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DIRECT HORIZONTAL-FLOW ROUGHING FILTRATION : AN IMPROVED PRETREATMENT PROCESS FOR HIGHLY TURBID WATER

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ABSTRACT

Turbidity removal and filter run length of Horizontal-flow Roughing Filtration (HRF) drop drastically at higher turbidity or relatively higher filtration rate. Flocculation with aluminium sulphate in HRF proves now to be an interesting process modification to overcome these limitations. This modified process is called Direct HRF (DHRF). This paper reports on the first results and experiences of DHRF based on lab-scale investigations. From the turbidity profiles developing in the filter compartments it can be assumed that the first compartment with coarse grains functions as a settler, whereas subsequent compartments with finer grains exhibit the characteristics of deep-bed filtration. Comparing the performance of HRF and DHRF, it was found that DHRF systematically performed better featuring longer filter runs and higher removal efficiencies at higher filtration rates. Due to DHRF's low capital and operation cost, it can be an attractive low cost pretreatment technology prior to e.g. Slow Sand Filtration for water with high turbidity.

INTRODUCTION

Many rivers in Asia, Africa and North and South America exhibit wide fluctuations in flow and turbidity level. During the rainy season huge amounts of suspended solids (SS), which originate from washed top soils, are transported by the rivers. SS concentrations can be as high as 2000 - 3000 mg/L. The final SS removal process in a water treatment plant always consists of sand filtration; the highest SS concentration the filter can accept in its influent is typically 50 NTU (SS concentration expressed as turbidity). Pretreatment is therefore usually necessary.

For rural and small urban areas in developing countries Slow Sand Filtration (SSF) is commonly considered the appropriate (so called low cost) technology for final filtration [1]. The appropriateness resides in low recurrent costs, unsophisticated operation and maintenance, reliability and a high use of locally available materials and manpower. However, performance of the SSF is very sensitive to high turbidity levels. Influent turbidity has to be less than 50 NTU and values less than 10 NTU are recommended for optimal operation [2]. In most cases pretreatment is required to lower the influent turbidity to the SSF to an acceptable limit. Obviously the pretreatment process should be such that its level of technology is compatible with that of the SSF.

Table 1 describes common treatment processes for SS removal. The Table roughly distinguishes sedimentation/flotation based pretreatment, filtration based pretreatment and filtration for final treatment. Plain sedimentation and prolonged storage are relatively simple technologies. Even after prolonged storage the turbidity of highly turbid rivers cannot be reduced sufficiently. Like in plain sedimentation only coarse matters can be removed; sand and clay particles down to 20 µm can be removed within a few hours detention time. But natural surface waters usually carry large fractions of SS smaller than 20 µm. The effluent of conventional sedimentation or prolonged storage will, therefore, hardly meet the high standards required by SSF though sedimentation can sometimes act as a first treatment to remove already a substantial part of SS before the actual pretreatment step [1]. Other alternatives like flocculation-sedimentation and flotation are more expensive and involve a more sophisticated technology. Vertical Roughing Filtration has a fair silt storage capacity but tends to clog rapidly at high influent turbidity [3]. Encouraging results were obtained in studies on Pebble Matrix Filtration [4]. SS concentration as high as 5000 mg/l could be reduced to less than 25 mg/l. Both processes are designed for backwashing rendering them more sophisticated.

Horizontal-flow Roughing Filtration (HRF) is a promising pretreatment process which combines good performance with an appropriate level of technology. It has been applied successfully in small demonstration plants prior to SSF in Colombia, Tanzania and Thailand on raw water turbidity of medium to low turbidity. Wegelin [1] investigated HRF extensively and proposed a design guideline. The normal filtration rate is 0.5 to 1.5 m/h for turbidity in principle up to 200-300 NTU. Filters are 8-12 m long and divided into 3 to 4 compartments for coarse to fine sand filtration. The main advantage of HRF is its high SS storage capacity in the first coarse compartment resulting in longer filter runs, and its sequential multi-media filtration (coarse to fine) resulting in good effluent quality. Other advantages are its simplicity in operations and its horizontal flow

