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ORIGINAL PAPER

Application of modified qualitative index for surveillance of water-filtration process in turbidity removal by different media

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Abstract Several media have been used in treatment plants, however, their efficiency for turbidity removal, which is determined by qualitative indices, has been considered. Current qualitative indices such as turbidity and escaping particle number could not completely measure the efficiency of the filtration system; therefore defining new qualitative indices is essential. In this study, the efficiency of two different dual media filters in turbidity removal was compared in different operating condition using qualitative indices. The pilot consisted of a filter column (1-m depth) in which the filter-1 was consisted of a layer of anthracite (450-mm depth) and a layer of silica sand (350-mm depth); and filter-2 had the same media characteristics except for the first layer that was light expanded clay aggregates (LECA). Turbidities of 10, 20, and 30 NTU, coagulant concentrations of 4, 8, and 12 ppm and filtration rates of 10, 15, and 20 m/h were considered as variables. Results showed that the media of filter-2 is a suitable substitute for the media of filter-1 (P value < 0.05). Turbidity removal efficiencies in different condition were 79.97 ± 1.79 to $91.37 \pm 1.23\%$ for the filter-2 and 75.12 ± 2.75 to $86.82 \pm 1.3\%$ for the filter-1. The LECA layer efficiency in turbidity removal was independent of filtration rates and due to its low head loss; LECA can be used as a proper medium. Results also showed that the particle index was a suitable index as a substitute for turbidity and escaping particle number as indices.

Keywords Anthracite · Dual media filter · Light expanded clay aggregates · Silica · Turbidity

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Introduction

The filtration processes are used primarily to remove particulate material from water. Filtration is one of the unit processes used in the production of potable water. Removed particulates may be those already present in water source or those formed during treatment processes (AWWA 2004; Baruth 2005; Taghizadeh et al. 2007). Examples of particulates include clay and silt particles; microorganisms (bacteria, viruses, and protozoan cysts); colloidal and precipitated humic substances and other natural organic particulates from vegetation decay; precipitates of aluminum or iron used in coagulation; calcium carbonate and magnesium hydroxide precipitates from lime softening; and iron and manganese precipitates (Davis 2010; Hammer 2011).

Selection of type and characteristics of filter media, that is the heart of a filtration system, is usually based on arbitrary decisions, tradition, or a standard approach. Pilot plant studies using alternative filter media and filtration rates can determine the most effective and efficient media for a particular water (Kawamura 2000).

The removal of suspended solids by the filter media involves two separate and distinct steps: transport of suspended particles to the solid–liquid interface presented by the filter and attachment of particles to this surface (Pawlowicz et al. 2006; Templeton et al. 2007). Some material already deposited on the medium can be detached due to increased shearing forces resulting from filter clogging. Straining becomes a dominant removal mechanism when the ratio of the particle size to media grain size is greater than 0.2 µm (Johnston 1999) and for the particles which are greater than 100 µm (Tansel and Vinal 2005; Devi et al. 2008). Straining is undesirable during granular media filtration, due to the formation of a surface layer, rapid head loss increase (Zouboulis et al. 2007). Filter ripening is the improvement of the removal efficiency with time after backwash. In this mechanism, retained particles provide additional removal possibility for the suspended particles. Although the particle size and distribution would change with the filter depth, the head loss within the filter is directly related to the surface area of captured particles (Brogowski and Renman 2004; Tansel and Vinal 2005; Roque-Malherbe 2007).

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The common types of media used in granular bed filters are silica sand, anthracite coal, and garnet or ilmenite (Mitrouli et al. 2009; Moazed and Viraraghavan 2002; Hatt et al. 2007). These may be used alone or in dual- or triple-media combinations; a number of properties of a filter medium are important in affecting the filtration performance and also in defining the medium. These properties include size, shape, density, and hardness. The porosity of the granular bed formed by the grains is also important (Moazed and Viraraghavan 2002; AWWA 2004).

Many studies have been done on filters media for enhancing treated drinking water (El-Taweel and Ali 2000; Melin et al. 2000; Babu and Chaudhuri 2005; Pawlowicz et al. 2006).

In general, turbidity is considered as a common index for filtration efficiency determination; however, this index is weak for the particles with 1–10 µm diameter including pathogen microorganisms. Along with the escaped particle number (EPN), turbidity is used to control filtration efficiency, nevertheless these indices are not satisfactory (Kawamura 2000).

Some studies have been conducted to evaluate the performance of filter media on removal of different pollutants from water and wastewater (Templeton et al. 2007; Devi et al. 2008; Remize et al. 2009; Fuerhacker et al. 2011; Ho et al. 2011). In these studies, however, no efficient indices have been applied to evaluate the performance of filter media and to compare the efficiencies of different media.

