Comparison of crushed rock sand and natural river sand as filter media for rapid filtration

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ABSTRACT

The objective of this work was to evaluate the crushed rock sand (CRS) as a filter bed in rapid filtration for water treatment. The experiments were carried out using pilot-scale filtration units: one with a CRS filter bed and the other with natural river sand (NRS). Both filter media were prepared in accordance with typical standards for rapid sand filtration (particle size range and distribution, and filter bed depth), and were further characterized in terms of chemical composition, particles and bulk density, porosity, acid solubility and sphericity coefficient. Over four months, 14 filter runs using filtration rates of 90, 180, 270 and 360 $m^3\ m^{-2}\ d^{-1}$ were monitored and characterized in terms of run length, head loss increase along filter bed depth, turbidity removal along filter bed depth. Overall, the performance of the CRS filter was similar to or even better than that of the NRS filter, producing filtered water with turbidity lower than 0.50 NTU along the entire run, with head loss increasing rates and run length similar to those of the NRS filter. It is concluded that CRS presents a high potential for use as filter media for rapid filtration in water treatment, without technical or operational disadvantages.

Key words | drinking water treatment, filter bed media, head loss, rapid filtration, turbidity

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HIGHLIGHTS

- Crushed rock sand is a suitable filter bed media for rapid filtration.
- Similar turbidity removal and head loss increasing rate compared to natural river sand.
- High efficiency even under high filtration rates and high influent water turbidity.

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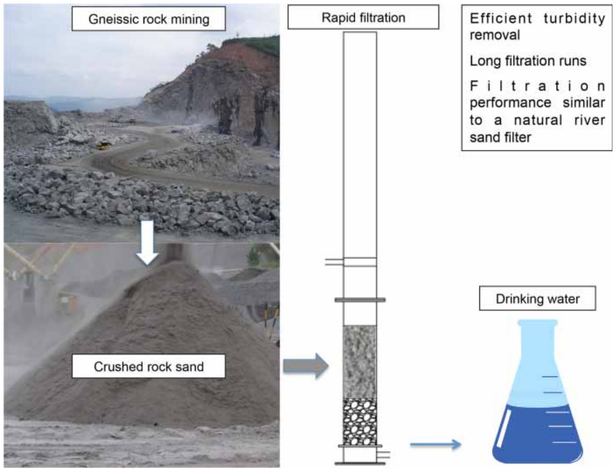
GRAPHICAL ABSTRACT



INTRODUCTION

Drinking water treatment (DWT) plays a major role in waterborne diseases' control. Currently, several techniques are available for particle removal and disinfection, presenting different efficiencies, complexity and costs. Technology selection for DWT relies mainly on raw water quality, regulatory requirements, operational constraints, and economical feasibility (Crittenden *et al.* 2012). Nowadays, available technologies for water treatment are able to grant drinking water production even from highly polluted water sources. For instance, membrane filtration promotes the removal of micropollutants, besides being more effective for the removal of particles and microorganisms compared to conventional systems (Mohammad *et al.* 2015). However, although membrane treatment technology costs have decreased, high needs for capital, energy and specialized personnel for operation are still limiting for developing countries (Schäfer *et al.* 2014), where simpler technologies are preferred. In Brazil, conventional DWT comprised of coagulation, flocculation, sedimentation, rapid filtration and disinfection is, by far, the most used treatment technology.

Granular media filtration is an important step in conventional DWT, since: (i) it is the last step for water clarification; (ii) it makes subsequent disinfection more effective (as suspended particles can protect microorganisms from the disinfectants' action); and (iii) it can effectively remove protozoa cysts (e.g. *Giardia*) and oocysts (e.g. *Cryptosporidium*) due to the similar characteristics presented by (oo)cysts and colloidal or suspended particles, such as size (Emelko *et al.* 2005) and surface negative charge (Bustamante *et al.* 2001), they can both be effectively retained in the filter bed by also similar mechanisms (physical-chemical mechanisms) (Betancourt & Rose 2004). Thus, filtration may be the last barrier against disinfectant-resistant organisms, such as *Cryptosporidium*, whose oocysts are extremely resistant to chlorine (the most frequently used disinfectant worldwide) (Tchobanoglous *et al.* 2003). However, due to financial and analytical constraints, monitoring protozoa removal in a water treatment plant (WTP) on a routine basis is rather difficult. Hence, among other surrogates (like aerobic spore-forming bacteria; Headd & Bradford 2016), filtered water turbidity has been used for evaluating protozoa removal in DWT, and such an approach is present in many drinking water quality regulations (USEPA 2006; Ministry of Health 2008; Brasil 2011; Health Canada 2017).

