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Effectiveness of combined up-flow roughing filter and up-flow slow sand filter to reduce turbidity in Citarum water as a source of drinking water

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Abstract. The turbidity of the Citarum River was high, fluctuating, and used as a drinking water source by PDAM (Regional Drinking Water Company). This study aimed to determine the ability of a combined up-flow roughing filter (URF) and an up-flow slow sand filter (USSF) in reducing turbidity, called multistage filtration (MSF). MSF was varied with and without settlers. Gravel diameters and perviousness: 0.5 cm was 0.243, 1 cm: 0.264, 2 cm: 0.265, 5 cm: 0.302 or 24-30% of URF's volume. When settler was run with surface loading 0.5 m³/m²/hour, flowrate 0.67 l/minute, turbidity 321.16-3,496.53 NTU, the efficiency was 57.9-96.2%. Settler reduced turbidity significantly. URF₁ enhanced turbidity removal. However, URF₂, URF₃, USSF were not effective. In an experiment without a settler, turbidity 130.78-533.00 NTU, but its reduction in URF₁ was bad. In URF₂ turbidity was almost the same as in the experiment with the settler. Efficiency was 41.9-89.1%. Here URF₁ and URF₂'s functions were almost the same as settler and URF₁. URF₃ was ineffective, can be removed. USSF was needed even though only able to reach 10-25 NTU. URF and USSF contributed to the higher efficiency of turbidity removal.

1. Introduction

Citarum is the longest river in West Java, Indonesia and is used as a source of drinking water by people and PDAM (Perusahaan Daerah Air Minum, *Regional Drinking Water Company*). Its turbidity is high and fluctuating. Citarum also receives domestic and industrial wastewater. Since the 1980s the people and government of Indonesia has issued Citarum water quality improvement programs such as MCC: Masyarakat Cinta Citarum, Clean River Program (Program Kali Bersih, *Prokasih*), GCB: Gerakan Cikapundung Bersih, Gerakan Citarum *Bergeutar* [bersih (clean), *geulis* in Sundanese is beautiful, lestari (sustainable) [1] and Citarum Harum on 2018 [2].

The Citarum Harum program improves drinking water sources for people, the community, and PDAM. However, Citarum water treatment is too expensive when using PDAM technology, i.e., settler or pra-sedimentation, coagulation, flocculation, sedimentation, rapid sand filter (RSF). Configuration of these unit operations and processes are called conventional treatment and always use chemicals. Since the 1970s, PDAM has applied conventional technology for its water treatment. PDAM does not have a new design, and the Ministry of Public Works consistently implements a conventional treatment called IPA Kedasih (*Instalasi Pengolahan Air Keluaran Direktorat Air Bersih*) [3]. Therefore, there is hope that the government and PDAM will use multistage filtration (MSF).

MSF is a combination of roughing filter (RF) and slow sand filter (SSF). MSF has been widely applied in developing countries in Latin America. This system was intensively researched in the last decades of the 20th century by IRC - CINARA (*International Water and Sanitation Centre - Instituto de Investigacion y Desarrollo en Abastecimiento de Agua*) in Colombia. CINARA built a pilot plant in Puerto Mallarino. Its turbidity was 80-3,600 NTU, coliform bacteria was 63,000-500,000 Colony Forming Units (CFU), and final turbidity was 3-24 NTU (*nephelometric turbidity units*) [4]. Indonesia is a developing country, but there is no PDAM from Sabang to Merauke use MSF

So far, many developing countries have implemented horizontal roughing filters (HRF) combined with slow sand filters [5]. Baker, in 1981, wrote a book, *The Quest for Pure Water*, that HRF was also used to treat surface water from the cistern by installed a gravel pack around it since the Middle Ages in the former castle of Hohentrins in the Swiss Alpine valley of Rhine River [6]. HRF is applied because gravel produces large perviousness so that solid particle penetration is more profound and has much more space. HRF can extend the lifetime of downflow slow sand filter (DSSF) up to five times [7], and HRF has successfully treated raw water quality with turbidity 200-400 NTU [8].

In Ghana, HRF is also used to treat highly turbid water [9]. HRF has been effectively made in developing countries like Iran, Malaysia, India, Sri Langka [10]. HRF is also studied in Iran to treat surface water [11]. HRF is also able to treat various raw water in Kenya, Africa [12]. Roughing filters can treat highly turbid water (1,000 NTU) to generate 10 NTU for SSF in Myanmar [13]. Besides HRF, a vertical roughing filter (VRF) is also developed viz. downflow and up-flow, and the filter media is completely submerged, different from HRF [14].