Table 1 Common Processes for Particle Removal

Options	Influent Turbidity	Effluent Concentration	Supervision Level Required	Remarks
Sedimentation/flotation based pretreatment				
1. Prolonged storage	No upper limit	50 - 70 %	Low	Removes only settleable particles.
2. Plain sedimentation	100 - 500 NTU	30 - 50 % reduction	Low	Only mineral particles >20 µm are removed within detention time of 3 h.
3. Flocculation-sedimentation	40 - 200 NTU	< 10 NTU	Medium	Coagulants to be added; produces bulky sludge; sensitive to water quality changes.
4. Flotation	40 - 200 NTU	< 10 NTU	High	Coagulant and dissolved air to be added; sensitive to water quality changes.
Filtration for Pretreatment				
5. Vertical roughing filtration	20 - 100 NTU	5 NTU	Medium	Moderate silt storage capacity; backwashing required after 24 h.
6. Pebble matrix filtration	< 5000 NTU	< 25 NTU	Medium	Can be applied directly to highly turbid water; backwashing required.
7. Horizontal-flow roughing filtration	< 300 NTU	< 5 NTU	Low	High silt storage capacity; requires large volume of construction and more land; cleaning done by hydraulic flushing and periodic manual cleaning.
8. Direct horizontal flow roughing filtration	< 1000 NTU	25 NTU	Low	Higher silt storage capacity; can be applied at higher filtration rate and influent turbidity than HRF; also smaller construction volume required; cleaning similar to HRF; requires coagulant at a smaller and constant dose.
Filtration for Final Treatment				
9. Slow sand filtration	10 - (50) NTU	< 1 NTU	Low	Manual cleaning (scraping) typically after 1 month.
10. Rapid sand filtration	20 - 50 NTU	2 - 5 NTU	Medium	Backwashing required to clean filters after typically 12-24 h.
11. Direct (rapid) filtration	20 - 50 NTU	< 2 NTU	High	- do -

direction which allows construction of shallow and structurally simple filters.

Limitations of HRF are that it requires a large surface for construction and volume of filter materials. Removal of sludge remains another critical aspect. In HRF sludge is flushed downward periodically through underdrains. If raw water contains organic matter, a slime layer gradually develops around the filter grains. This sticky layer is difficult to flush out and eventually reduces the filter run time. Therefore, once or twice a year the filter materials have to be excavated, cleaned and replaced manually [3]. More importantly, it has also been observed in field experiences [5] and lab scale studies [6] that turbidity removal efficiency and filter run length of HRF drop drastically at higher turbidity (>200 NTU) or relatively higher filtration rates (>1 m/h).

Therefore it is attempted to overcome these drawbacks in a modified process called Direct Horizontal-flow Roughing Filtration (DHRF).This process involve coagulation in the roughing filter. Preliminary evidence indicates it can effectively combine in a sustained way the high removal efficiencies of Direct Filtration (DF) and the high SS storage and other characteristics of HRF.

AIMS

Research is being conducted to obtain an understanding of the DHRF's behaviour and to further develop it. In the first part of this research programme lab scale investigations are being carried out to study the removal mechanisms and the process parameters. This paper reports on the results obtained so far. Experiments were also conducted without coagulation to compare the performance of DHRF with HRF.

MATERIALS AND METHODS

A schematic diagram of the experimental set-up is show in Fig 1. The model raw water suspension is made of kaolin suspended in tap water; kaolin has shown to be representative for a majority natural waters [7,8]. Plain sedimentation (approx 1 h retention time) is applied before the filter to eliminate the coarsest, unrepresentative particles. Experiments were done with (i) moderate influent turbidity of 160 and 200 NTU to represent the average presettled water of most tropical turbid rivers, and (ii) higher turbidity of 510 NTU to represent presettled water of highly turbid rivers.

A constant filtration rate and thus water flow was achieved by means of a variable head water column in the influent side of the filters. Headloss over the filter could be built up as the filter is completely closed. For in-line coagulation, predetermined amounts of aluminium sulphate solution were injected with a volumetric dosing pump into a rapid mix chamber. The coagulant was stirred at a constant speed to obtain a desired G value [8]. Coagulant dose was varied from 0-4 mg Al/L. The Gt value in the rapid mix chamber were varied from 22,500 to 48,000.

Normally HRFs are constructed with 3 to 4 compartments; media size in these compartments varies from coarsest 25 mm to finest 4 mm. The turbidity removal in function of the filter lengths and the effect of different media sizes were intended to be used to understand the behaviour of DHRF. This information can also be used to optimize the length and media size of DHRF.

