Desalination and Water Treatment
www.deswater.com
doi:10.5004/dwt.2017.20862

79 (2017) 221–227
June

Assessment of a roughing filtration as a pre-treatment for slow sand filtration of canal water with highly variable feed water turbidity

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Received 14 August 2016; Accepted 9 March 2017

ABSTRACT

The slow sand filtration plant (SSF) that produce drinking water for the refugee camp at Aqbat Jaber in Jericho (Palestine) is taken out of operation frequently during the rainy season due to the excessively high feed water turbidity. To allow continuous operation of SSF, the suitability of a pre-treatment process based on 4 layer upflow roughing filters (RFs), with optional coagulation using ferric chloride, was assessed at filtration rates of 0.5 and 1.5 m/h. The RFs without coagulant addition, at both filtration rates, effectively reduced turbidity of feed water from about 90 NTU to <20 NTU. Lower filtration rate resulted in lower filtrate turbidity. The major turbidity removal was attained in the bottom 20 cm layer of the filter column. Very high turbidity of feed water (800–1000 NTU) could be reduced to values acceptable for SSF (<20 NTU) with coagulation supported RF (Fe^{3+} dosage 9 mg/L) that operated at filtration rate of 0.5 m/h.

Keywords: Roughing filter; Pre-treatment; Slow sand filtration; High turbidity; Coagulant

1. Introduction

In comparison to other water treatment technologies slow sand filter offers advantages in terms of simple operation and maintenance, and the high quality of produced treated water, making it an attractive technology for small to medium communities in developing countries and remote locations [1]. In spite of that, its application is limited by the required low raw water quality. High turbidity levels can reduce the efficiency and/or duration of the filtration run [2]. Presence of colloidal and suspended matter in feed water to SSF, even when turbidity is <20 NTU, can result in relatively fast clogging with the associated need to clean slow sand filters by removing a few centimetres of the top filter bed layer [3]. In addition to the interruption of the plant operation during the cleaning process, that typically takes several days, a ripening period of several days to weeks is required after each cleaning cycle to produce filtrate of acceptable quality. Therefore, a pre-treatment is essential for slow sand filtration when turbidity of raw water can exceed 10–20 NTU [4].

Roughing filters have often been employed as pre-filters to remove large portion of suspended solids, and, to consequently prolong the run time of slow sand filters between two cleaning cycles [3–6]. Roughing filters can operate in up flow, or horizontal mode. Upflow filters were found more efficient compared to horizontal filters [7]. Filter media height and composition, number of filter steps or layers, type and size of media, and feasible filtration rate are the main process parameters of a roughing filtration [2,8,9].

Some studies reported under performance of roughing pre-filtration, which is attributed to presence of colloidal particles in the feed water [6,8,10]. Filtration theory, based on impaction probability calculations, suggests that colloidal particles (i.e. <1 μm) would be less efficiently removed than larger particles [10]. One possibility to improve performance of roughing filtration, when raw water contains col-

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loidal particles, is to consider the addition of coagulants in the feed water [6,11,12]. Coagulation enhanced roughing filtration is called direct roughing filtration. Dorea and Clarke [2] demonstrated that chemically enhanced roughing filters were more efficient (93.2–99.5 %), in terms of turbidity reduction, than conventional roughing filters (50.6–79.3%). It has been reported that surface water sources in arid countries experience high seasonal variability of turbidity [6,7].

The only one surface water treatment plant (WTP) in Palestine provides drinking water to the Aqbat Jaber Refugee Camp, nearby Jericho, with approximately 7000 inhabitants. The main water supply system for the camp originates from raw water coming from Al-Qilt and Al-Fawwar-Springs, which is conveyed through an open 13 km canal, to the Aqbat Jaber WTP. Raw water from springs is of very good quality during the dry season; however, during the rainy season (November to March) raw water occasionally has very high turbidity, with values occasionally exceeding 1000 NTU. The WTP at AqbatJaber includes 2 slow sand filters. An automatic on line turbidity meter is installed on the raw water supply line, that automatically stops raw water supply to slow sand filters,when raw water turbidity exceeds 20 NTU. Under such conditions, the drinking water supply to the camp is interrupted for several days.

This research aim was to screen suitability of (direct) upflow roughing filters, with layers of graded gravel, as a pre-treatment step for SSF at the WTP Aqbat Jaber with highly variable feed water turbidity.