Japan has implemented VRF. Community Water Supply Support Center in Niigata, Japan, studied a pilot plant in 2008-2010. Its treatment consisted of one settler (pra-sedimentation), five up-flow roughing filters (URF), one DSSF, and treated water from Kariyata and Shinano River. The pilot plant had three variations, i.e., five steps URF, three steps URF, multilayers URF. The last one was a DSSF. The video of the pilot plant is available at this link [15]. Another URF study for rural water treatment with velocity 5-20 m/hour achieves an 85-90% [16].

In addition to HRF and URF, available many roughing filters like dynamic gravel filter, up-flow gravel filter in layers and series, downflow gravel filter in layers and series, and slow sand filter. All filter media are gravel, average diameter 0.5-3 cm and specific gravity 2.6-3.0. Gravel filters mainly improve physical water quality: as suspended solids are removed, turbidity is reduced, the water becomes apparent. Bacteriological improvement can also be expected as bacteria and viruses are solids too, in size approx. 10-0.2 μm and 0.4-0.002 μm respectively. Bacteriological water quality can be improved to 60-99% [7]. Some research results on MSF, RF, and SSF are shown in table 1 [10].

Table 1. Research on roughing filter, slow sand filter, and multistage filtration.

Reference	Filtration Rates (m/h)	Parameters	Mean percent removed (%)
Pacini (2005)	1.20	Iron and manganese	85 and 95
Dome (2000)	0.3	Algae and turbidity	95 and 90
Mahvi (2004)	1.5	Turbidity	90
Ochieng, Otieno (2004)	0.75	Turbidity and algae	95 and 90
Dastanaie (2007)	1.8	Turbidity, TSS and Coliforms	63.4, 89 and 94
Jayalah (1994)	1.5	Colour and turbidity	50 and 60
Rabindra (2008)	1.0	TSS and turbidity	95 and 95
Mukhopadhyay (2008)	0.75	Turbidity	75

Source: [10]

HRF research and papers are more than URF. Both are usually equipped with DSSF or USSF. This research is focused on URF and USSF to obtain characteristics and performances in reducing the

turbidity of Citarum water. A study reports turbidity of such a river is 320 NTU [17]. The first experiment is run to obtain the perviousness of local gravel available around the river. It provides an estimation of URF's capacity of sludge volume or lifetime and a key of URF effectiveness and cleaning mechanism.

The second experiment evaluates the settler's performance and examines whether the settler needs it or not. The third experiment is applied to get turbidity reduction efficiency by URF and USSF. This USSF differs in the flow direction from SSF developed by Huisman [18]. However, the function of USSF and SSF is the same, i.e., improving the filtrate quality of effluent. The filtrate is collected in the reservoir where chlorination takes place to disinfect microorganisms. As a developing country, there is a hope that the government and PDAM should try MSF to treat the highly turbid water of any river. MSF is a challenge and a prospect for community water treatment and to grow science and technology.

2. Methodology

The research was carried out at the banks of Citarum River, Bojongsari Village, Bandung Regency, West Java, Indonesia. MSF consisted of three URFs and one USSF. Each unit was separated by a 5 mm steel plate and equipped with a 1/2" drain pipe of PVC valves. A perforated plate (steel, 5 mm thick) that separated the under space and the gravel layers were installed to hold gravel media layers and to distribute water to all of the cross-sectional areas of URF. It is under space, and perforated plates were the most difficult to build in this study.

URF length was 40 cm, URF width was 20 cm, USSF length was 40 cm, USSF width was 50 cm. Gravel diameter were 5 cm, 2 cm, 1 cm, 0.5 cm. Local sand was used as USSF filter media. Water was pumped about 10 l/minute to CHB, a significant portion then overflowed back to the river, and a little flowed to MSF with surface loading $0.5 \text{ m}^3/\text{m}^2/\text{hour}$ and flowrate 0.67 l/minute. Turbidity was measured with a turbidimeter. A diagram and photo of MSF at the riverside of Citarum River are shown in figure 1.

Figure 1. MSF treated highly turbid water.

3. Results and discussion

The first experiment of multistage filtration (MSF) produced gravel perviousness. Perviousness (no porosity) is the ratio of water volume in URF containing gravel to empty URF volume. It depends on the average diameter of gravel. Perviousness of gravel diameter 0.5 cm was 0.243, diameter 1 cm was 0.264, diameter 2 cm was 0.265, diameter 5 cm was 0.302. The larger the gravel diameter, the greater the perviousness. The largest gravel was placed in the initial URF, while the smallest was placed in the

last. This configuration effectively removes coarse solid at the initial URF [4]. All of the papers that are cited above use gravel as filter media in their studies.