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Materials and method

Filter

The pilot used in this study consisted of several units such as artificial turbidity injector, chemical coagulant injector and flash mixer, coagulant, flow meter, two dual-media filters with anthracite–silica and LECA–silica media, and filter backwash. Details have been shown in Fig. 1.

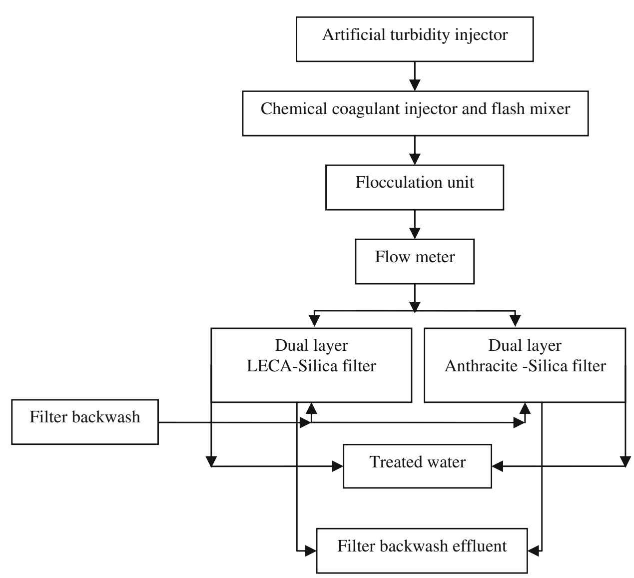


Fig. 1 Pilot diagram of dual media anthracite–silica and LECA–silica filters

Artificial turbidity injector

This unit was consisted of a turbidity stock solution tank and stable height tank for water storage with specified turbidity to inject in the next unit. The stock solution tank was made of polyethylene with total and net capacity of 80 and 50 L, respectively, and equipped with a 1,450 rpm electromechanical mixer and a dosing pump for injecting turbidity solution to a stable tank. The stable height tank was made of polyethylene with 500-L capacity and equipped with an afloat, a 1,450 rpm electromechanical mixer and a globe valve. The municipal drinking-water pipe was connected to this tank and stock turbidity solution with a specified dose was straightly injected to the tank such that the final solution had a stable turbidity. By means of a globe valve, the effluent of this tank was conducted to the chemical coagulant injector and flash mixer.

Chemical coagulant injector and flash mixer unit

This unit was consisted of a flash mixing tank, a variable rate mixer and a mixer wing (shovel). The flash mixing tank was made of Plexiglas with a quadrangle section and 15.6-L capacity and special actions were done to prohibit short circuiting. The mixer used for this tank was a variable rate with average 1,450 rpm having two-blades shovel flat wing and the 4:1 length to width ratio. In regard to retention time and velocity gradient in mixing tank, the mixing rate used in this study was 250 rpm.

Flocculation unit

This unit is consisted of three parts including flocculation tank, the variable rate mixer and mixing wing. The flocculation tank was made of polyethylene with a net volume of 300 L having a 0–650 rpm variable rate mixer.

Flow meter unit

The flow meter used in this study was consisted of a Plexiglas tank having inlet, regulator, flow conductor to filter and backwash water effluent parts. A 30^o triangle-channel section was used to regulate the quantity of water entered to filters and excess water was collected by a separate pipe. The considered water quantities of this study for each filter were 5.24, 7.86 and 10.48 L/min yielding filtration rates equal to 10, 15 and 20 m/h (m^3/m^2 h), respectively.

Dual media filter

Filters used in this study had several parts including filter column, filtration-rate regulator, head-loss monitoring system, and filter media. To explain filters that were used in this study, the detailed specifications were noticed in the next section.

Filter column

Filter columns were made of Plexiglas with 200-mm internal diameter and 2-m height. The column diameter was selected to decrease the effects of column walls on the filter efficiency. The filter column was consisted of two 1 m columns that were joined and sealed by means of some flanges made of column materials. The required instruments such as head loss measurer, sampling valves and backwash accessories were installed properly.

Filtration rate regulator

The filtration rate regulator used in this study was a stable head and quantity type. For obtaining this condition, a 120 L tank and a floated valve were used. By artificial head creation in the length of filter, this tank provided head and outlet quantity stability. In effect, the stability of filtration rate was achieved.

Head-loss monitoring system

For measuring the head loss in filter columns, seven manometers and a manual gauge were used in each filter. Table 1 shows manometer depths that were installed on filter column.