Rapid filtration is a combined result of physical and physical-chemical processes that take place as a dilute water suspension passes through a granular medium (Hendricks 2006). Particles are transported near the surface of the bed grains and are retained by attachment mechanisms, narrowing the pores of the filter media. Thus, the interstitial velocity continuously increases during the filter run, increasing the head loss both over time and through the filter bed depth. After some time of effective filtration, breakthrough may occur due to either a decrease in particle capture and/or an increase in detachment (Crittenden *et al.* 2012). When the available head loss is exceeded and/or filtered water turbidity reaches a threshold value (generally imposed by drinking water standards) the filter must be cleaned, usually by backwashing. However, since backwashing uses treated water, it is desirable to optimize treatment operation in order to increase the filter run.

The main factors that affect rapid filtration performance are: influent water quality (e.g. turbidity, particle concentration, particle size distribution, level of pre-treatment), filtration rate, and the filter bed characteristics (e.g. porosity, depth, grains density, shape and zeta potential, size distribution – effective size and uniformity coefficient) (Crittenden *et al.* 2012). Depending on the coagulation process, flocs with different sizes and destabilization levels (floc strength) may be formed, affecting the adherence of the particles to the filter bed and, consequently, turbidity removal and increasing head loss rate.

The material most commonly used in single medium rapid filters is natural river sand (NRS) (silica sand) (Soyer *et al.* 2010), which is usually extracted from river beds and is sieved according to the rapid filtration media requirements for size distribution. Anthracite coal, garnet sand and ilmenite are examples of materials used in multimedia rapid filters (AWWA 1998). Depending on the availability, price and, most importantly, filtration performance, other materials may be employed instead of sand. According to Uluatam (1991), limited availability of sand suitable for rapid filtration, along with the high cost of other materials (e.g. anthracite, garnet sand), has led to a search for alternative materials as substitutes for sand in Turkey, and successful experiences have been reported using perlite (Uluatam 1991, 1992), pumice (Farizoglu *et al.* 2003) and crushed glass (Soyer *et al.* 2010). Crushed glass has also been evaluated by Rutledge & Gagnon (2002) and Cescon *et al.* (2016), along with expanded clay in the latter. In Canada, as far back as 1995, the performance of a crushed quartz filter was compared to that of an anthracite-sand dual-media filter (Suthaker *et al.* 1995). Earlier, in India, Rao (1981) had looked at using a crushed stone filter media prepared out of the waste dust from stone quarries.

In Brazil, and elsewhere, there is a high demand for sand for construction purposes. In big cities, sand has to be transported over long distances to meet the demand, hence increasing costs (Hofmann *et al.* 2009). In addition, extraction of NRS severely impacts the environment, causing exposure of groundwater, deforestation and changes in the morphology of river channels as well as in its biotic communities (Santo & Sánchez 2002). Thus, fine aggregates from rock mining have been studied as a substitute for sand for concrete production (Manasseh 2010; Manguriu *et al.* 2013). This material, often named artificial sand, industrial sand or crushed rock sand (CRS) has less impurities, is more environmentally friendly and cheaper compared to NRS (Mundra *et al.* 2016). In this paper, the performance of a rapid filter with gneissic CRS as filter bed was compared to a conventional NRS filter in pilot-scale experiments.

METHODS

Filter media characterization

NRS was obtained from a local WTP that had recently replaced the filter bed of its rapid filters. CRS was provided by a mining company that produces aggregates for civil construction. Firstly, the raw materials (NRS and CRS) were sieved in order to obtain the typical size distribution for rapid sand filtration: effective size (d_{10}) = 0.45 mm and uniformity coefficient (UC) = 1.4. Both materials were then washed with treated water and dried in an oven at 105 °C for 24 hours prior to physical and chemical characterization. For the chemical characterization, a 100 g sample of each material was crushed to obtain particle sizes lower than 0.075 mm. Chemical analyses were carried out by X-ray fluorescence (XRF) using a Shimadzu equipment, model EDX-700. The following physical characteristics of both NRS and CRS grains were determined: particle density (ρ_s), bulk density (ρ_b), clean bed porosity (ε_o), acid solubility (S) and sphericity coefficient (ψ). Particle density was determined using a water displacement technique. Bulk density was obtained by measuring the mass needed to fill a 10 L-cylinder. Bed porosity was then calculated from the relationship between particle and bulk densities. Acid solubility was obtained by measuring the mass of each material after immersion of 100 g in HCl 1:1 (v/v) for 30 minutes (AWWA 1998). The sphericity coefficients were determined by measuring clean bed head losses at different filtration rates, using the Ergun equation as described by Soyer & Akgiray (2009), and Soyer *et al.* (2010).