However, the perviousness was too small, just 24-30% of the total volume for trapping solid particles. It was not good, although gravel was cheap and available locally. It is proposed to use synthetic material with the same size, lighter than gravel, specific gravity of about 1.2 so that the URF shape is compact, small, and easy to be cleaned. In this study, cleaning solid particles (sludge) was a big problem because it consumed much time to clean gravel. If synthetic material can be made, it will support MSF to be applied in full-scale treatment. Probably it will be more expensive than gravel but will give better treatment, clearer water, and more effortless operation and maintenance.

The second experiment was to determine the effect of settlers. Its function was to remove solid particles (coarse solid) and the most popular unit operation in PDAM. In this second experiment, Citarum water was pumped into the constant headbox (CHB), and a tiny portion of water flowed gravity to the settler, and the remain overflowed to the river. Surface loading of settler and MSF was set 0.5 m³/m²/hour and flowrate 0.67 l/minute. Turbidity was observed at all sampling points on the 1st, 3rd, 6th, 10th days. Observation of turbidity at the outlet (effluent USSF) was recorded daily. Turbidity and reduction efficiency (in brackets) can be seen in table 2.

Table 2. Turbidity in sampling point of filters with the settler.

Day	Turbidity (NTU)						Efficiency %
	Citarum water	Settler	URF ₁	URF ₂	URF ₃	USSF	
1	321.16	135.31 (57.9%)	84.52 (73.7%)	93.10	97.44	98.20	69.4
2	-	-	-	-	-	64.67	-
3	1,101.58	42.12 (96.2%)	30.17 (97.3%)	26.65	28.00	40.04	96.4
4	-	-	-	-	-	31.07	-
5	-	-	-	-	-	29.60	-
6	3,496.53	1,342.52 (61.6%)	371.05 (89.4%)	122.30	71.75	33.08	99.1
7	-	-	-	-	-	30.57	-
8	-	-	-	-	-	25.62	-
9	-	-	-	-	-	26.44	-
10	994.00	91.27 (90.8%)	47.80 (95.2%)	29.97	27.15	20.34	98.0

The turbidity of Citarum water fluctuated daily. In the second experiment, the lowest turbidity was 321.16 NTU, and the highest was 3,496.53 NTU. On day-1 turbidity reduction efficiency reached 57.9%, day-3 was 96.2%, day-6 was 61.6%, day-10 was 90.8%. Settler effectively reduced turbidity of Citarum water. The increase of turbidity reduction efficiency from settler to URF₁ was varied. On day-1 it was 15.8%, day-3 was 1.1%, day-6 was 27.8%, day-10 was 4.4%. URF₁ increased turbidity reduction by an average of 12.3%. However, the function of URF₂ and URF₃ was not optimal. It means MSF equipped with settler-only need one URF₁ to achieve turbidity reduction efficiency of at least 90%. Even though the final turbidity in USSF effluent has not reached 5 NTU yet, refer to drinking water standard.

The third experiment was without settlers. Citarum water was pumped to CHB and flowed to MSF. Water in URF₁ and URF₂ was more turbid than in the second experiment with the settler. Turbidity was observed on the 1st, 5th, 10th day. Turbidity at the outlet (effluent USSF) was observed daily. Turbidity and its reduction efficiency (in brackets) in the experiment without settlers are given in table 3.

Table 3. Turbidity in sampling point of filters without settler.

Day	Turbidity (NTU)					Efficiency %
	Citarum water	URF ₁	URF ₂	URF ₃	USSF	
1	130.78	87.90 (32.2%)	75.94 (41.9%)	68.04	61.10	53
2	-	-	-	-	42.28	-
3	-	-	-	-	22.56	-
4	-	-	-	-	20.21	-
5	533.00	60.00 (88.7%)	58.00 (89.1%)	54.00	16.64	97
6	-	-	-	-	19.48	-
7	-	-	-	-	12.29	-
8	-	-	-	-	10.37	-
9	-	-	-	-	7.53	-
10	219.00	103.00 (52.9%)	25.79 (88.2%)	8.49	3.39	98

In the third experiment, turbidity was 130.78-533.00 NTU. Turbidity reduction efficiency in URF₁ was lower than in the second experiment with the settler. Efficiency on day-1 was only 32.2%, day-5 was 88.7%, day-10 was 52.9%. Turbidity reduction efficiency in URF₂ was almost the same as in the second experiment with the settler. On day-1 reduction was 41.9%, day-5: 89.1%, day-10: 88.2%. However, the function of URF₁ and URF₂ were almost the same as the settler and URF₁. URF₃ was not effective, but USSF was still needed even though only able to reach 10-25 NTU. USSF helped decrease final turbidity at the outlet as written in the USSF column in the two tables mentioned.

