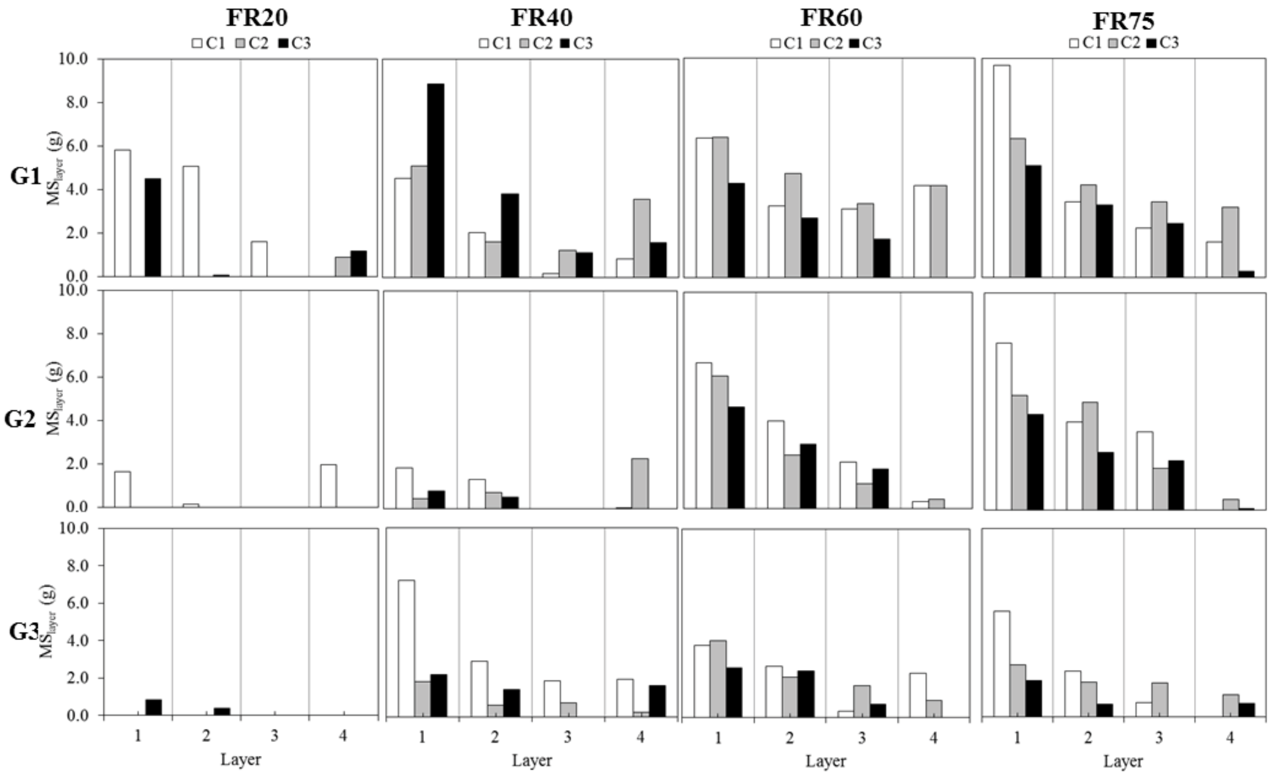

Fig. 9. Particle mass removed during the filtration process from different sand bed layers (MS_{layer}) (g) for sand particle sizes (G1, G2 and G3) combined with different filtration rates (FR20, FR40, FR60 and FR75) and cycles (C1, C2 and C3).

