

Application of roughing filter to pre-treat 1,000 NTU raw water for slow sand filter

Yuichi Hashimoto*, Hiroshi Takashima and Somasundaram Jayamohan

Water & Energy Development/Project Management Dept., Oriental Consultants Global, Tokyo Opera City Tower 9F, 3-20-2 Nishisinyuku, Shinjyuku-ku, Tokyo 163-1409, Japan

*Corresponding author. E-mail: hash-488@ocglobal.jp

Abstract

It was confirmed experimentally that a Roughing Filter (RF) is effective as a pre-treatment system for Slow Sand Filter (SSF) with coagulant dosing and mixing with raw water. This RF system can pre-treat high turbidity raw water (1,000 NTU) to generate low turbidity (10 NTU) pre-treated water for SSF treatment. In the experiment, the types of filter media, height of the filter media, filtration rate and coagulant dosing were varied and the characteristics of each item were evaluated and the design guidelines were formulated. Water Treatment Plants (WTPs) consisting of pre-treatment with RF followed by SSF to treat river water were designed and constructed in Myanmar based on the design guidelines, and the operational performance was confirmed as effective to generate treated water with a turbidity under 5 NTU, which is in compliance with the WHO guideline despite the rather short working period of about one year. Sand scraping of SSF at a frequency of about once in every one to two months was implemented to maintain the design filtration rate.

Key words: model experiment, plastic media, roughing filter (RF), slow sand filter (SSF), treating river water, turbidity removal

INTRODUCTION

This study was conducted to design the pre-treatment facility necessary for purifying river water by Slow Sand Filtration (SSF) treatment process in Myanmar. For applying SSF, it is necessary that turbidity of raw water generally be less than 10 Nephelometric Turbidity Units (NTU) in order to prevent clogging of slow sand filter media (Wegelin 1996). The quality of river water generally satisfies this condition in the dry season, but in Myanmar there are cases when the turbidity increases to 500–1,000 NTU during the rainy season. Consequently, river water purification by SSF generally becomes difficult, such that Rapid Sand Filtration (RSF) is then adopted in many cases. However, if a pre-treatment system for SSF can reduce the raw water turbidity to less than 10 NTU with reasonable construction and Operation and Maintenance (O&M) cost and the required area for the facility can be secured, then SSF can be applied even when a river is used as the water source. A roughing filter (RF), generally composed of three-stage tanks mostly using gravel filter media with upward-flow, is commonly utilised as the pre-treatment for the SSF.

References for RF to pre-treat high turbidity raw water of 1,000 NTU are not available yet, although some reports on treating raw water up to 500 NTU are available with plastic media among other media (Wegelin 1996; Kapranis 1999) and with coagulant dosing (Mahvi 2004; Mwiinga *et al.* 2004). There

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are operational cases using RF with gravel media that encountered clogging by sediments while pre-treating high-turbidity water and the water treatment plant (WTP) eventually stopped operation. In order to adopt the combination of RF and SSF, it is necessary to demonstrate that stable water purification to pre-treat 1,000 NTU turbidity raw water to attain less than 10 NTU pre-treated water with easy maintenance including the washing of filter media is practical. However, we understand that the design criteria satisfying these aspects are not yet currently developed and demonstrated.

In this study, we conducted experiments with RF model tanks by varying the RF performance factors to identify the efficiencies, and we prepared RF design guideline as well as maintenance guidelines so as to obtain stable water purification with easy maintenance.

The use of coagulant agents in SSF pre-treatment is reported as effective in reducing turbidity, though it is cited that sand filter surface is clogged when water containing floc or uncoagulated components flowed to the SSF (WA-Links 2018), and also the use of coagulant agents hinders the growth of microorganism and damages the biological treatment function of SSF (Arakawa *et al.* 2014). Therefore, operation and maintenance method is prepared considering these aspects so as not to affect the SSF operational performance.

WTPs consisting of the pre-treatment with RF and SSF to treat river water were designed and constructed in Myanmar based on the design guidelines, and their performance were confirmed as effective. Due to simplicity of the system and the use of less mechanical and electrical equipment, the combination of RF and SSF has advantages compared to RSF with respect to: (1) simpler design, (2) easier construction, (3) easier maintenance, and (4) more economical in operation and maintenance. Hence, this system is recommended for water treatment when sufficient land for the building of a water treatment plant can be secured.