2. Materials and methods

2.1.Upflow roughing filters set up

A pre-treatment based on upflow roughing filtration was selected having in mind reported higher efficiency of this treatment, and also availability of a concrete slow sand filter that can be used for the future RF unit. Two upflow roughing filters (RF1 and RF2) were installed and operated in parallel at the Aqbet Jaber WTP site (Fig. 1). The RF columns were made of PVC with 0.25 m in diameter and 1.70 m effective height, filled with 4 gravel layers of different size fractions (Table 1). Four sampling taps and piezometer tubes were installed at the end of each filter media layer for sampling and head-loss measurements. Filters were operated in parallel at constant filtration rates of 0.5 and 1.5 m/h, in agreement with recommendations made by Wegelin [5]. In total 6 filter runs were conducted with pilot roughing filter plant. Filter runs were designed to assess reproducibility of results achieved with two filter columns, and to study the effect of filtration rate and addition of coagulant using feed water of variable quality.

2.2. Operation of roughing filters

Process conditions applied in five filter runs conducted with the pilot RF columns are summarized in Table 2. The roughing filters were operated under gravity. The flow to each pilot column was measured by rotameters, and controlled by hand operated needle valves. Acidic coagulant stock solution was pumped from the 5 L storage PVC vessel, and mixed with feed water with a help of static mixers upstream the RFs entrance points (Fig. 1). The coagulant

Table 1
Filter media composition of pilot roughing filter columns

Layer (from bottom to top)	Layer height (cm)	Gravel size (mm)
L1	20	12–20
L2	50	8–12
L3	50	6–10
L4	50	3–6

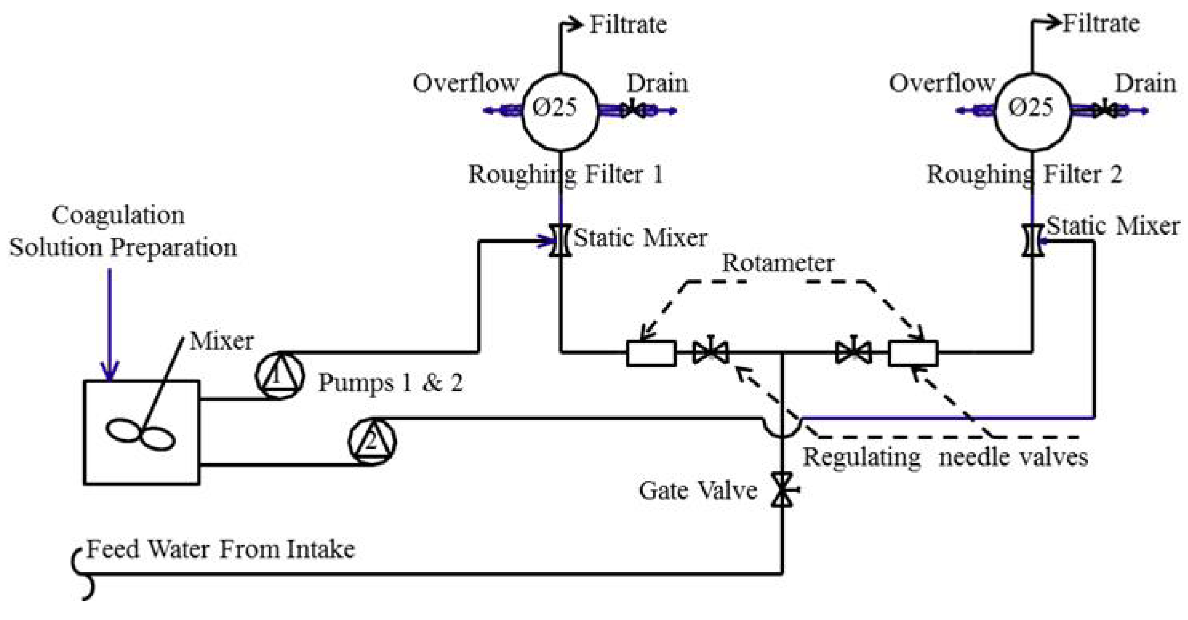

Fig. 1. Sketch of the pilot roughing filter plant.