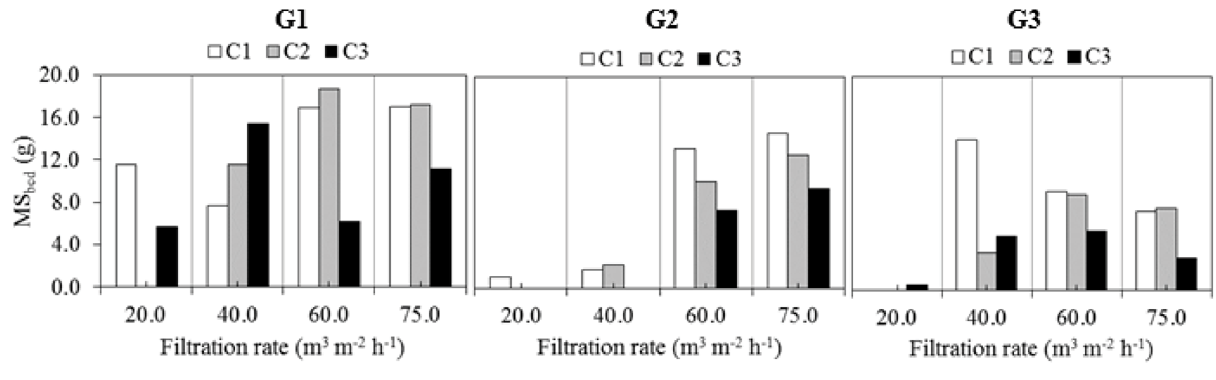

Fig. 10. Particle mass removed during the filtration process for all sand bed layers (MS_{bed}) (g) for all sand particle sizes (G1, G2 and G3) combined with different filtration rates (FR20, FR40, FR60 and FR75) and cycles (C1, C2 and C3).

with the G3. In addition, the increase in filtration rate for a given sand particle size provided an increase in the amount of solids removed. Such increase was smaller as the sand particle size increased, that is, finer sands provided greater differences in removal as the filtration rates increased compared with coarser sand. It is possible to observe exceptions in the variations of the filtration rate behavior for G1. For C1 and C2, the increase was up to RF60, and for C3 the increase was up to RF40. Additionally, in C1, MS_{bed} was higher for RF20 compared with RF40.

Considering the average values among filtration cycles, the behavior discussed above becomes more evident. It is shown in Fig. 11.

3.4. Removal efficiency of filtration process using sand samples as indicators (RE_{sand}) (proposed method)

Fig. 12 shows the behavior of the removal efficiency index calculated by sand sampling (RE_{sand}) for different combinations of filtration rates, cycles and sand particle sizes.

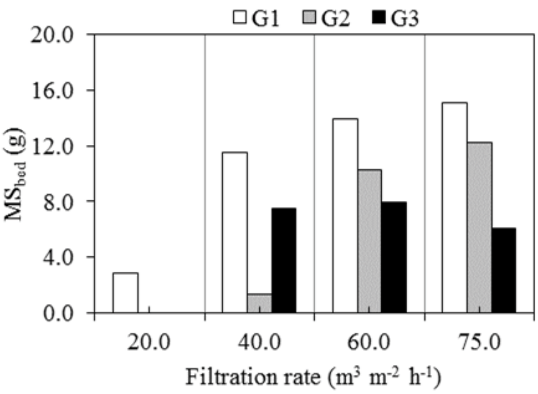

Fig. 11. Particle mass removed during the filtration process for all sand bed layers (MS_{bed}) (g) for sand particle sizes (G1, G2 and G3) combined with different filtration rates (FR20, FR40, FR60 and FR75) considering the average among filtration cycles (C1, C2 and C3).

By comparing it with the removal efficiency calculated using the TSS in water, the values of RE_{sand} were lower in all treatments. This difference may be due to the inefficiency of the standard methodology [12] in expressing the reality. The removal of solids by sand filters is very dynamic, as advocated by Di Bernardo and Dantas [14]. According to the researchers, the detachment of particles adhered to filter media is evident and results in different removal efficiencies during the times of the filtration process.

The highest value was 17.1% (treatment G1FR60). By fixing the sand particle size, it is possible to observe an increase in RE_{sand} as the filtration rate increases, however in different magnitudes for each filtration cycle. In the first cycle, there was an increase in RE_{sand} up to the filtration rate FR60 for sand particle sizes G1 and G3. The highest values of RE_{sand} were observed for G1, followed by G2 and G3, when using the same filtration rate. However, for G1, the RE_{sand} initially decreased up to the FR40, and then increased up to the FR60. For G2, the increase was observed up to the FR75. In the second cycle, RE_{sand} values increased for G1 up to the FR60; for G2 and G3, up to the FR75. At the last cycle, the RE_{sand} variation increased up to the FR40 for G1 and G3, and up to the FR60 for G2.