Filter media

Filter media in filter-1 was consisted of one layer of anthracite with 450-mm depth and one layer of silica sand with 350-mm depth. Filter-2 had the same media characteristics except for the first layer that was LECA. A support layer of silica gravel with 200-mm depth was also used in each filter. The detailed specification of filter media has been shown in Table 2.

Table 1 Manometer depths of filter columns

Manometer no.	1	2	3	4	5	6	7
Depth from bed surface (cm)	10	20	30	40	55	70	80

Table 2 Filter media specifications

No.	Media type	Layer depth (mm)	Uniformity coefficient	Effective size
1	LECA	450	≈ 1	2.14
	Silica	350	1.4	0.9
2	Anthracite	450	≈ 1	2.14
	Silica	350	1.4	0.9

Backwash accessories

The backwash method of this study was up flow water wash with air scour. By application of AWWA related equation (AWWA 2004), water quantity for filter backwash was determined 35 L/min. The backwash system was similar for both filters. For uniform distribution of water and air currents in backwash phase, a Plexiglas plate with 3 mm pores was installed in the bottom of the filter, and was also wrapped by aluminum net to prevent particle escaping. In backwash phase, water and air currents were entered to the filter by two independent pipes with 1 and 0.5 in. diameter, respectively. The backwash phase was continuing until the system head loss reached 200 mm, and backwash effluent was gathered at the end of the phase.

Sample characteristics

Inlet turbidity, coagulant concentration and filtration rate were the most important variables of this study. The inlet turbidity was produced by adding clay of 200 meshes. In addition, ferric chloride was used as the coagulant agent.

In this study, turbidities of 10, 20, and 30 NTU, coagulant concentrations of 4, 8, and 12 ppm and filtration rates of 10, 15, and 20 m/h were considered as variables. The filtration rates of 10 and 15 m/h were chosen as filtration rates of water treatment plants and the 20 m/h for critical conditions. Coagulant concentrations were selected by jar test and based on different inlet turbidity. All operating conditions adjusted similarly for both filters to compare the considered filters better.

Sampling methods and analysis

Samplings were done from 30-cm depth of LECA and anthracite layers of both filters for efficiency determination of those media, and at the water outlet for efficiency determination of total system. Samples were gathered from 1-mm diameter valves to prevent a turbulence condition in filter media. Head-loss measurements were done in sampling valves.

All sampling methods and analysis were done in accordance with the standard methods for the examination of water and wastewater (APHA 2005). Samples turbidities were measured by portable turbidity meter HACH-2100 and the escaping particles were analyzed by diameter measurer LATS-1 (ASTM 1994). This study was conducted within about 1 year based on several variables. All samples were gathered after backwash phase and during 0–17 h after filter operation. The maximum head loss for backwash phase in each filter was 160 cm (20 cm for system head loss and 140 cm for operation head loss).

Statistical analysis

To compare the efficiency of the media on turbidity removal (in different condition), statistical analyses of analysis of variance (ANOVA) and *t* test were used (P value < 0.05) (Berthouex and Brown 2002).

Results and discussion

Tables 3 and 4 show the outlet water turbidities in 30 cm and final depth of each filter, respectively. As can be seen, standard deviations of turbidity averages were high in lag and breakpoint operation phases, however, they were more proper in stable phase due to stability of filters operation and efficiency. Table 5 shows the removal efficiencies of turbidity in 30 cm and final depth of filter beds in the stable phase.

Table 3 Outlet water turbidities in 30-cm depth of filter beds

Inlet turbidity (NTU)	Coagulant con. (ppm)	Filtration rate (m/h)	Operation time (h)	Outlet water turbidity (NTU)			
				Anthracite filter		LECA filter	
				During stable phase	During total operation phase	During stable phase	During total operation phase
10	4	10	18	0.99 ± 2.48	2.79 ± 3.73	2.2 ± 0.97	3.33 ± 2.63
		15	11	1.54 ± 2.77	2.87 ± 4.01	1.96 ± 1.08	3.21 ± 2.7
		20	8	1.55 ± 2.22	3.07 ± 3.72	1.85 ± 1.58	3.29 ± 3.03
20	8	10	9	0.69 ± 2.4	6.5 ± 7.42	1.75 ± 0.65	6.12 ± 5.27
		15	8	0.54 ± 3.17	7.07 ± 7.95	2.79 ± 1.1	6.17 ± 5.02
		20	6	0.56 ± 3.17	5.5 ± 9.6	2.74 ± 0.52	6.31 ± 3.65
30	12	10	6	0.25 ± 3.68	8.4 ± 9.83	2.33 ± 0.68	6.45 ± 5.75
		15	5	1.58 ± 4.23	11.0 ± 11.6	2.85 ± 1.85	8.75 ± 8.28