Table 2
Experimental conditions applied in filter runs with the roughing filters pilot plant

Run no.	RF in operation	Feed water				Filtration rate (m/h)	Coagulant dose (mg Fe^{3+}/L feed water)	Length of each filter run (h)
		Type	Turbidity (NTU)	pH	Temp. (°C)			
1	RF1	Canal water	25–75	8.3	11	0.5	0	8
2	RF1	Canal water	35–75	8.4	16	0.5	0	8
	RF2	Canal water	35–75	8.4	16	0.5	0	8
3	RF1	Canal water	25–87	8.1	10	1.5	0	24
	RF2	Canal water	25–87	8.1	10	0.5	0	24
4	RF1	Canal water	0.0–4.0	8.4	26	1.5	0	288
	RF2	Canal water	0.0–4.0	8.4	26	0.5	0	288
5	RF1	Spiked canal water	950	8.1	25	0.5	9	14
	RF2	Spiked canal water	950	8.1	25	0.5	0	14

dose was based on the optimum dose obtained in jar tests (*see the supplementary section*). Feed water and filtrate samples were collected at regular time intervals from sampling points installed along the RF columns. As the roughing filters (RFs) were operated in upflow direction, the sampling point for each layer with different grain size fraction was positioned directly at the top of that layer, to allow assessment of the performance of each RF media layer. Cleaning of pilot RF columns was performed at the end of each filter run, by opening the drainage valve at the column bottom. Due to the cleaning (draining) of pilot filters, pilot filters were dry (without water) at the start of the next run. The first samples were consequently taken only 3 h after the start of a filter run, when regular flow was established in both pilot filters. Turbidity, pH and temperature of freshly taken samples were measured at the site during all runs.

2.3. Feed water quality

Water used in RF columns: In the filters runs 1 to 4 canal water was taken directly from the raw water supply pipeline of the existing full scale WTP Aqbat Jaber, and used as feed water for pilot RF columns. In filter run 5, turbidity of natural raw canal water was increased by spiking soil deposits from the main open raw water transport open canal, which is deposited during (extreme) rain events. It was assumed that such model water (modified natural raw water) will adequately mirror the nature of raw water during extreme rain events. It was assumed that model water prepared in this way will mirror real canal water with high turbidity found during strong rain events. The spiked water was prepared by bringing feed canal water to a holding tank, where soil deposits collected from the raw water canal were added to simulate the targeted turbidity level. Performance of RF columns using feed water of very high turbidity was studied to assess potential of this pre-treatment to allow operation of the full scale plant SSFs even under extreme feed water quality.

2.4. Coagulation system

Ferric chloride ($FeCl_3$) was used as a coagulant. A stock coagulant solution was prepared by dissolving 100 g of $FeCl_3 \cdot 7H_2O$ in 10 L demineralised water. Concentrated HCl was used for pH correction of demineralised water before addition of $FeCl_3 \cdot 7H_2O$, to keep pH below 2. Prepared stock solution was stored in dark at room temperature. A peristaltic pump was used to introduce targeted coagulant dosage to feed water to pilotroughing filters. Effective mixing of the raw feed water and coagulant was achieved with a help of static mixers (Komax, USA).

2.5. Analytical methods

Turbidity was measured with the turbidity meter (Hanna turbidity meter HI 93703). pH measurements were carried out using Metrohm-691 pH meter. Concentration of total Fe was determined using DR/890 HACH colorimeter.

2.6. Statistical analysis

Statistical comparisons of means was followed by “Paired samples *t*-test” for the measured turbidity of the two roughing filters using the SPSS program for windows, version 20.0 [13], with P value < 0.05 considered significantly different.

3. Results and discussion

The results of the RF pilot plant runs are presented in the below sub-sections.

3.1. RF performance screening (Run No. 1)

As a preparatory experiment designed to examine technical performance of the pilot column and to preliminary screen the performance of RF pre-treatment, one pilot filter column was operated at a filtration rate of 0.5 m/h. Raw water turbidity during the run was between 25 and 75 NTU. Throughout the 8 h long filter run,filtrate turbidity ranged from 0 to 3.8 NTU (Fig. 2), corresponding to overall average removal efficiency of 97% (94–100%).These preliminary results strongly suggest that, under the given process conditions,RF is very effective pre-treatment method. The results of this and other filter runs reveal that removal