METHODS OF THE EXPERIMENTS

The experimental setup for the RF model tanks are shown in Figure 1. The experiments were conducted with varied RF filter media (material and size), height of the filter, number of stages, filtration rate, and coagulant dosing.

RF model tanks were prepared with water tanks for delivery (volume: 20 L, diameter: 25 cm). The water used for the experiments was public water being supplied to the capital of Myanmar, Nay Pyi Taw and also well water. The pH of the water was around 7. The test raw water was prepared using clay collected in Nay Pyi Taw to obtain predetermined turbidity water. Turbidity was measured using a portable turbidity meter (Sato TU-2016).

Raw water was sent using an orifice so that a fixed amount of water flowed through RF model tanks with upward flow. Filtration rate applied in RF generally amounts to 7.2–36 m/d (AWWA 1991). Out of the 42 experiments, 40 of these were conducted with flow rate of 36 m/day and 2 experiments were conducted with 24 m/day.

Alum available in Nay Pyi Taw was used as coagulant.

As filter media, plastic, gravel and coconut fibers were used. The plastic filter media was prepared by cutting commercially available corrugated flexible pipes produced for cable cover pipe or drain water pipe (low-density polyethylene (PE) material with specific gravity of 0.9 and thickness of 0.5 mm) so as to have the same length as the pipe diameter. Experiments were carried out on four kinds of PE media with diameter of 12 mm, 19 mm, 25 mm and 32 mm (hereinafter called 'PE12 mm'). Since PE media float in water, nets were installed above and below the filter media so as to prevent flow-out. The plastic cylinder media was applied to high speed filtration study for sewage (Ishii & Morita 2005).

For gravel filter media, spherical gravel of 5–10 mm and 10–20 mm was used (hereinafter called 'G5–10 mm'). When using the gravel media, G20–40 mm was laid as the base to facilitate uniform upward flow over the entire RF model tank section.