Pilot filtration units

Two identical pilot-scale filters were built with acrylic columns, 190 mm internal diameter and 265 cm height, one with CRS and the other with NRS as filter bed media. At 10 cm above the filter bottom, a perforated acrylic plate containing 56 holes (4.76 mm) was placed as a false floor. Over the plate, 30 cm of gravel (1.68–19 mm) was used as a support layer. The filter bed of both materials was 45 cm height, with effective size (d_{10}) of 0.45 mm and uniformity coefficient of 1.4. The filter internal diameter (190 mm) was more than 100 times the effective size of the filter media (0.45 mm), as recommended by Kawamura (2000) in order to minimize sidewall effects. Through the filter bed depth, eight piezometers were installed for head loss measuring: one at the support layer-bed interface; the next two at 10 and 20 cm above the support layer, respectively; and the remainder at 5 cm intervals. The water inlet was made by a 32 mm pipe connected to a channel placed 20 cm above the filter bed, which was also used for collecting the backwash water. The flow rate was controlled by globe valves. In the lower part of the filters there was a water outlet pipe and the backwash water inlet. The water outlet tap was placed above the filter layer to avoid negative pressure inside the bed. The pilot filters received settled water from a full-scale conventional WTP located next to the experimental setting (coagulation with alum, hydraulic flocculation, sedimentation, rapid sand filtration and chlorination). Figure 1 presents, schematically, the experimental setup.

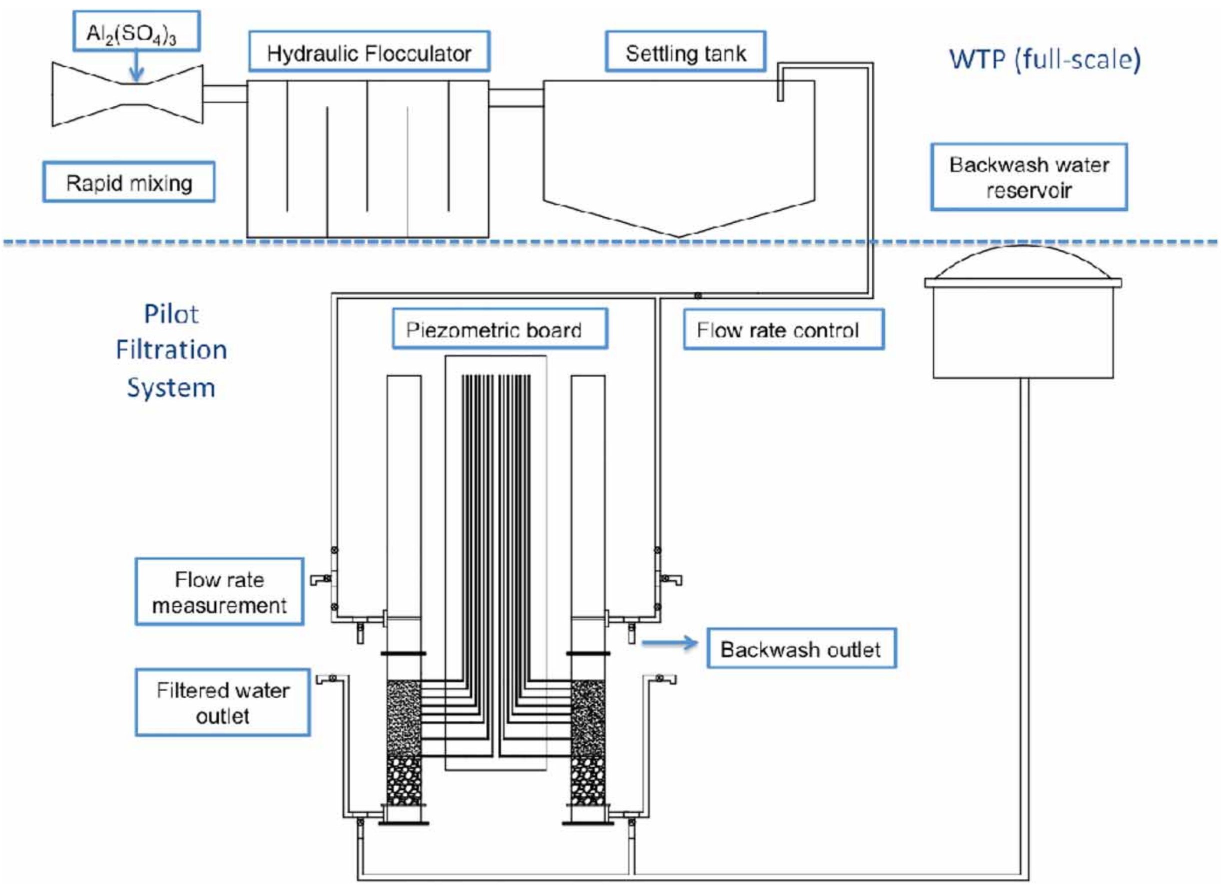


Figure 1 | Schematic representation of the experimental setup.

Filtration experiments

Preliminary tests

Firstly, laboratory-scale experiments were carried out to verify whether the passage of treated water from the full-scale WTP through the CRS bed would negatively affect the filtered water quality, e.g. altering the water pH. Also, the raw CRS contained a high fraction of fine aggregates (<0.075 mm) which might be leached and deteriorate the filter water effluent. The preliminary tests were carried out using a 2 L-glass measuring cylinder containing a water outlet, a false floor, 10 cm of support layer and 20 cm of CRS filter bed. Two 10 min-trials were undertaken, during which the influent and effluent waters were monitored every minute for pH, conductivity and turbidity.