De Deus et al. [6] evaluated, in a same experiment, the removal efficiency of different particle diameters in water. The researchers observed that the equipment had the capacity to remove particles from 60 μm, according to the sand filter and water quality used, referring to fine sand. In general, the information presented is similar to the results presented in this paper. Considering the removal of all particles from fine sand and the average removal of approximately 2.08% from silt [6], an average removal efficiency of 10.49% is obtained. This is a magnitude obtained using the methodology proposed.

Despite the same behavior presented for both methodologies, the values found using the sand samples were lower. Table 2 shows the average values of filtration removal efficiency for both methodologies, allowing comparison. This is evidence against the standard method [12] for sand filter evaluation, which uses punctual water samples to estimate removal efficiency. It also presents a new possibility to evaluate sand filter removal efficiency. The RE_{sand} does not

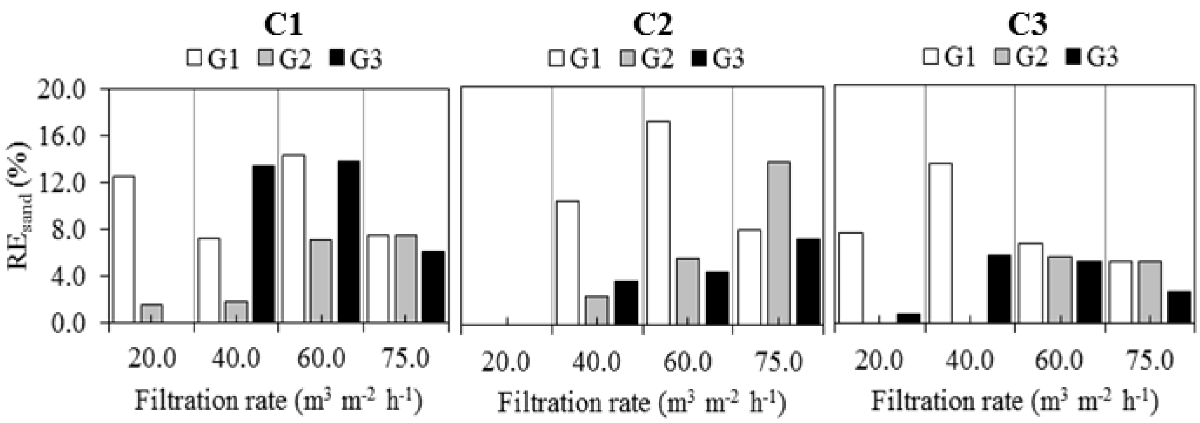

Fig. 12. Performance of filtration removal efficiency using TSS values of the sand (RE_{sand}) (%) for different combinations of filtration rates, sand particle sizes and filtration cycles.

Table 2
Average filtration removal efficiency for different combinations of filtration rates and sand particle sizes in both methodologies (Standard and proposed methods [12])

Filtration rate ($m^3 m^{-2} h^{-1}$)	G1		G2		G3	
	Standard	Proposed	Standard	Proposed	Standard	Proposed
20.0	17.45	6.68	14.23	0.50	7.51	0.26
40.0	38.66	10.36	37.94	1.38	21.92	7.61
60.0	44.56	12.69	35.31	6.05	28.09	7.79
75.0	54.80	6.86	47.06	8.75	23.32	5.32