Table 4 Outlet water turbidities in final depth of filter beds

Inlet turbidity (NTU)	Coagulant con. (ppm)	Filtration rate (m/h)	Operation time (h)	Outlet water turbidity (NTU)			
				Anthracite filter		LECA filter	
				During stable phase	During total operation phase	During stable phase	During total operation phase
10	4	10	18	0.21 ± 0.17	0.06 ± 0.1	0.12 ± 0.05	0.16 ± 0.14
		15	11	0.18 ± 0.19	0.05 ± 0.1	0.09 ± 0.05	0.18 ± 0.2
		20	8	0.27 ± 0.3	0.01 ± 0.15	0.18 ± 0.05	0.31 ± 0.23
20	8	10	9	1.73 ± 1.79	0.20 ± 0.47	0.4 ± 0.1	1.51 ± 1.53
		15	8	2.26 ± 1.86	0.10 ± 0.35	0.42 ± 0.07	1.3 ± 1.45
		20	6	1.75 ± 2.34	0.12 ± 0.82	0.51 ± 0.21	1.79 ± 1.59
30	12	10	6	2.6 ± 2.63	0.06 ± 0.33	0.24 ± 0.1	1.82 ± 1.54
		15	5	2.72 ± 3.44	0.59 ± 1.18	0.62 ± 0.26	2.57 ± 1.83

Table 5 Outlet water turbidity efficiencies in 30 cm and final depth of filter beds in stable phase

Filer type	Depth (cm)	Inlet turbidity (NTU)	Efficiency (%)
LECA filter	30	10	79.97 ± 1.79
		20	87.87 ± 2.92
		30	91.37 ± 1.23
	80	10	98.67 ± 0.46
		20	97.77 ± 0.30
		30	98.56 ± 0.90
Anthracite filter	30	10	75.12 ± 2.75
		20	84.43 ± 3.42
		30	86.82 ± 1.30
	80	10	98.84 ± 0.29
		20	97.29 ± 1.22
		30	97.48 ± 2.00

Head losses of LECA and anthracite layers were 16.59 ± 1.1 and 25.5 ± 1.45% (of total head losses of systems), respectively. These head losses were stable in different turbidities and filtration rates (P value < 0.05).

Head losses consideration showed that head losses of LECA and anthracite layers with 40-cm depth were 16.59 ± 1.1 and 25.5 ± 1.45% (of total head losses of systems), respectively. These head losses were changed slightly in different turbidities and filtration rates. These variations were 14.75 ± 1.26 to 17.68 ± 2.2 for LECA layer and 23.4 ± 1.8 to 26.99 ± 1.98 for anthracite layer.

Other indices for filter efficiency evaluation considered were the EPN and the PI which was calculated by multiplying the EPN to particle diameter (PD) (Eq. 1).

$$\mathrm{PI}\ (\mathrm{N}\,\mu\mathrm{m}) = \mathrm{PD}\ (\mu\mathrm{m}) \times \mathrm{EPN}\ (\mathrm{N}) \quad (1)$$