Pilot tests

The two pilot filters were operated in parallel. Settled water from the full-scale WTP was conducted to the pilot filters by gravity and the flow rate was adjusted according to the desired filtration rates. Filters were operated with constant flow rate and variable water level above the filter bed. During the filter runs, head loss and the filtrate turbidity were monitored through the bed depth in each filter every two hours. Turbidity was analysed using a HACH 2100 AN turbidimeter. Filter runs ended either by limiting head (available head ≈ 180 cm) or breakthrough (filtrate turbidity >0.50 NTU – Brazilian standard (Brasil 2011)). Filters were then backwashed with treated water for 10 minutes with a suitable flow rate in order to achieve 33% bed expansion. Filtration rates were selected taking into account the upper threshold stated in the Brazilian standard for the design of drinking water treatment plants - 180 $m^3 m^{-2} d^{-1}$ (ABNT 1992), half (90 $m^3 m^{-2} d^{-1}$), 1.5 times (270 $m^3 m^{-2} d^{-1}$) and twice (360 $m^3 m^{-2} d^{-1}$) that value. Originally, an equal number of filter runs per filtration rate was intended to be carried out over both the dry and rainy seasons, but field constraints ended dictating the experimental plan, with 14 runs in total, as follows: (i) 12 runs over the dry season (raw water turbidity <20 NTU; settled water turbidity <1.0 NTU), one of them with a filtration rate of 90 $m^3 m^{-2} d^{-1}$, four with 180 $m^3 m^{-2} d^{-1}$, four with 270 $m^3 m^{-2} d^{-1}$, and three with 360 $m^3 m^{-2} d^{-1}$; (ii) two runs during the rainy season (raw water turbidity in the range of 20–200 NTU; settled water turbidity ranging from 2.0 to 5.0 NTU), one with a filtration rate of 270 $m^3 m^{-2} d^{-1}$ and the other with 360 $m^3 m^{-2} d^{-1}$ (the short duration of the rainy season explains the limited number of trials; the choice for high values of filtration rate was influenced by the promising results obtained over the dry season). All water quality analyses were performed according to Standard Methods procedures (APHA *et al.* 2005).

Filtration efficiency evaluation

NRS and CRS filters were compared regarding turbidity removal, head loss increasing rate and run length, under the same operating conditions of filtration rates and influent water quality.

RESULTS AND DISCUSSION

Filter media characterization

Table 1 shows the chemical composition of the two filter bed media. The NRS was composed of more than 90% silica, 5% aluminium oxides and smaller amounts of calcium, potassium, iron, sulphur and selenium oxides. Although in smaller amounts than in NRS, silica was also the major compound of the CRS (62.5%). In turn, CRS

Table 1 | Chemical composition of the filter bed media

Compound (%)	CRS	NRS
SiO_2	62.48	91.06
Al_2O_3	18.46	5.02
CaO	6.97	0.10
K_2O	4.96	1.32
Fe_2O_3	4.77	0.53
SO_3	1.46	1.60
TiO_2	0.72	ND
Ca_2O	ND	0.211
Sn_2O_3	ND	0.156
Others	0.18	0.02

ND: not detected.

showed higher amounts of alkaline materials, as lime (7%) and potassium oxides, as well as aluminium (18.5%) and iron oxides (4.8%). The higher iron oxides content gives CRS a dark-grey colour.

Table 2 shows the physical properties of the filter bed media. The CRS particles' density was slightly higher than that of NRS. Thus, it was necessary to apply higher backwashing flow rates to CRS in order to achieve the same 33% bed expansion as in NRS. The CRS filter was backwashed with a water velocity of 106 cm min^{-1}, as opposed to 94 cm min^{-1} in NRS, resulting in 13% more backwash water consumption.

Both materials presented similar sphericity coefficients. The CRS coefficient was slightly lower than that of NRS, hence CRS porosity was slightly higher than that of NRS. The CRS acid solubility was five times higher than that of NRS, probably due to the higher amounts of alkaline compounds (lime, potassium oxides) and iron oxides present in CRS. However, both materials presented acid solubility values lower than 5%, being then classified as suitable for filtration (AWWA 1998).

Filtration experiments

The influent water used in the preliminary experiments had the following characteristics (mean values): pH = 6.3; turbidity = 0.48 NTU; electrical conductivity (EC) = 83 μS cm^{-1}. The filter effluent was monitored during 10 minutes over two trials and no marked changes were noticed in the water quality: pH = 6.2–6.5; turbidity = 0.4–0.5 NTU; EC = 80–87 μS cm^{-1}. Subsequently, as described in the Material and Methods section, 14 filter runs were evaluated, covering different influent water quality (turbidity) and filtration rates. Worst-case scenarios in terms of filtration rate were selected to be highlighted here, along with an overview of the results as a whole: Run 8 (dry season) and Run 13 (rainy season), both operated with 360 $m^3\ m^{-2}\ d^{-1}$.