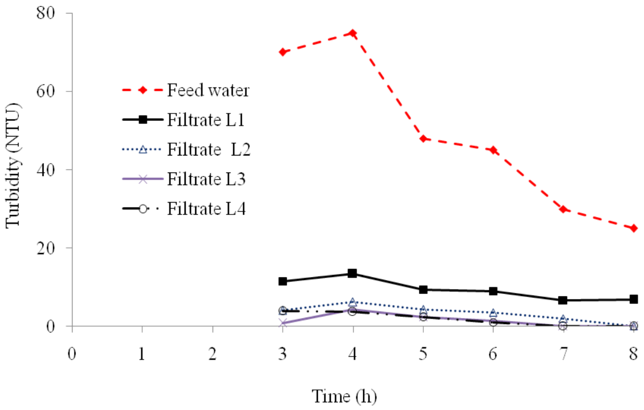

Fig. 2. Turbidity removal profile in the pilot roughing filter treating canal water; Filtration rate 0.5 m/h, no coagulant addition, L1 (bottom) to L4 (top) represent sampling points along the depth of the column.

occurs mainly in the bottom gravel layer (sampling point L1, Table 1), which is attributed to preferential removal of larger and heavier particles earlier in the filter in an up flow condition, leaving only the finer particles to travel deeper in the filter bed, which is indicative of deep bed filtration [8].

3.2. Similarity of two pilot roughing filters (Run. No. 2)

The two roughing filter pilot columns were operated in parallel under identical conditions at filtration rate of 0.5 m/h. The feed raw canal water turbidity, that was supplied to both columns varied from 35 to 75 NTU, which is typical turbidity range observed after rain events (Fig. 3). The filtrate turbidity from both filter column was found to be very similar, and remarkably low (close to zero), even without any coagulant addition. Results obtained show that two pilot roughing filter columns can be used for parallel operation and comparison of different process conditions.

3.3. Effect of filtration rate (Run No. 3)

The two roughing filter columns were operated in parallel, one at filtration rate of 0.5 m/h, and the other at 1.5 m/h. Turbidity of feed water was in the range 25–87 NTU. Both roughing filter columns consistently produced filtrate turbidity of less than 20 NTU throughout the whole filtration run (Fig. 4). The pilot RF that operated at lower filtration rate of 0.5 m/h resulted in lower filtrate turbidity (2–9.8 NTU) compared to the RF operated at 1.5 m/h (2.4–15 NTU).

It was also observed that very high efficiency of turbidity removal was consistently achieved at relatively high filtration rate of 1.5 m/h, even without any coagulant addition, e.g. 82% at the highest raw water turbidity of 87 NTU.

The major turbidity removal was attained in the first gravel layer of the filter column (Fig. 4). Further turbidity removal was achieved in the subsequent filter layers with finer filter media. Fig. 4 also reveals that performance of roughing filters improves during initial hours of filter run, and remains rather stable over the prolonged filter run. Filtrate turbidity, remained consistently <20 NTU throughout the filter run of both filters. No increase of filtrate turbidity

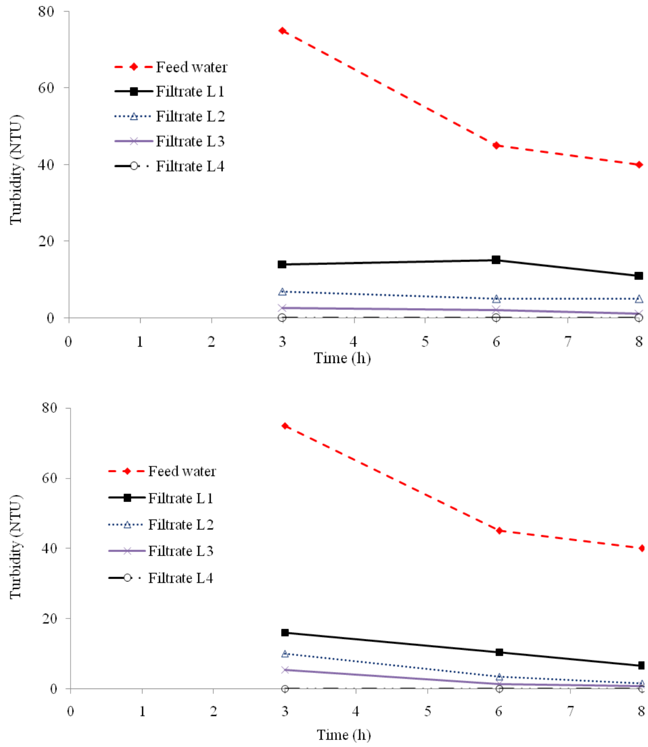

Fig. 3. Turbidity removal achieved with two pilot roughing filter columns, treating canal water; filtration rate 0.5 m/h, no coagulant addition.

was observed for both columns till the end of the run, suggesting that filter runs much longer than 24 h are likely possible without cleaning the filter. In general results emerging from this filter run confirmed reliable performance and robustness of this pre-treatment process.