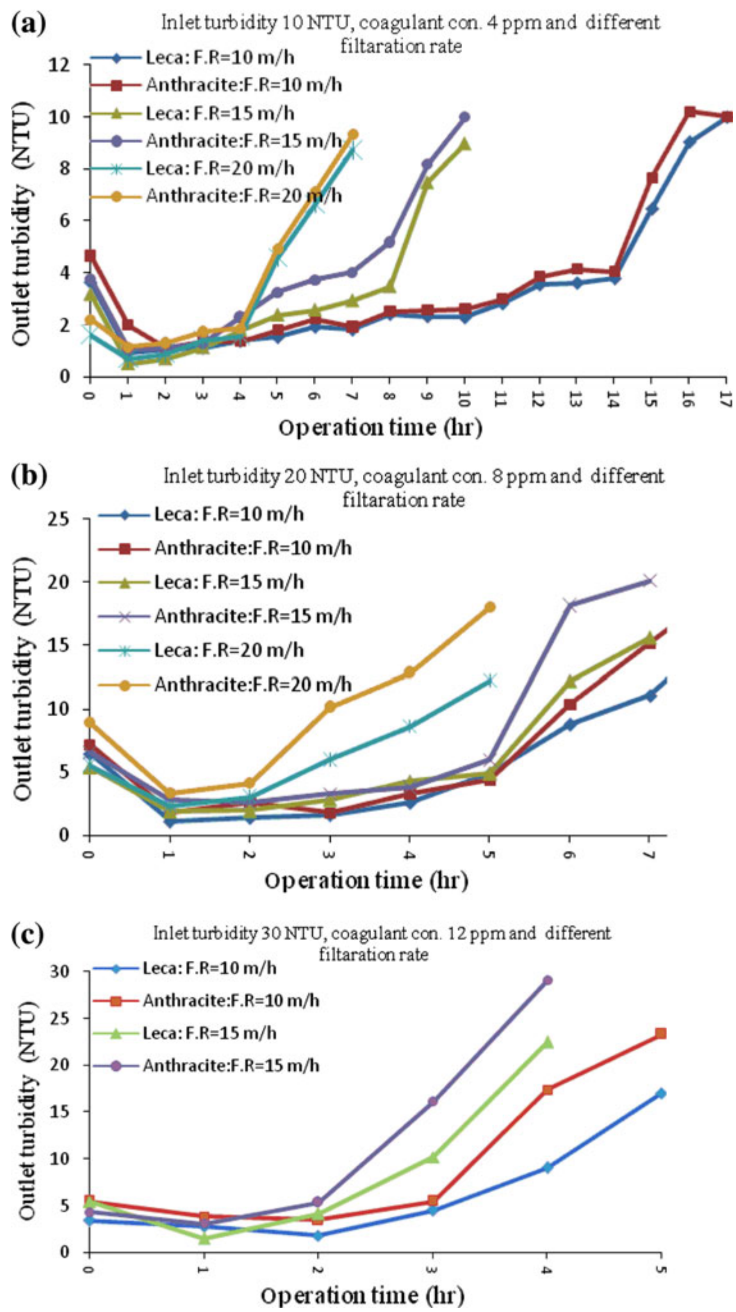
These indices were used, because, escaped particles from filter are related to the outlet water quality, while the inlet turbidity was stable. In other words, the less number and diameter of the escaped particles, the more removal efficiency of filters were achieved. Therefore, the EPN and PI were suitable indices. According to American drinking water standards (AWWA 2004), the allowable particles in drinking water are 50/mL with diameter limit of 2–10 μm. Thus, the PI is between 100 and 500 N μm/mL. The average of the EPN is more than 300/mL corresponding to 99.99% Giardia and Cryptosporidium removal. Therefore, unlike the turbidity and EPN indices, the PI index is suitable for filter efficiency determination. Table 6 shows simultaneous comparison of turbidity, the EPN and the PI for LECA and anthracite filters. As can be seen, turbidities and the EPN are in standard range while the PI is more than them.

Results of Table 5 show that anthracite and LECA layers, specially the first 30-cm depth of those, had considerable effects on turbidity removal (79.97 ± 1.79 to 91.37 ± 1.23% for LECA layer and 75.12 ± 2.75 to 86.82 ± 1.3% for anthracite layer in stable phase). It seems that LECA layer efficiency was slightly more than anthracite layer in turbidity removal, although the one-way ANOVA test shows no significant differences between these layers efficiencies (P value < 0.05) in turbidity removal. By comparison of different operating condition (turbidity and filtration rate) of LECA and anthracite layers by paired sample t test, it was deduced that the LECA layer efficiency had significant differences with turbidity changes while filtration rate could not affect turbidity removal of this layer (P value < 0.05). Besides turbidity, the filtration rate has also affected the efficiency of the anthracite layer in rates of 10 and 15 m/h. It means that although the LECA layer can be operated in different filtration rates without any efficiency failure, its efficiency may be decreased in different turbidities (10, 20 and 30 NTU). Mitrouli et al. (2008) have shown that the performance of

Table 6 Simultaneous comparison of turbidity, particle number and new index for LECA and anthracite filters

Inlet turbidity (NTU)	Filtration rate (m/h)	Operation time (h)	LECA			Anthracite		
			Outlet turbidity during operation phase (NTU)	EPN (N/mL)	PI (N × μm)	Outlet turbidity during operation phase (NTU)	EPN (N/mL)	PI (N × μm)
10	10	6	0.18	33	621	0.11	10	303
	10	11	0.17	29	514	0.12	13	326
	10	13	0.15	38	814	0.06	15	355
	15	8	0.15	48	807	0.12	21	347
	15	1	0.15	17	428	0.14	39	623
	20	3	0.14	37	604	0.16	24	591
	20	4	0.19	38	821	0.16	38	494