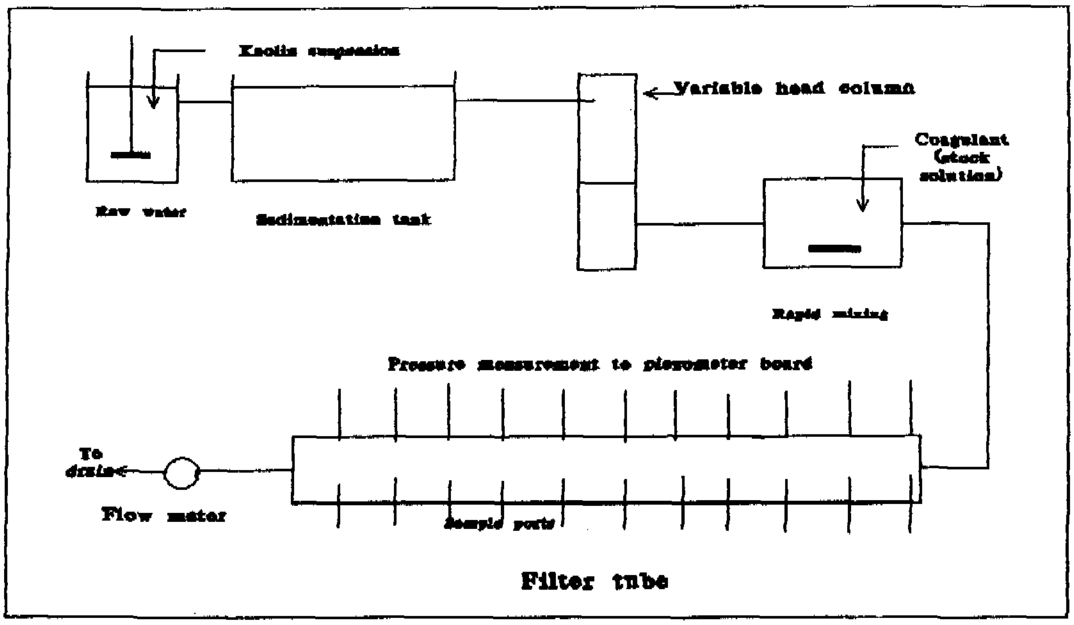


Fig 1 Schematic diagram of experimental DHRF set-up

The filter consists of perspex tubes, 2 m long and 0.19 m I.D. Over their length the tubes can be divided into compartments for different media. For some experiments filter tubes were connected in series to obtain longer filter beds. A description of the filter media used in the tests are given in Table 2.

Table 2 Description of filter media

category	mean size	size range	porosity
coarse	20 mm	15-20 mm	.38
medium	8 mm	5-10 mm	.38
fine	4 mm	3-5 mm	.40

For a typical 10 m HRF the allowable headloss is around 20-40 cm. In our experiments (run 1 to 20) with 2 m filters runs were terminated at 40 cm headloss to have data on full utilization of filter lengths. However, run 21 to 24 were terminated when the effluent turbidity was in excess of 20 NTU. Samples from filters were collected at regular intervals in the inlet and outlet of each compartment and also at each 20 cm of the filter bed lengths. The piezometric levels were also recorded for the corresponding points. Turbidity of the samples were measured by a turbidity meter (Dr. Lange Trübungspotometer LTP 4) and were expressed in NTU (Nephelometric Turbidity Unit). In total 24 experiments were conducted. The details of different process conditions are given in Table 3. The main variation in the parameters with each previous set of experiments is highlighted by the bold characters.