Table 2 | Physical properties of the filter bed media

Characteristic	CRS	NRS
Particles density (g cm^{-3})	2.72	2.64
Bulk density (g cm^{-3})	1.28	1.33
Porosity	0.53	0.50
Sphericity coefficient	0.77	0.82
Acid solubility (%)	1.16	0.22

Filter Run 8: influent water turbidity between 1.0 and 1.1 NTU

The results of Run 8 are shown in Figures 2–4. In both NRS and CRS filters, the filtration run ended due to limiting head, after 13 hours (i.e. there was no breakthrough). At the first 5 cm of the filter bed, the filtered water turbidity already presented values lower than 0.50 NTU for both filters (Figure 2). The remaining 40 cm reduced the filtered water turbidity from values slightly higher than 0.40 NTU to values between 0.24 and 0.30 NTU in the CRS filter, and between 0.25 and 0.31 NTU in the NRS filter. This trend was observed over the entire run, meaning that filtration took place, essentially, at the surface, leaving the bulk of the filter beds unused.

Usually, rapid-sand filters work with design filtration rates between 5 and 15 m h^{-1} (Crittenden *et al.* 2012). At high filtration rates, solids tend to penetrate deeper into the filter bed and the rate of head loss accumulation may be slower because of the more efficient use of the filter bed depth. However, according to the same authors, filter

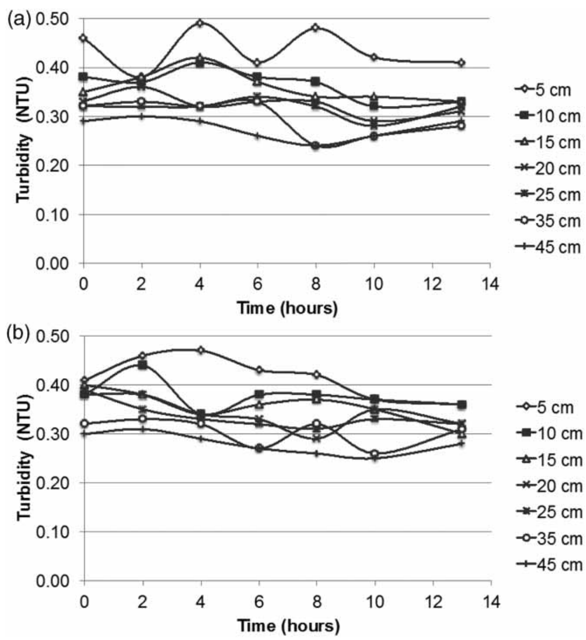


Figure 2 | Filtered water turbidity during filtration Run 8: (a) CRS filter (b) NRS filter.

effluent quality tends to get worse at filtration rates above 12.5 m h^{-1} (300 m^3 m^{-2} d^{-1}), specially with weak chemical flocs, such as alum floc without polymer. Filtration rates are often subject to regulatory limits and the current Brazilian standard for rapid down flow sand filtration is 180 m^3 m^{-2} d^{-1} (or 7.5 m h^{-1}). Despite the use of a filtration rate as high as 360 m^3 m^{-2} d^{-1} (or 15 m h^{-1}) in Run 8, the head loss increase was mainly due to particle accumulation in the first 5 cm of the filter bed, as presented in Figure 3, and no filtered water quality deterioration was observed. Both filters presented a similar behaviour during the run, with slightly higher head loss values being noted in the NRS filter.

Figure 4 summarizes the results of Run 8. Both settled (1.0–1.1 NTU) and filtered water turbidity (0.2–0.3 NTU) varied only narrowly through the filter run in both filters. Moreover, NRS and CRS filters presented a rather similar behaviour, both in terms of effluent water quality and head loss increase.

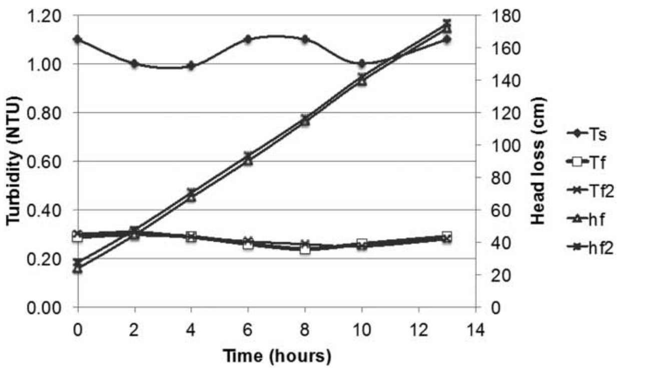


Figure 4 | Influent (settled) and effluent (filtered) water turbidity and total head loss during filtration Run8. Ts = settled water turbidity; Tf = filtered water turbidity (CRS); Tf_2 = filtered water turbidity (NRS); hf = total head loss (CRS); hf_2 = total head loss (NRS).