3.4. Performance of roughing filtration in longer filter runs (Run No. 4)

The two filters were operated continuously for 12 d in order to assess their performance during longer period. Raw water turbidity during this filter run was rather low (1–4 NTU) and consequently no coagulant addition was required. Turbidity of filtrate from both RFs that operated at 0.5 m/h and 1.5 m/h over the whole filter run was extremely low, practically below the detection limit of the turbidity meter used, directly after the first gravel layer. Though the pre-treatment of raw water with turbidity levels ≤ 4 NTU is not necessary, results obtained suggest that the incorporation of RF will prolong the operation period of sand filters between two cleaning cycles. The very long filter run of roughing filters without any sign of turbidity breakthrough, and without any filter cleaning also demonstrated that this unit has very high capacity to store colloidal and particulate matter.

3.5. Treatment of model water with extremely high turbidity (Run No. 5)

An additional filter run study with the roughing filter pilot plant aimed to assess the capability of this process to treat water with very high turbidity, similar to values occasionally observed in practice. Turbidity of spiked natural raw water that was used as feed to roughing filters was within the range 800–1000 NTU. Both filter columns were operated at the same filtration rate of 0.5 m/h, one with, and the other without coagulant addition. In feed water to a one pilot filter column 9 mg Fe^{3+}/L was introduced. Fig. 5 shows that both filters achieved effective turbidity removal, however, required turbidity level of <20 NTU was achieved only with the RF column that treated coagulated raw water during the initial 8–9 h of filter run. Further extension of filter run resulted in rapid deterioration of filtrate quality with turbidity levels of approximately 110 NTU after 14 h. High turbidity of feed water was accompanied with strong increase of head-loss, and frequent flow adjustments were required.

The turbidity of filtrate from the column with no coagulant addition was within the range 160–180 NTU through-

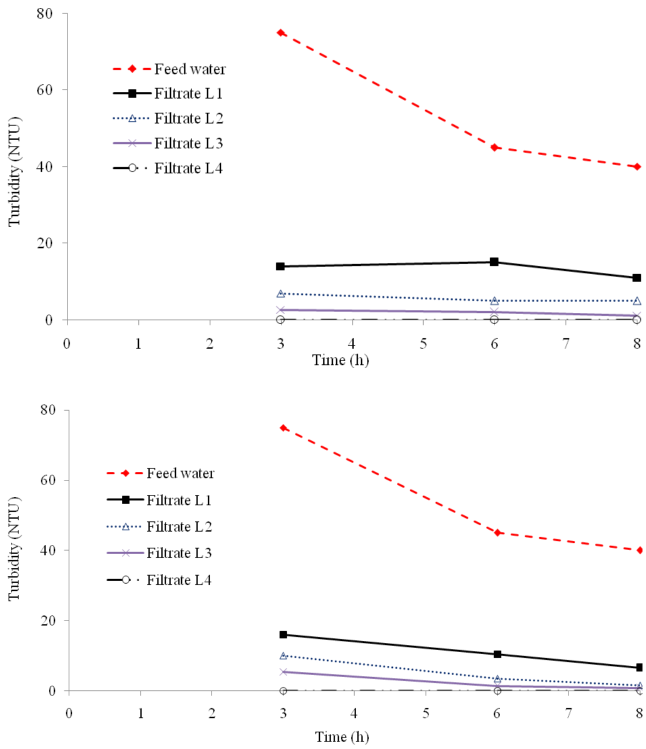

Fig. 4. Feed water and filtrate turbidity for two pilot roughing filter columns treating canal water; filtration rate: 0.5 m/h (top) and 1.5 m/h (bottom); no coagulant addition.