Table 3 Process Conditions of Experimental Runs

Run No	Length of 1st compartment (m) (Media size mm)	Length of 2nd compartment (m) (Media size mm)	Filtration rate (m/h)	Coagulant dose (mg(Al)/l)	Rapid mix time (min)	Rapid mix G value (s^{-1})	Average influent turbidity (NTU)
1	1 (20)	1 (4)	3	-	-	-	160
2	1 (20)	1 (4)	3	4.0	¾	500	160
3	1 (20)	1 (4)	3	1.0	¾	500	160
4	1 (20)	1 (4)	3	0.5	¾	500	160
5	1 (20)	1 (4)	3	1.0	2	400	160
6	1 (20)	1 (4)	3	0.5	2	400	160
7	1 (20)	1 (4)	3	1.0	4	200	160
8	1 (20)	1 (4)	3	0.5	4	200	160
9	1 (20)	1 (8)	3	-	-	-	160
10	1 (20)	1 (8)	3	1.0	4	200	160
11	1 (20)	1 (4)	5	-	-	-	160
12	1 (20)	1 (4)	5	1.0	4	200	160
13	1 (20)	1 (8)	5	-	-	-	160
14	1 (20)	1 (8)	5	1.0	4	200	160
15	1 (20)	1 (4)	5	-	-	-	510
16	1 (20)	1 (4)	5	1.0	4	200	510
17	1 (20)	1 (8)	5	-	-	-	510
18	1 (20)	1 (8)	5	1.0	4	200	510
19	1 (20)	1 (4)	5	3.0	4	200	510
20	1 (20)	1 (8)	5	3.0	4	200	510
21	2 (20)	2 (8)	7	1.0	4	200	200
22	2 (20)	2 (8)	5	1.0	4	200	200
23	2 (20)	2 (8)	3	1.0	4	200	200
24	2 (20)	2 (8)	1	1.0	4	200	200

RESULTS AND DISCUSSION

Comparing the Performance of DHRF with HRF

A summary of the results of different runs are given in Table 4. Turbidity removal efficiencies and headlosses of the the filter compartments and the filter run time is shown for each run. When comparing performance of DHRF and HRF it can be seen that DHRF yielded systematically higher removal efficiencies and longer filter runs. For these experiments improvements on turbidity removal efficiency is 20-50% higher and filter run length 0-110% longer. Fig 2 e.g. compares the results of two typical runs. For influent turbidity of 160 NTU and maximum headloss of 40 cm water column the average effluent turbidity of DHRF was 12 NTU as compared to 78 NTU for HRF. The run time for DHRF was 32 h as compared to 15 h for HRF. It is important to note that the run termination in HRF is caused by the amount of deposit that is

Table 4 Summary of Results

Run no.	Average influent turbidity	1st compartment			2nd compartment			Overall		
		Average effluent turbidity (NTU)	Removal efficiency (%)	Headloss at end of run (cm)	Average effluent turbidity (NTU)	Removal efficiency (%)	Headloss at end of run (%)	Average efficiency (%)	Headloss at end of run (cm)	Filter run length (h)
1	160	107	33	3	38	69	37	76	40	26
2	160	75	53	5	30	60	35	81	40	25
3	160	85	47	6	4	95	34	98	40	28
4	160	107	33	11	6	94	29	96	40	22
5	160	78	51	11	4	95	29	98	40	41
6	160	96	40	12	7	93	28	96	40	62
7	160	74	54	7	5	92	33	97	40	51
8	160	90	44	11	5	94	29	97	40	26
9	160	122	24	2	78	36	28	51	40	15
10	160	68	58	5	12	82	35	93	40	32
11	160	125	22	3	77	38	37	52	40	13
12	160	90	44	16	6	93	24	96	40	26
13	160	135	16	2	100	26	38	38	40	24
14	160	77	52	7	14	82	33	91	40	39
15	510	400	22	7	270	33	33	37	40	15
16	510	280	45	19	175	38	21	66	40	27
17	510	430	16	3	340	21	37	33	40	15
18	510	225	56	5	100	56	35	80	40	21
19	510	105	79	10	55	48	30	89	40	28
20	510	120	76	10	52	57	30	90	40	34
21	200	128	36	1.1	10.8	92	20.3	95	21.4	40
22	200	124	38	1.0	9.3	93	15.3	95	16.3	55
23	200	103	49	1.1	6.4	94	9.5	97	10.6	121
24	200	105	48	2.7	6.1	94	14.8	97	17.5	571

accumulated in the first coarse compartment [1]. The amount of deposit accumulated in the first coarse compartment of DHRF is much higher than HRF and yet the filter run time is consistently longer for the same headloss.

For example in case of HRF with filtration rate of 3 m/h and influent turbidity 160 NTU the amount of deposit per unit filter volume of the first compartment is around 4 g/L whereas in DHRF the amount is about 6 to 12 g/L.