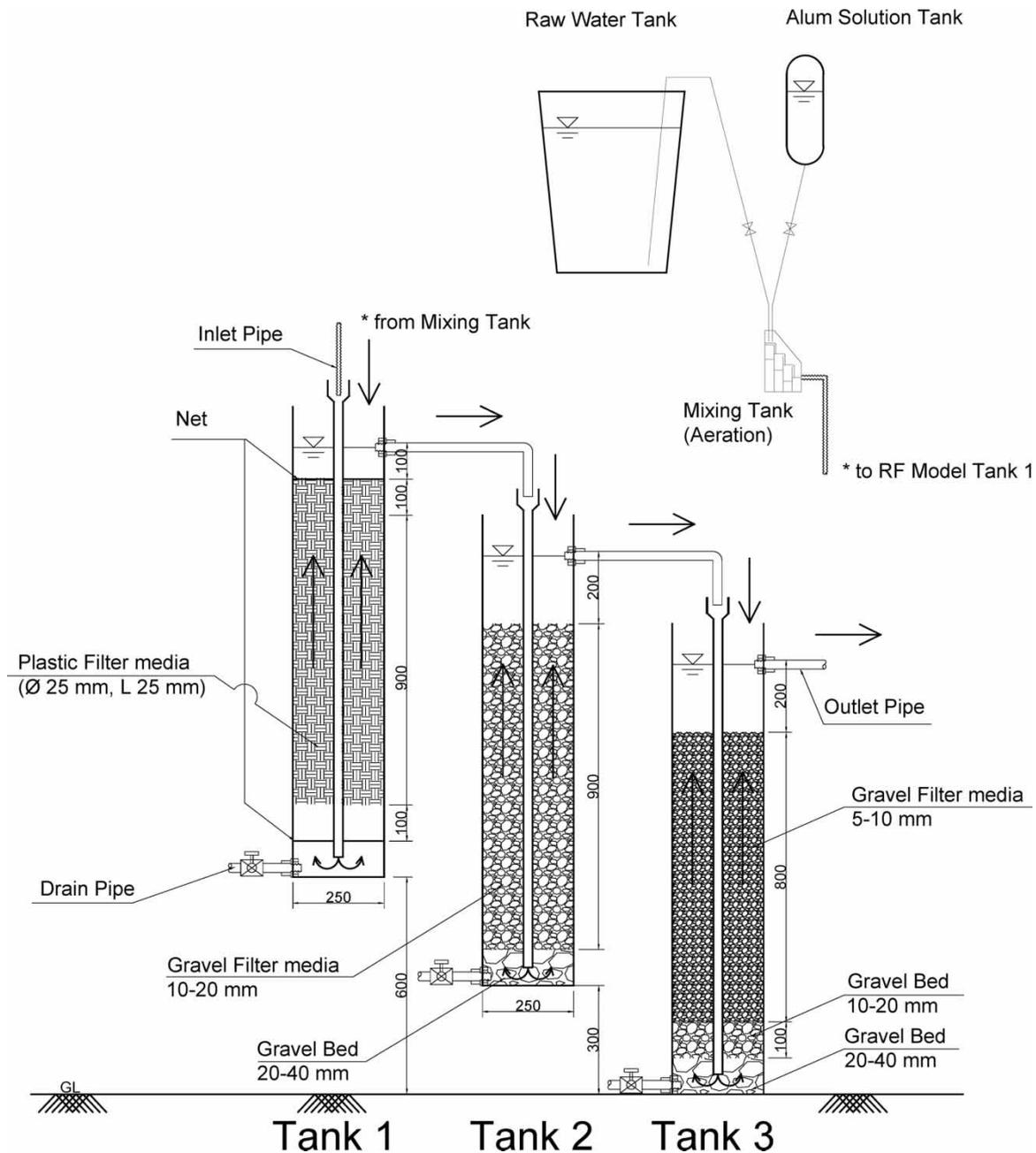


Figure 1 | Roughing Filter (RF) Experimental Model Used for Test 23.

Experiments were conducted with RF model tanks having the filter height of 30 cm, 60 cm and 90 cm, and the number of RF model stages utilised was not only one-stage, but also two-stage and three-stage series. In the experiments, turbidities of raw water and pre-treated water for each RF model tank were measured with elapsed time, and the turbidity removal performance of each RF model tank was examined.

RESULTS OF THE EXPERIMENTS AND DISCUSSIONS

All test results

Extracts of all 42 experimental test results showing Test No., RF performance factors, measured turbidity and turbidity removal efficiency are shown below. [Figure 2](#) summarises the extracts of

1) Test No.	Test 3	Test 5	Test 11	Test 12	Test 19	Test 20	Test 21	Test 23	Test 26	Test 27	
2) Flow Rate	36 m/day	24 m/day	36 m/day								
3) Alum Dose	60 mg/L				0 mg/L	60 mg/L	70 mg/L	80 mg/L	0 mg/L		
4) Filter Height	300 mm		600 mm	900 mm							
5) Filter Media	Tank 1	PE12 mm			PE25 mm			G10-20 mm	PE25 mm		
	Tank 2	PE19 mm		PE12 mm	G10-20 mm			G5-10 mm	G10-20 mm		
	Tank 3	Coconut fibre			PE12 mm	G5-10 mm			-	-	
6) Turbidity (NTU)	Raw Water	648	654	1051	1142	165	1067	1082	1101	34	33
7) Efficiency (%)	Tank 1	77	87	91	95	77	91	94	96	61	70
	Tank 2	28	26	43	33	20	43	48	40	12	9
	Tank 3	41	31	35	29	16	35	41	43	-	-
	Total	90	93	97	98	85	97	98	99	68	74

Figure 2 | Experimental results of Test 1 to Test 28 (extract).

Test 1 to Test 28 to identify the efficiencies of the factors. Figure 3 summarises the extracts of Test 29 to Test 42 conducted to grasp the long-term operational performance of the RF model tank.

1) Test No.	Test 29	Test 37	Test 38	
2) Flow Rate	36 m/day			
3) Alum Dose	60 mg/L			
4) Filter Height	900 mm			
5) Filter Media at Tank 1	PE 25 mm			
6) Turbidity (NTU)	Raw water	978	955	931
7) Efficiency (%)	-	98	94	97

Figure 3 | Experimental results of Test 29 to Test 42 (extract).

Detailed experimental results of test 23

As representative test results, Figure 4 shows turbidities with elapsed time at Test 23 obtained at an interval of 15 minutes for 195 minutes under the following conditions: raw water turbidity of about 1,100 NTU, RF filter height of 90 cm with three stages with filter media (Tank 1: PE25 mm, Tank 2: G10-20 mm, Tank 3: G5-10 mm), filtration rate of 36 m/day and 80 mg/L alum dosing.