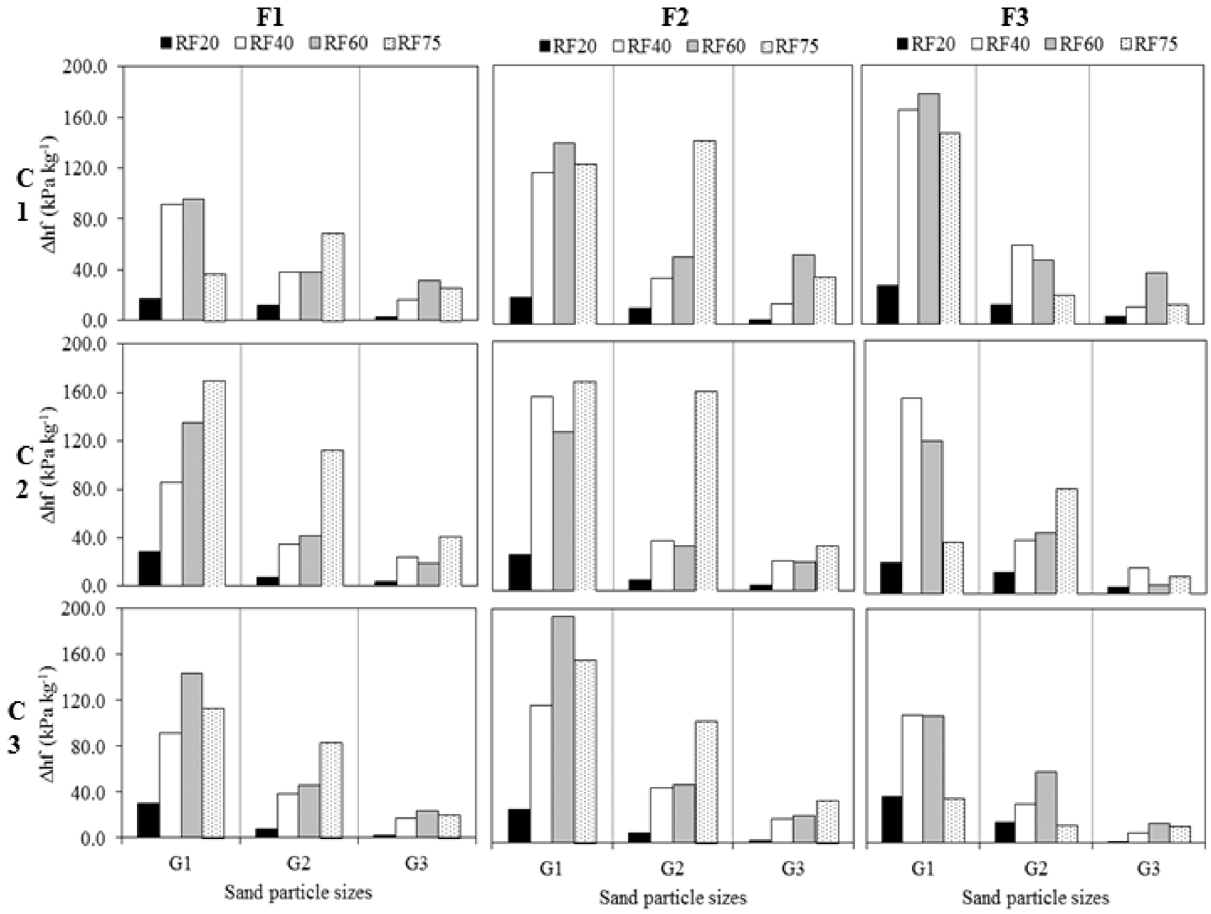

Fig. 13. Behavior of increase in filter head loss of the sand filter weighted by total suspended solids caught at each evaluation.

have the problem as reported for punctual water samples during the filtration process.

3.5. Hydraulic characterization of the filtration process

Fig. 13 shows the behavior of increase in filter head loss weighted by TSS caught at each evaluation.

For all filtration rates and cycles (except for RF75 in C1), there was a decrease in Δhf as the sand particle size increased. This indicates a decrease in solids retention in the filtration process. In addition, there is a tendency to increase Δhf as filtration rates increase. In some treatments, the increase occurs up to RF60; in others, up to RF75. This behavior indicates that the treatments with a higher filtration rate (RF60 and RF75) led to higher solids retention.

It was possible to observe a behavior pattern in relation to filtration cycles due to the complex dynamic of solid retention in filter beds, as described by Di Bernardo and Dantas [14].

4. Conclusions

- The removal efficiency of the sand filters evaluated, for the water quality used, increases as the filtration rate increases and sand particle size decreases.
- In summary, based on the boundary conditions of this experiment, it is recommended the use of fine

sand particle size (effective diameter of 0.55 mm) with filtration rates between 60 and 75 $m^3 m^{-2} h^{-1}$.

- Between the methodologies applied to evaluate the filtration system, TSS retained in the sand show a greater potential when compared with the standard method. The evaluation methodology proposed provides a global and accurate evaluation of the filtration process. This form of estimation does not present the problem of representability of punctual water samples collected during filtration times. In addition, it is a potential methodology for farmers and technicians to carry out evaluations of equipment in the field.

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