Filter Run 13: influent water turbidity between 2.4 and 5.0 NTU

The results of Run 13 are shown in Figures 5–7. Again, in both cases (NRS and CRS) the filtration run ended due to limiting head, after 20 hours. In spite of the higher influent water turbidity, the run length of both NRS and CRS filters was longer than those of the dry season trials with the same filtration rate of 360 m^3 m^{-2} d^{-1}. Figure 5 shows the filtered water turbidity along the filtration run for CRS and NRS filters. Differently from all the other runs, filtered water turbidity was higher than 0.50 NTU at the beginning, but after two hours CRS and NRS filters already produced filtered water with, respectively, 0.38 NTU and 0.49 NTU. As the filtered water samples were collected every two hours, it was not possible to identify clearly the filters ripening times, but looking at the filtered water turbidity data, it seems that the CRS filter had a shorter ripening period compared to the NRS filter. Afterwards (approximately from six hours of operation onwards) CRS and NRS filters steadily produced water with average turbidity values of 0.29 NTU and 0.32 NTU, respectively. In Figure 5, the gradual saturation of the first layers of the filters over time is noticeable; i.e. the increasing clogging of the first layers until both the influent and filtered water turbidity values were virtually the same. After 10 hours, in both filters, filtered water turbidity at 5 cm deep was the same as that of

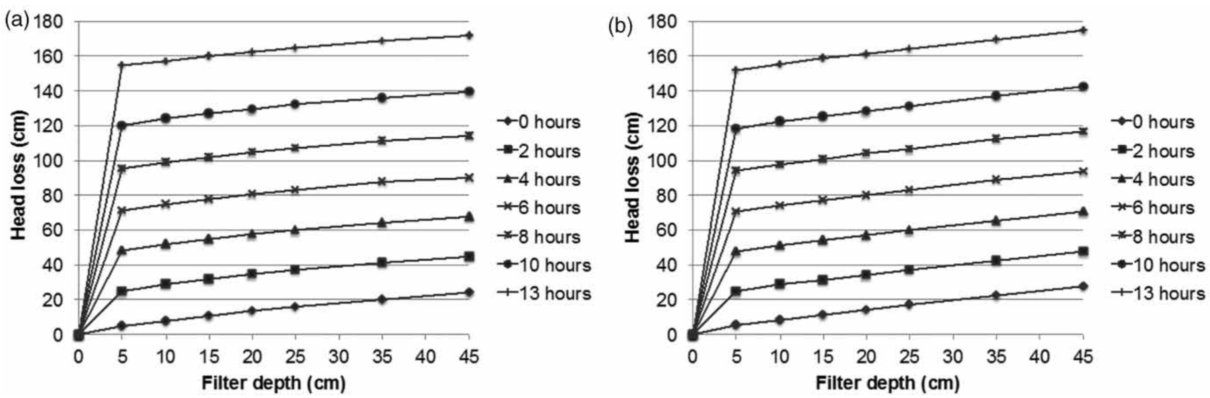


Figure 3 | Head loss increase along the filter bed depth and over time, filtration Run 8: CRS filter (left) and NRS filter (right).

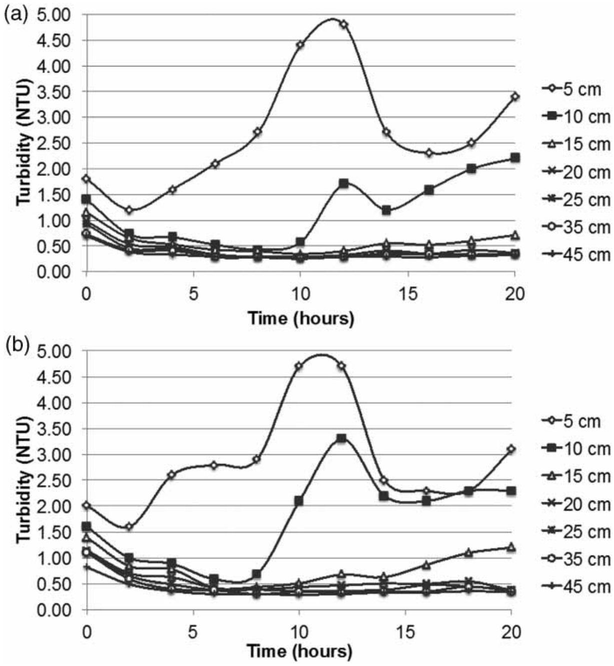


Figure 5 | Filtered water turbidity during filtration Run 13: (a) CRS filter, (b) NRS filter.