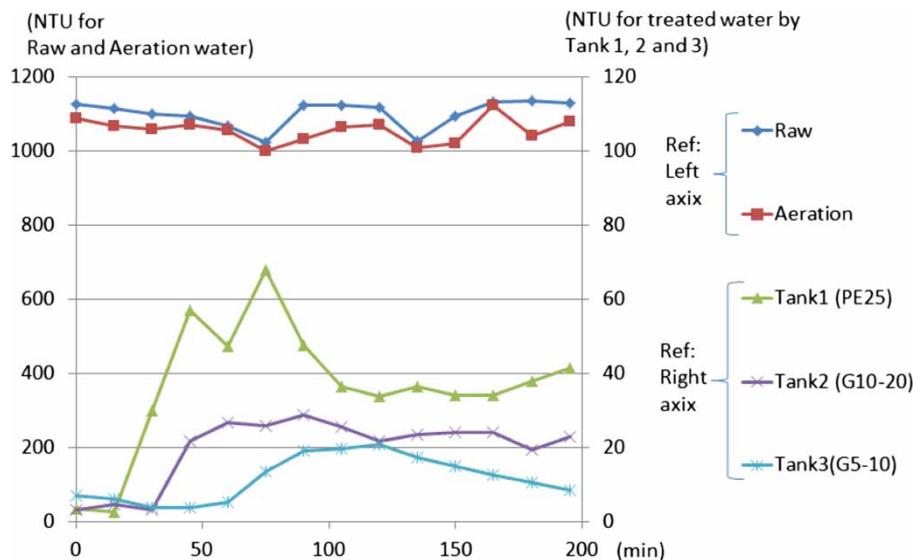


Figure 4 | Experimental result of Test 23 showing variation in turbidity with time.

Efficiencies of filter media

Comparing plastic, gravel and coconut fibre as filter media, it turned out that plastic media is very effective. Although the effectiveness of turbidity removal by coconut fibre was recognised, detailed examination was not carried out due to risk of flavoring the water during long filter operation (Wegelin 1996).

Evaluation of plastic filter media size

Generally, it is expected that the smaller filter media size, the higher turbidity removal effect. However, under the following conditions – raw water turbidity of 110–160 NTU, one stage of 90 cm-high RF model tank, filtration rate of 36 m/day and no alum dosing – and the PE filter size was varied from PE 12 mm (Test 13) to PE32 mm (Test 15), no highly significant difference in efficiency was observed as shown in Table 1.

Table 1 | Turbidity removal efficiencies with different size of plastic media

Size of Plastic Media Test No.	PE 12 mm Test 13	PE 19 mm Test 14	PE 25 mm Test 19	PE 32 mm Test 15
Turbidity Removal Efficiency (%)	83	84	77	80

Comparison of plastic and gravel filter media

In Tank 1, the plastic filter media (PE25 mm) had higher turbidity removal efficiency than the gravel media (G10–20 mm). On the other hand, in Tank 2 and Tank 3, gravel media (G10–20 mm, G5–10 mm) had higher turbidity removal efficiencies than the plastic filter media (PE32 mm).

- (1) Under the following conditions – raw water turbidity of 30–35 NTU, one stage of 90 cm-high RF model tank, filtration rate of 36 m/day and no alum dosing – RF filter media performances were tested with PE25 mm (Test 26) and G10–20 mm (Test 27). As a result, the turbidity removal efficiency of PE25 mm (70%) was found to be higher than that of the G10–20 mm (61%) (ref. Figure 2).
- (2) Under the following conditions – raw water turbidity of Tank 2: about 100 NTU, 2 stages of 90 cm-high RF model tanks, filtration rate of 36 m/day and 60 mg/L alum dosing – RF filter media performances were tested with PE32 mm, G10–20 mm and G5–10 mm. As a result, as shown in Table 2, the gravel media (10–20 mm, 5–10 mm) had higher turbidity removal efficiencies than the PE media (32 mm), and these were the opposite test results of the above case.