Fig. 2 Outlet turbidities of the filters in 30-cm depths in different condition



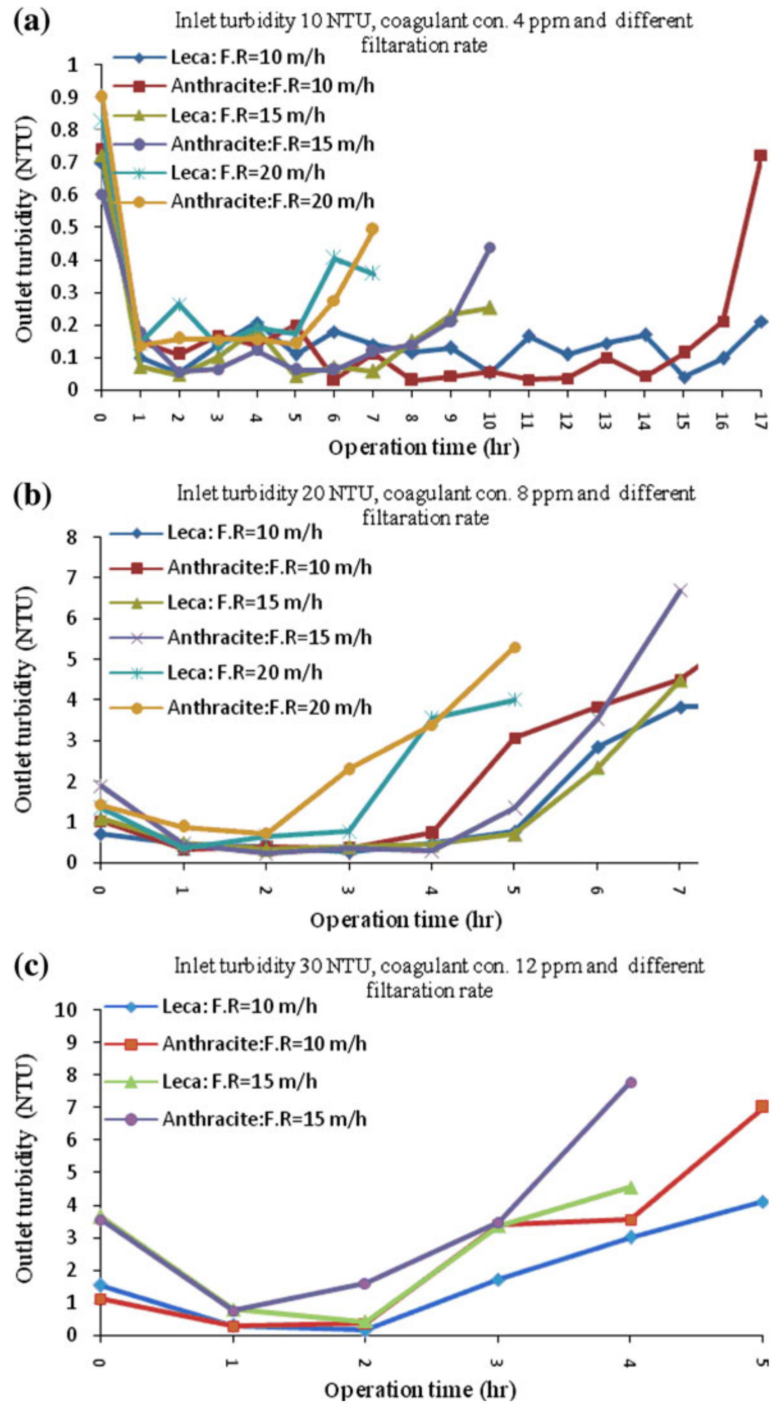


Fig. 3 Outlet turbidities of the whole depths of filter columns in different condition

the anthracite layer for sea-water filtration, in the filtration rate of 5 m/h, was significantly better than that of 10 m/h. Furthermore, the turbidity removal in the total depth of two filter columns had not significant changes and the efficiency of the total system for mentioned phase was 97.77 ± 0.30 to 98.67 ± 0.46% for the LECA column and 97.29 ± 1.22 to 98.84 ± 0.29% for the anthracite column. These tables show the efficiency of silica layer and proportion of each layer in the turbidity removal. Hence, LECA and anthracite layers play an important role in turbidity removal. However, the filtration cycle of the anthracite layer was broken after 22 h (head losses of 60 cm) (Templeton et al. 2007).

Figures 2 and 3 illustrate outlet turbidities of each filter in 30 cm and whole depths of filters column in different conditions. These figures show that the stable phases of filter operation were decreasing when the filtration rates were increasing. Moreover, with increase in the inlet turbidity, the stable phases of filter operation decrease and outlet turbidities and lines slope increase.