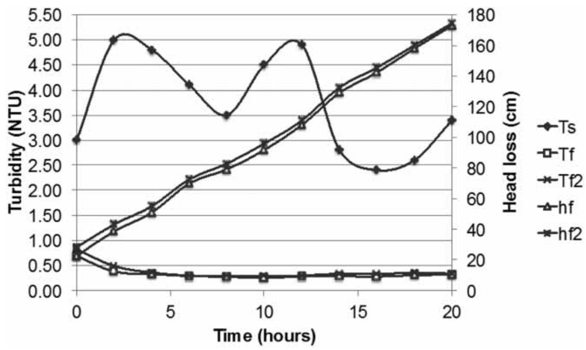


Figure 7 | Influent (settled) and effluent (filtered) water turbidity and total head loss during filtration Run 13; Ts = settled water turbidity; Tf = filtered water turbidity (CRS); Tf_2 = filtered water turbidity (NRS); hf = total head loss (CRS); hf_2 = total head loss (NRS).

the influent water; the same happened in NRS filter at 10 cm after 14 hours. Thus, depth filtration seems to have happened more clearly during this filtration run.

Figure 6 illustrates the head loss development along filter Run 13. Differently from the dry season trials, particles removed at deeper layers seem to have contributed to the head loss increasing along the filter bed depth: the head loss curves lose their parallelism in relation to the initial head loss curve (t = 0) at gradually deeper layers of the filter along the filtration run.

Results of Run 13 are summarized in Figure 7. The influent water presented relatively high turbidity values and wide variations during the filtration run. Even so, both filters showed an increasing efficiency over the first six hours (mainly in the first two hours of filter ripening), producing filtered water with turbidity around 0.30 NTU from there onwards. The NRS and CRS filters presented a similar behaviour during Run 13 regarding filtered water turbidity values and head loss increasing rates. However, differently from Run 8, particles removal took place at deeper layers resulting in a more efficient use of the filter bed and, consequently, in longer filter runs.

Overview of the filtration runs results

Table 3 summarizes the main results of all the 14 filtration runs. Run 5 was conducted with 90 $m^3 m^{-2} d^{-1}$, but due to

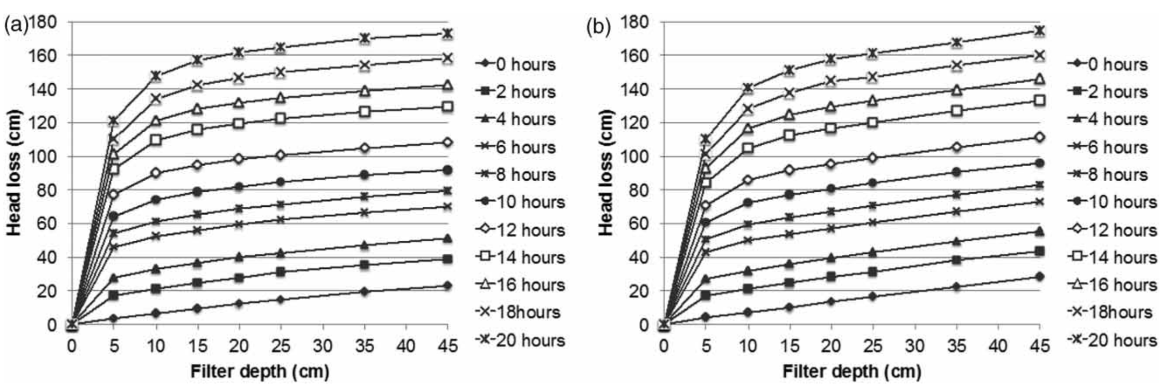


Figure 6 | Head loss increase through the filter bed depth and over time, filtration Run 13: CRS filter (left), NRS filter (right).

operational problems, this filtration rate was not tested anymore. Only three runs ended due to breakthrough (filtered water turbidity >0.50 NTU), all of them during the dry season trials. During Run 6 (360 $m^3\ m^{-2}\ d^{-1}$), breakthrough (filtered water turbidity = 0.51 NTU) occurred in both filters, at different moments of the run, but with the same head loss values. At a lower filtration rate (180 $m^3\ m^{-2}\ d^{-1}$) (Run 9), breakthrough (filtered water turbidity = 0.56 NTU) occurred only in the NRS filter.

The current Brazilian standard for filtered water turbidity is 0.50 NTU (for rapid filters) in 95% of collected samples (Brasil 2011). In addition, the filtered water turbidity must not exceed 1.0 NTU in any sample. Filtered water turbidity remained below 0.30 NTU (a rather strict standard, like those of the USA (USEPA 2006) and Canada (Health Canada 2017) drinking-water regulations)) in eight out of the 13 CRS filtration runs which ended due to limiting head loss, and below 0.50 NTU (the Brazilian standard) in the other five runs. Also, it is worth noticing that in the only CRS filtration run that ended because of breakthrough (Run 6), the Brazilian standard of 0.50 NTU was only slightly exceeded (0.51 NTU).

Table 3 shows that increasing the filtration rate from 180 to 360 $m^3\ m^{-2}\ d^{-1}$ did not affect the filtered water quality but reduced the average run length from 33.5 h to 13.7 h. However, during the rainy season the run length was around 20 h for both the 270 and 360 $m^3\ m^{-2} d^{-1}$ filtration rates; that is, six hours longer than the dry season runs, in spite of the higher influent water turbidity during the rainy season. This behaviour was observed for both filter media (CRS and NRS).