Table 2 | Turbidity removal efficiencies of PE and gravel media

Test No.	Test 16			Test 20		
	Media	NTU	Efficiency (%)	Media	NTU	Efficiency (%)
Raw water	–	1,052	–	–	1,067	–
Tank 1	PE32 mm	97	–	PE25 mm	98	–
Tank 2	PE32 mm	68	30	G10–20 mm	56	43
Tank 3	PE32 mm	51	25	G5–10 mm	36	35

Sequencing effect of installing different size of filter media in multiple stage RFs

Under the following conditions – raw water turbidity of about 650 NTU, three stages of 90 cm-high RF model tank, filtration rate of 36 m/day and 40 mg/L alum dosing – the sequencing orders of the

filter media were varied by setting PE19 mm in Tank 1 and PE12 mm in Tank 2 (Test 1), and setting PE12 mm in Tank 1 and PE19 mm in Tank 2 (Test 2), and the entire removal efficiencies were compared. As a result, as shown in Table 3, Test 1 was more effective than Test 2; hence, setting larger size filter media first and smaller size filter media next results in higher effectiveness in turbidity removal.

Table 3 | Turbidity removal efficiencies by varied sequencing order of PE media

Test No.	Test 1		Test 2	
	Media	Efficiency (%)	Media	Efficiency (%)
Tank 1	PE19 mm	52	PE12 mm	56
Tank 2	PE12 mm	32	PE19 mm	15
Total of Tank 1 and 2	–	67	–	63

Effect of filtration rate

Under the following conditions – raw water turbidity of about 650 NTU, filter height of 30 cm of three stages RF model tank with filter media (Tank 1: PE12 mm, Tank 2: PE 19 mm and Tank 3: coconut fibre) and 60 mg/L alum dosing – filtration rate performances were tested with 36 m/day (Test 3) and 24 m/day (Test 5). As a result, the turbidities in Tank 3 were 62 NTU and 44 NTU, and the turbidity removal efficiencies were 90% and 93% respectively (ref. Figure 2).

The experiments with a filtration rate of 24 m/day had a filtration rate difference of 1.5 times, (which means the required site area for the RF was also 1.5 times larger than the one with 36 m/day filtration rate) and only 3% increase in the turbidity removal efficiency was observed. As such we concluded that a filtration rate of 36 m/day is beneficial and applicable to obtain sufficient RF efficiency, and only two experiments were conducted with a filtration rate of 24 m/day.

Effect of filter length

The turbidity removal efficiency was greater when the filter media height was higher, although it was not proportional.

Under the following conditions – raw water turbidity of about 1,100 NTU, three stages of RF model tank with PE12 mm filter media, filtration rate of 36 m/day and 60 mg/L alum dosing – filtration height performances were tested with 60 cm (Test 11) and 90 cm (Test 12).

As a result, the turbidities at Tank 3 were 31 NTU (60 cm three tanks) and 27 NTU (90 cm three tanks) and the turbidity removal efficiencies were 97% and 98%, respectively (ref. Figure 2). Only 1% better turbidity removal was obtained at 90 cm compared to 60 cm with three tanks. The turbidity removal efficiency by only Tank 1 case was 91% (60 cm tank) and 95% (90 cm tank); hence, 4% better efficiency was obtained in 90 cm tank.

Effect of alum dosing

It was observed that the more alum dose, the higher turbidity removal efficiency.

Under the following conditions – raw water turbidity of about 1,100 NTU, filter height of 90 cm in three-stage RF model tank with filter media (Tank 1: PE25 mm, Tank 2: G10–20 mm and Tank 3: G5–10 mm), and filtration rate of 36 m/day – alum dosing performances were tested with 60 mg/L (Test 20), 70 mg/L (Test 21) and 80 mg/L (Test 23).

As a result, the turbidities in Tank 3 were 36 NTU, 20 NTU and 13 NTU and the entire turbidity removal efficiencies were 97%, 98% and 99%, respectively (ref. Figure 2).

Time of reaching the filtration effect

Test 23 (ref. Figure 4) experiment was carried out without draining the water stored in RF model tanks after the previous experiment was finished the day before. After starting the experiment, the turbidity of the outflow water from Tank 3 was less than 10 NTU for about the first 60 minutes. This could be done to turbidity parts of silt and clay in Tanks 1, 2, and 3 remained for one day and settled before clear water flowed out. On the other hand, subsequent turbidities increased due to the flow-up effect of silt and clay that settled on the filter media. In Tank 1 turbidity rose up to 68 NTU and became stable at about 40 NTU after about 100 minutes. In Tank 2, it rose up to 29 NTU and it became stable at around 23 NTU after about 120 minutes. In Tank 3, it rose up to 21 NTU and it decreased to 9 NTU after 195 minutes and the turbidity was still falling, but the experiment had ended at that time. From these results, it was concluded that stable pre-treatment is progressing at about twice retention time, and it is postulated that RF pre-treatment should become stable within about three times of the retention time.