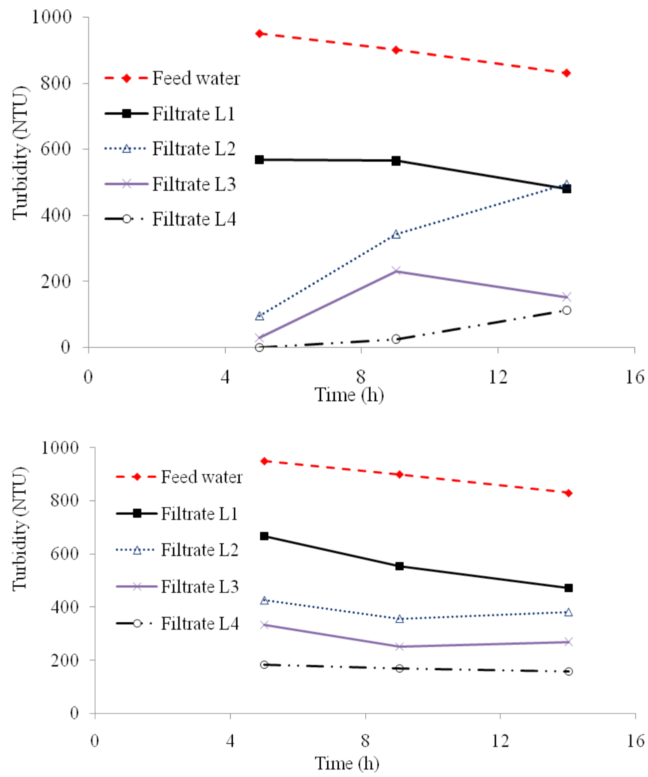

Fig. 5. Feed water and filtrate turbidity for two pilot roughing filter columns treating canal water. Feed water: raw canal water with spiked turbidity; Filtration rate 0.5 m/h; 9 mg/L Fe^{3+} added to feed water (left); no coagulant addition (bottom).

Table 3
Treated volume considered as volume of filtrate that achieved the target turbidity of less than 20 NTU in the roughing filters pilot plant during the experimental runs

Run no.	RF in operation⁺	Feed water type	Filtration period that achieved the treated volume (h)⁺⁺	Treated volume (L)⁺⁺
1	RF1	Canal water	>8	>196
2	RF1	Canal water	>8	>196
	RF2	Canal water	>8	>196
3	RF1	Canal water	>24	>1752
	RF2	Canal water	>24	>588
4	RF1	Canal water	>288	>21024
	RF2	Canal water	>288	>7056
5	RF1	Spiked canal water/ with coagulant	9	221
	RF2	Spiked canal water/ without coagulant	0	0

⁺: see Table 2
⁺⁺>: means that at the end of the filter run, filtrate turbidity remained below 20 NTU

out the whole filter run. Even though very high turbidity removal efficiency was achieved (>82%), quality of produced filtrate exceeded the feed water turbidity for SSF. Addition of coagulant presumably resulted in agglomeration of fine particulate and colloidal matter, and associated higher removal efficiency. Relatively fast turbidity breakthrough of the filter treating coagulated water is likely due to rapid clogging of the filter pores by retained flocs that caused an increase of flow velocity in filter voids, and resulted subsequently in reduced separation efficiency. In addition high flow velocity in partially blocked filter media possibly also resulted in re-suspension of a part of earlier separated flocs and hence turbidity breakthrough.

Under conditions applied, no rapid blocking of RF units that could lead to reduction of the capacity was observed. This is likely a consequence of selected filter media composed of four coarse to fine gravel size fractions (Table 1). Turbidity measurements clearly showed that majority of impurities were retained in the first layer with rather coarse gravel (12–20 mm) that consequently has large capacity to store impurities, while other 3 layers had a polishing function with associated limited head loss development. Strong increase of filtrate turbidity (breakthrough) during a filter run was only observed in the run with extremely high turbidity (900–1000 NTU) in combination with coagulant dosing. Such high turbidity levels of raw canal water are not very common, and, if present, have very short duration.

3.6. Assessment of residual iron in filtrate water

Iron content in the canal water was below the detection limit (0.01 mg/L).Analysis of residual iron in filtrate from the RF pilot column with 9 mg/L of Fe^{3+} dosage showed highest measured Fe concentrations of approximately 1.20 mg/L. Given the high pH of feed water iron passing filtrate was present as Fe^{3+} in colloidal form. Although it is expected that iron escaping the roughing filter column will be very effectively removed by slow sand filtration, presence of iron could contribute to clogging of both RF and SSF [2]. Addition of coagulant to the roughing filter feed water, though very effective for turbidity removal, should be minimized to periods with extremely high turbidity of raw canal water, to avoid such a problem in SSF performance. Further field (pilot) experiments including both RF and SSF are required to verify beneficial effect of coagulation supported RF.