Results of filters head losses in different condition of turbidities and filtration rates showed that with increasing operation period and filtration rate in stable turbidity, head losses were increased nonlinearly. As well, the LECA layer in comparison with the anthracite layer caused less head loss and more turbidity removal efficiency in the filter column. Hegazy (2008) reported that the LECA layer could be a proper media for filtration process, the performance of which is independent of the filtration rate.

Outlet turbidities, the EPN and the PI in whole depths of filter columns in different conditions are shown in Figs. 4 and 5. In some cases, the outlet turbidity was in standard condition while the EPN was more than standards and it shows that the turbidity index was not enough for filter efficiency determination. These figures obviously show that while the outlet turbidity was in standard range, the EPN was not low and also diameter distribution of particles was inconsistent; thus, using the EPN without consideration to their diameter effect is useless.

The PI can be used as a suitable index. By analyzing the graphs, it can be concluded that with increase in the considered index, filters reached stable and breakpoint phases. Moreover, with increase or decrease in the EPN and the PI, filters reached the stable and breakpoint phases, respectively. However, when the outlet turbidity was in standard ranges, the PI may not be less than 300/mL and this condition shows again that the turbidity and the EPN were not solely enough for the determination of filter efficiency. The PI and its cumulative values were used for comparing LECA and anthracite filters' efficiencies (Fig. 6). It is

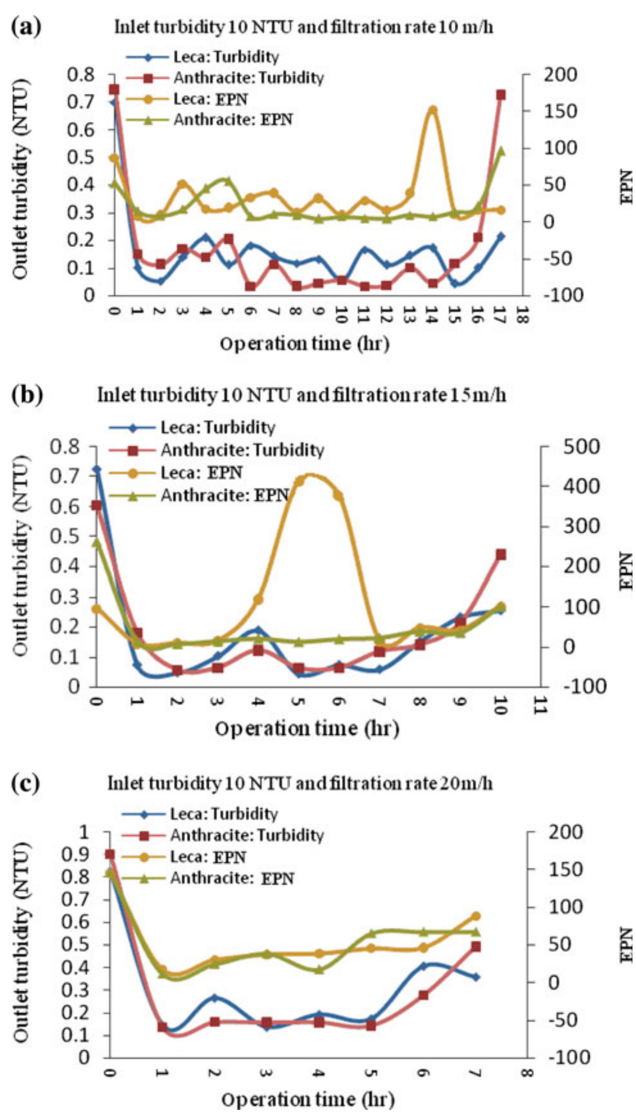


Fig. 4 Outlet turbidities and the EPN in whole depths of filter columns in different condition