Performance of RF

In the results of Test 23 (ref. Figure 2 and Figure 4), the turbidity of the pre-treated water was 13 NTU on the average and the turbidity removal efficiency was about 99%, and the turbidity was decreased to 9 NTU, which is less than 10 NTU at the last measurement time. Accordingly, it was demonstrated that water with a turbidity exceeding 1,000 NTU can be pre-treated to less than 10 NTU with this system.

RF operational issues and effect of washing PE filter media

Under the following conditions – raw water turbidity of about 1,000 NTU, filter height of 90 cm in one stage RF model tank with PE 25 mm, filtration rate of 36 m/day and 60 mg/L alum dosing – experiments were carried out for about 42 hours from Test 29 to Test 42.

Based on the results (ref. Figure 3), it was observed that continuous operation of the RF model tank gradually deteriorated the turbidity removal performance as the pre-treatment efficiencies decreased from 98% (Test 29) to 94% (Test 37). In addition, continuous operation of the RF removed the turbidity within the filter media and increased the flowing load, and overflow occurred from the inlet pipe of RF model tank during Test 38. By opening the drain valve of RF model tank at the base and backwashing the media, the restoration of RF model tank pre-treatment effect was achieved. In addition, it was confirmed that it is easy to clean the PE filter media that contained a lot of dry silt following its removal from the RF model tank. Accordingly, we understand that PE media can be easily cleaned manually by washing with water.

DESIGN AND OPERATION GUIDELINES

Filter media of RF

In the experiment of Test 20 to Test 23, the turbidity removal efficiency of RF in Tank 1 (PE25 mm) was 91% to 96%, in Tank 2 (G10–20 mm) was 40% to 48% and in Tank 3 (G5–10 mm) was 35% to 43%. When the turbidity removal efficiency in Tank 1 is high but if the cleaning system of this filter media is not good, clogging occurred in the filter, which could affect the WTP operation. As mentioned in Sec. RF operational issues and effect of washing PE filter media, PE media can be easily cleaned manually and filter media clogging can be easily prevented. For the PE media, the filter media with a smaller diameter had higher effect in removing the turbidity but the differences in the

turbidity removal efficiencies of PE12 mm, 19 mm, 25 mm and 32 mm were not significant as described in Sec. Evaluation of plastic filter media size. So it was concluded that any of these four PE media can be adopted. When comparing the PE media unit cost with the diameter from 12 mm to 50 mm, the media with the diameter of 32 mm and 25 mm are relatively inexpensive per unit volume. So, PE25 mm filter media was selected for the 1st RF tank considering the effective turbidity removal efficiency and economical material cost.

The unit price of the PE media is higher than gravel media by about five times, and in Tank 2 and Tank 3, gravel media of 10–20 mm and 5–10 mm have been more effective in removing turbidity than PE 32 mm (ref. Table 2). Accordingly, 10–20 mm gravel media for 2nd RF Tank and 5–10 mm gravel media for 3rd RF Tank were selected. There are cases where gravel size smaller than 5 mm such as 2–4 mm is used in some WTPs; however in this experiment the use of finer media was not considered to avoid ease of media clogging.

About 50% to 95% of the turbidity of the raw water was removed by the 1st RF tank with PE media. And due to the relatively small amount of trapped turbidity particle in 2nd and 3rd tanks with gravel media, it was concluded that maintenance of the gravel filter media can be done with regular backwashing. For each RF tank, backwashing will be carried out by opening the backwash valve, and the pipe and valve size are set to secure the water level down with rate to be over 20 m/hour (Kapranis 1999). However, with due monitoring of the water quality and water flow at RF, it is recommended that the gravel media be removed from the RF body and externally washed once in every several years or whenever necessary.

RF filtration rate

Upward flow rate of 36 m/day was applied (ref. Sec. Effect of filtration rate).

Height of filter media and water flow control in RF

In the 1st RF Tank, the height of the filter media using PE25 mm was set at 1.6 m which was about 1.8 times of the 0.9 m used in the experiment. Furthermore, 0.5 m space for settling silt and clay was provided under the filter media. Perforated pipes were placed in this space for supplying and discharging water. A net was stretched at the upper end of the filter media so that the PE filter media would not flow out. A water depth of 30 cm was provided from the upper end of the PE filter media to the water surface to facilitate good cleaning effect by backwash. Weirs were set at the outlet of the first to measure flow rate into the second tank. The water level was monitored by adjusting RF inlet valves so that flow rates of the multiple RFs were uniform.