Over the rainy season (alum dose = 16–18 mg/L; pH = 6.7–7.0), sweep coagulation mechanisms may have taken place during the water pre-treatment in the full-scale WTP, combined with or even prevailing over charge neutralization (Ghernaout & Ghernaout 2012). Hence, coagulation may have produced more fragile flocs during the rainy season, when raw water turbidity was higher than in the dry season. In effect, in all the dry season trials (alum dose = 8–12 mg/L; pH = 6.3–6.9), regardless of the filtration rate, filtration seems to have occurred mainly at the filter bed upper layers, probably as a result of higher floc strength. Conversely, during the rainy season depth filtration seems to have more clearly taken place. Thus, due to a deeper

Table 3 | Main results of the filtration runs

		Run length (hours)		Total head loss (cm)		Influent water turbidity (NTU)		Filtered water turbidity (NTU)			
								CRS		NRS	
Run	Filtration rate ($m^3\ m^{-2}\ d^{-1}$)	CRS	NRS	CRS	NRS	Min.	Max.	Min.	Max	Min.	Max
1	270	16	16	155.2	157.0	0.60	1.20	0.16	0.30	0.19	0.25
2	270	12	12	153.4	155.6	0.59	0.76	0.17	0.25	0.18	0.25
3	270	15	15	173.9	174.0	0.51	0.74	0.12	0.16	0.13	0.17
4	270	16.5	16.7	173.8	174.0	0.57	0.88	0.14	0.17	0.14	0.17
5	90	86	86	156.9	156.7	0.74	1.00	0.14	0.20	0.14	0.20
6	360	13	12	149.3	150.8	1.10	1.30	0.29	0.51	0.28	0.51
7	360	14.3	14.3	172.7	174.7	1.00	1.50	0.31	0.39	0.31	0.42
8	360	13	13	171.9	174.6	0.96	1.10	0.24	0.29	0.25	0.30
9	180	35	22	174.1	122.2	0.78	1.10	0.25	0.42	0.29	0.56
10	180	31	31	173.8	174.4	0.80	1.10	0.26	0.38	0.27	0.43
11	180	30	31	173.3	174.5	0.62	1.10	0.17	0.28	0.21	0.31
12	180	38	36.5	174.1	174.5	0.51	0.88	0.13	0.27	0.14	0.27
13	360	20	20	172.9	174.5	2.40	5.00	0.25	0.38	0.29	0.49
14	270	20.5	20.5	176.0	173.5	2.10	4.40	0.27	0.48	0.30	0.48

penetration of the particles into the filter bed, the head loss accumulation rate was slower during the rainy season; consequently, the respective filter runs were longer, revealing a more efficient use of the filter bed during filtration runs with higher influent water turbidity.

As previously discussed, the main factors that affect rapid filtration performance are the influent water quality, filtration rate and filter bed characteristics. In this study, the filters were fed with the same influent water and the same filtration rate; moreover, some bed characteristics (e.g. size distribution and bed length) were practically identical. Thus, despite other differences between the filter bed materials (chemical composition, sphericity coefficients and porosity), the NRS and CRS filters presented similar filtration performances in terms of run length, filtered water turbidity and head loss increasing rate. Hence, the same filtration mechanisms supposedly took place in both filter media, mainly surface capture, known as the principal mechanism of in-depth filtration (Tobiason *et al.* 2010). Given that the grain shape of the filter media also affects particle capture and storage, and that angular particles are preferable to rounded particles, the crushed stone surface roughness may have favoured absorption characteristics, even better than the more rounded natural sand (Rao 1981; Tobiason *et al.* 2010). Summing up, given the suggestions presented herein of high treatment efficiency, the use of CRS as filter bed for rapid filtration in drinking water treatment should be encouraged. Nevertheless, further studies should be undertaken in order to evaluate the filtration efficiency based on other water quality indicators (e.g. colour and surrogates for pathogens such as bacteriophages and aerobic spore-forming bacteria), as well as with varied filter bed characteristics (e.g. depth and size distribution), operating conditions and filtration techniques, such as direct filtration, slow sand filtration or upflow filtration.

CONCLUSIONS

- Crushed rock sand (CRS) did not present harmful compounds and the CRS filter bed did not negatively affect the quality of the filtered water (turbidity, pH and electrical conductivity).
- Filtration run length, turbidity removal and head loss accumulation were similar in both the CRS and the natural sand river (NRS) filters.
- The CRS filter was able to steadily produce filtered water turbidity lower than 0.50 NTU, and often below 0.30 NTU, even with high filtration rates and relatively high influent water turbidity.

In conclusion, under the same operating conditions (similar filter bed media characteristics, the same filtration rates and the same influent water quality), CRS filter efficiency (run length, turbidity removal and head loss accumulation) was shown to be at least as good as that of the NRS filter.

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DATA AVAILABILITY STATEMENT

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

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