4. Conclusions

Under the applied conditions, roughing filtration without coagulant addition, operated at filtration rates of ≤1.5 m/h, demonstrated a potential to very effectively reduced raw water turbidity of ≤90 NTU to low levels (≤20 NTU), that are suitable for direct feed to SSF. RF operated at lower filtration rate of 0.5 m/h achieved higher turbidity removal efficiency.

At extremely high feed water turbidity levels, *ca*. 800-1000 NTU, coagulant addition and low filtration rates, e.g. 0.5 m/h, are required to produce treated water with turbidity levels <20 NTU. Filter runs will, however, be short due to both high turbidity in raw water and coagulant addition.

Addition of a coagulant could result in elevated residual iron level in the filtrate of roughing filter. Addition of coagulant should consequently be as low as possible, and limited to periods of extremely high turbidity events.

Results from pilot column experiments under field conditions, and specifically very effective turbidity removal strongly suggest that RF is very robust and simple technology that can be considered to extend filter run time of SSF between two cleaning cycles. It is also expected that RF pre-treatment will prolong operation of SSF during the year including (a part) of the rainy season, when turbidity of raw water is too high for direct application of SSF.

Acknowledgment

This research was supported by the Dutch Government. The technical support provided by the Palestinian Water Authority and UNRWA is highly appreciated.

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Supplementary data

Seventeen sets of jar tests were conducted at the Birzeit University laboratory and at the Aqbat Jaber WTP to assess the need for coagulant (ferric chloride $FeCl_3$) dosing, and to establish an indicative dosage required.

Jar tests experimental setup

Addition of coagulant (ferric chloride $FeCl_3$) was followed by rapid mixing at 100 rpm for 1 min. The stirring speed was subsequently reduced to 35 rpm, and the slow mixing was continued for 15 min. The mixers were subsequently turned off, and water in jars allowed to settle for 30 min. Turbidity and pH were measured in samples taken from the upper half of jars. Due to the difference in separation step, results from jar tests cannot be directly extrapolated to performance of RF, but can still provide a useful indication. It is expected that results from jar test under-estimate the optimal dosage, having in mind that in addition to sedimentation, responsible for removal of particulate matter in jar test experiments, other removal mechanisms like mechanical straining and adsorption also play in RF.

Feed water quality

Water used in Jar tests: Raw water was taken from the feed canal at the Aqbat Jaber treatment plant during rainy season with turbidity that ranged from 20 to ≥ 1000 NTU.

Jar test results

The required coagulant doses, defined as doses just adequate to reduce turbidity to ≤ 20 NTU, the maximal turbidity level acceptable for slow sand filtration [4], are presented in Table S1. No coagulant was required to achieve turbidity of ≤ 20 NTU when turbidity of raw water was < 40 NTU. With the minimal coagulant dosage applied of 3 mg Fe^{3+}/L, turbidity of settled water was much lower than targeted value of 20 NTU, when the raw water turbidity was within the range 40 to 240 NTU. It may be consequently concluded that required (optimal) coagulant dosage to achieve turbidity of < 20 NTU is likely < 3 mg Fe^{3+}/L for raw water with turbidity ≤ 240 NTU. Further increase of raw water turbidity resulted in proportional increase of required coagulant dosage. It should be, however, noted that, due to different removal mechanisms of particulate and colloidal matter, direct extrapolation of results from jar tests to performance of roughing filter is not necessarily always reliable. It may be further argued that removal efficiency in roughing filters will expectedly be higher given the fact that in addition to sedimentation other removal mechanisms (e.g. mechanical straining, adsorption and chemical interactions) contribute to overall removal efficiency. Consequently, coagulant dosages required to achieve targeted quality of filtrate of roughing filtration will likely be lower than values suggested by jar tests.

Table S1
Optimum Fe^{3+} coagulant dose to reduce canal turbidity to < 20 NTU established in jar test experiments

Turbidity Canal water	Optimum dose (mg Fe^{3+}/L)
30–40	0
40–240	< 3
240–800	3–6
800–1000	6–9