Total gravel media height of 1.8 m in second RF tank and 1.5 m in the third RF tank were set considering easy maintenance to conform to the guideline figure of 1.5 m (AWWA 1991). The differences in water level among first, second and third tanks were set at 30 cm, so that even if there was higher load due to some degree of clogging through the filter media, water flow to the subsequent RF tanks would not be affected.

The formulated design guideline for Roughing Filter (RF) based on the experimental results is shown in Table 4.

The design filtration rate of slow sand filter was set at 5 m/day (MHLW 2012) for this treatment system.

Alum dosing, alum and raw water mixing, and water quality management for RF

It has been determined that excessive alum dosing should not be applied so as to reduce the adverse effect on coagulant dosing to SSF, and to be economical. Accordingly, alum dosing is provisionally set as follows: If raw water turbidity to RF is less than 50–100 NTU, no alum dosing is done. If it is over

Table 4 | Design guideline for roughing filter (RF)

No.	Item	Design Criteria
1	Filtration rate	36 m/day
2	Number of tanks in series	Three tanks for one series
3	Number of series	More than two series including one stand-by series
4	Filter media and thickness	First tank: Low density PE (diameter and length = 25 mm): Height = 1.6 m Second tank: Gravel 20–40 mm: H = 0.4 m, G10–20 mm: H = 1.4 m Third tank: Gravel 20–40 mm: H = 0.4 m, G10–20 mm: H = 0.2 m, G5–10 mm: H = 0.9 m
5	Back wash	Back wash filtration rate >20 m/hr. (480 m/day)
6	Water depth above the filter surface	Water level: 0.3 m above the filter surface

50–100 NTU, the required alum dosing is set through the jar test with monitoring of the constructed RF operation so that the pre-treated water turbidity of the RF will be under 10 NTU.

Mixing of alum solution with raw water adopted a cascade aeration facility that does not require mechanical equipment. According to the cascade aeration specification, the weir load is set at $0.01 \text{ m}^3/\text{sec} \cdot \text{m}$, the fall height at 0.4 m, and the number of weirs at three units (Wegelin 1996).

The pre-treated water by RF is allowed to flow to the SSF when the RF pre-treated water turbidity is less than 10 NTU. If the turbidity exceeds 10 NTU, RF can release the pre-treated water without feeding it to the SSF. Also, if the treated water turbidity by SSF exceeds 5 NTU, it can be discharged without being sent to the clean water tank for consumer supply (WHO 2011).

APPLICATION OF RF + SSF IN MYANMAR

In 2017 to 2018, the Myanmar Government (i.e., Department of Rural Development (DRD) under the Ministry of Agriculture, Livestock and Irrigation) constructed water supply facilities that include roughing filter (RF) and slow sand filter (SSF), according to the above design guidelines, in five townships of Pyapon, Magway, Sagaing, Phaang and Thatyet Chaung whose water source was river.

As of June 2018, all WTPs were operating satisfactorily with growth of algae and microorganisms in the SSF basins along with sand scraping at the SSF conducted at a frequency of about 1–2 months to maintain the design filtration rate. Scraped sand was being stored for the use of future replacement to SSF after cleaning. This sand scraping frequency is rather short compared to 1–12 months (Health 2003) but still acceptable, to produce treated water with turbidity under 5 NTU.

WTP capacities and their processing performance are summarised in Table 5.

It is concluded that SSF with the pre-treatment of RF designed according to the guidelines of Table 4 is capable of treating river water with a high turbidity up to about 1,000 NTU to produce treated water with turbidity under 5 NTU in compliance with the WHO guideline.

Table 5 | Performance of WTPs (RF + SSF) using river water sources in Myanmar

WTP Location	WTP capacity (m ³ /day)	Turbidity (NTU)				Alum dose (mg/L)	Remark
		River	Inlet of RF	Outlet of RF	Outlet of SSF		
Pyapon	3,080	–	67	5.0	1.0	5–10	July 2017
Magway	330	336	150	2.0	1.0	45	Oct. 2017
Sagaing	2,100	29	18	2.0	2.0	0	Jan. 2018
Bar-Me Hill, Phaang	4,320	–	25	6	1.0	0	Feb. 2018, 50% operation
Thatyet Chaung	70	–	1.3	0.9	0.4	0	Nov. 2017

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