Turbidity of USSF effluent in the third experiment without settler was lower than turbidity of USSF effluent in the second experiment with the settler. Turbidity of USSF effluent in the second was 20.34-98.2 NTU. The turbidity of effluent in the third experiment was 3.39-61.1 NTU. When the third experiment without settlers was run, the turbidity of Citarum water was relatively low, as written in table 3.

Referring to the regulation of Ministry of Health No. 492/Menkes/Per/IV/2010 [19], the maximum permissible level for turbidity is 5 NTU. This regulation becomes a reference for water treatment of PDAM. PDAM water that can reach effluent turbidity 5 NTU always uses chemical treatment in the coagulation and flocculation process before sedimentation and RSF. This conventional technology is the mainstay of PDAM to treat river water. To reduce turbidity caused by coarse particles, PDAM uses a settler. In this study, the function of the settler as pre-treatment proved significantly in reducing turbidity.

To treat river water, PDAM always uses RSF, not DSSF or USSF. PDAM has not used MSF yet. It also happened because the Ministry of Public Works has not implemented MSF yet too and the consultants in the field of water treatment just focused on using settlers for new treatment projects like IPA Kedasih. Observed the experimental results in table 3, MSF without settler has succeeded to reach 3.39 NTU on the 10th day and has complied with regulation No. 492/Menkes/Per/IV/2010 [18]. If running was continued, turbidity in USSF effluent should be lower due to clogging in sand media. The same thing happened to MSF, which was equipped with the settler. That was, the settler may or may not be installed. URF can be one or just two units, but the USSF must remain.

Compared to the pilot plant in Niigata, Japan, this pilot plant uses one settler (pra-sedimentation), five URFs, and one SSF [15]. In other studies, SSF is effective in increasing turbidity reduction. Surface loading of SSF by design criteria will produce low effluent turbidity [20]. SSF can be operated up to three months before clogging and flow rate decreases [18]. A multistage household filter (HMSF) that combined a dynamic gravel filter (DGF) and a household slow sand filter (HSSF) achieve an efficiency

of 60% [21]. DGF and URF confirm the role of filters in protecting against high turbidity and avoiding filter clogging in SSF or USSF [22].

Combining settler with MSF or URF and USSF greatly contributes to higher efficiency. However, the divergence of efficiencies in such studies is caused by differences in influent turbidity. Gravel size and shape, and layers also differentiate the results. There is hope in the future that PDAM should build it as an alternative to conventional treatment with chemicals. Students and researchers can use the full-scale MSF as a field laboratory by students and researchers, build a reversible collaboration in waterworks between water companies, the government, and the university.

The last one is about how to clean the accumulated sludge in MSF that causes clogging. Clogging can be cleaned by repeatedly open-close URF drain-pipe valve to allow water to become turbulent flow. Clogging in SSF is cleaned by backfilling (not backwashing like in RSF). This process is done after scraping the upper layer of sand to avoid air-locking in filter media. This upper layer is called filter skin (dirt or physical layer, filter cake, *Schmutzdecke*) and consists of organic-inorganic particles, the biofilm of microorganisms, protozoa, and Mesozoic. After cleaning, the SSF can be operated again, and it is called the one running-cycle of MSF.

The same procedure is also applied to USSF on the surface of the sand. In this experiment, along with the observation, there was no *Schmutzdecke* on the surface of USSF. It occurred because the flow was upward, and the running time of each experiment was not more than three months like in DSSF or conventional SSF [18]. The possibility of physical layer growth in USSF will be an object of future research with gravel media or a new lighter synthetic media.

4. Conclusion

Local gravel perviousness was 0.243-0.302 or 24-30% of total URF's volume, too small. URF was also difficult to be cleaned because the gravel was too heavy, and the perforated plate received too much weight. This constraint may be solved by synthetic material lighter than gravel, at least 70% perviousness, and specific gravity ± 1.2 . The settler was effectively removed turbidity with efficiency 57.9%-96.2%. If MSF was combined with settler, need URF₁. URF₂, URF₃ can be removed.

In an experiment without a settler, the turbidity reduction was worse than a settler. However, turbidity reduction efficiency in URF₂ was almost the same as in the experiment with the settler. Efficiency was 41.9%-89.1%. URF₁ and URF₂'s function in the third experiment were almost the same as settler and URF₁ in the second experiment. Here settler can be replaced by two URFs (URF₁ and URF₂). URF₃ was ineffective, can be removed. USSF was still needed even though it was only able to reach 10-25 NTU.

As a whole, turbidity of Citarum water can be effectively reduced by settler and URF₁. Also effective by URF₁ and URF₂. This study proved that two URFs were effective in reducing turbidity and required USSF to remove fine particles. This study showed that settler, URF, USSF significantly contributed to the high efficiency of total turbidity removal.

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