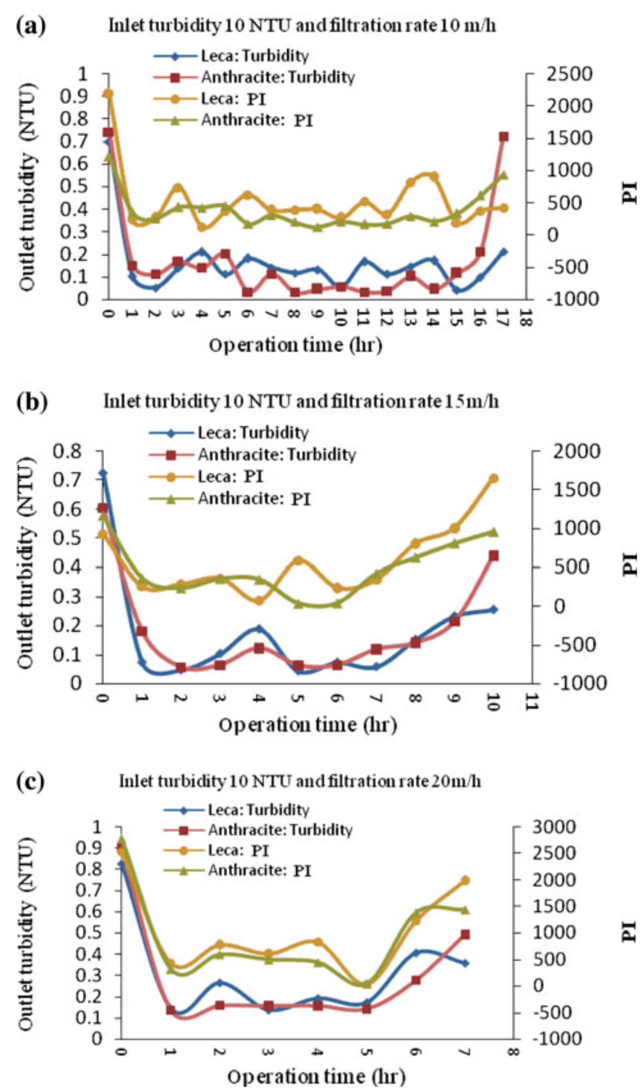


Fig. 5 Outlet turbidities and the PI in whole depths of filter columns in different condition

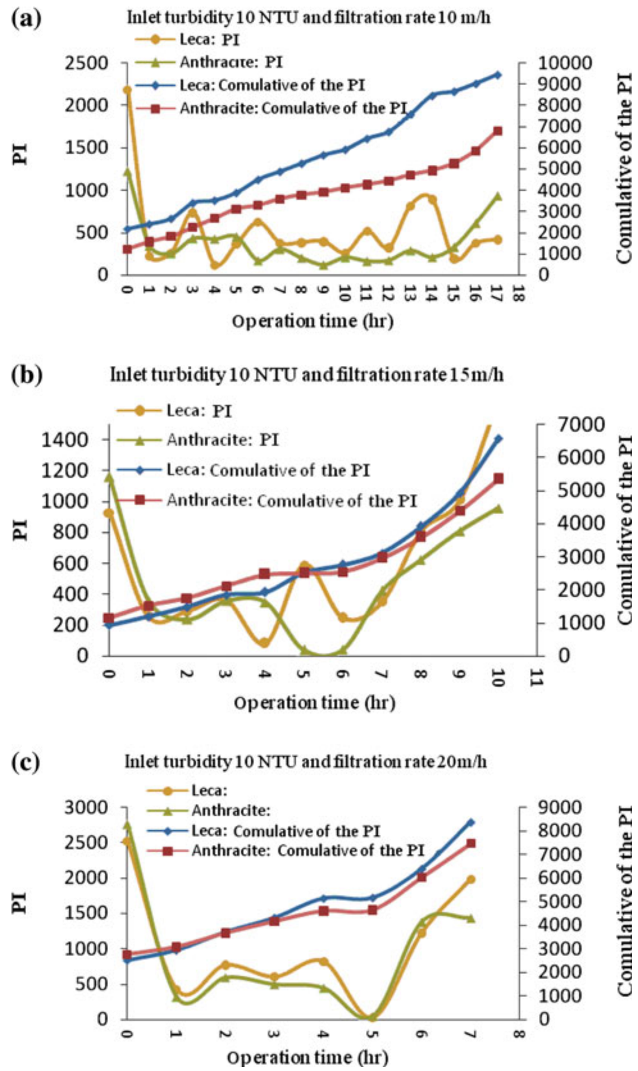


Fig. 6 The PI and its cumulative values in whole depths of filter columns in different condition

obvious that for lesser PI, higher filtration efficiency is obtained. As shown in Table 6, the turbidity and/or EPN may be in standard range while the PI is more than standards. Thus, it can be concluded the PI is suitable for determination of filter efficiencies.

Conclusion

Application of proper media for the filtration process of water-treatment plants and precise determination of their performance and efficiency has been considered. This study shows that the LECA–silica media had significant efficiency in turbidity removal in compare with anthracite–silica media, in different operating condition. The LECA layer was independent from filtration-rate effects and played the main role in turbidity removal. The PI index could be properly applied as a qualitative index for determining the efficiency of filters turbidity removal instead of the EPN and turbidity, due to its more precise changes during filtration period, and therefore, better determination of breakpoint phase of the filter.

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