The lower headloss development rate of DHRF could possibly be due to

(i) the enhanced removal (flocculation) of particles in the first coarse media compartment at the expense of 2 to 13 cm of total additional headloss. This would leave approximately 30% lower turbidity than HRF to be tackled in the next finer media compartment. The finer media (filtration) are more sensitive with respect to headloss development due to retained particles;

(ii) coagulation causes a reduction in number and hence the surface area of the flocs/particles retained in the filter pores. This is according to Edzwald [9] when explaining the lower headloss development in direct filtration and coagulation supported direct filtration;

(iii) the mode of deposition of the flocculated material in the pores, and the way it interacts with the flowing susprnsion, may create a condition less prone to headloss development;

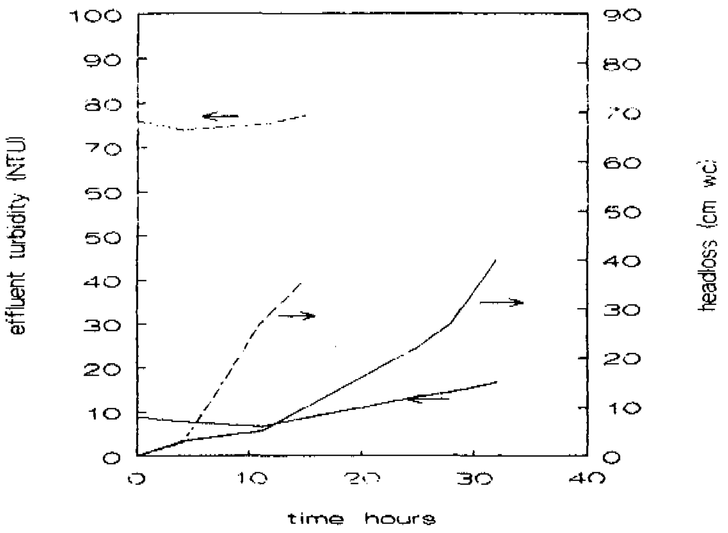


Fig.2 Comparing the performance of HRF and DHRF in terms of effluent turbidity and headloss. In both cases influent turbidity = 160 NTU, filtration rate = 3 m/h, 1st filter compartment length L_1=1m, d_1 = 20 mm and 2nd compartment L_2 = 1 m, d_2 = 8 mm. Coagulant dose [Al]=1 mg/l. Broken lines represents HRF and firm lines DHRF.

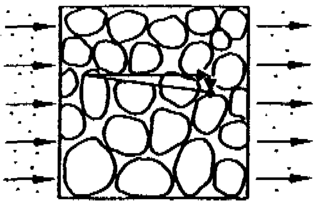
(iv) the deposited flocs may be easier to be dislocated under mounting hydraulic pressure and drift under gravity to the lower lying pores, thereby cleaning the upper pores. Visual observation shows that at the bottom of the filter the flocs age and form a progressively less voluminous and more granular sludge.

Mode of particle deposition

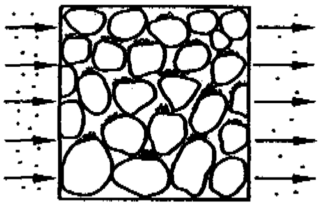
As mentioned earlier it can be observed from Table 4 that about half the initial turbidity and the bulk of $Al(OH)_3$ are removed in the first coarse media compartment. The perspex filter tubes allowed observation of the pattern of particle/floc deposition. It appears that the predominant particle removal process in the coarse media is sedimentation whereas the second media acts more like a conventional filter bed. This mode of particle deposition in the first compartment is similar to what was reported by Wegelin [7] for the smallest media size up to 4 mm. The horizontal movement of the particles through the filter pores is combined with a gravitational downward drift of particles. The solids settle on the top of the grains in the shape of heaps of sometimes several mm height. As the deposits exceed their slope stability, small lumps of settled matter will drift downward and resettle at the bottom of the filter. Fig 3 [7] schematises the mechanism described. This drifting process is advantageous as the removal capacity of the upper layers is restored to a certain extent.

The first coarse compartment of DHRF acts as a flocculator-settler and as mentioned earlier, the amount of particles deposited there is much higher compared to HRF. The reasons for this could be that :

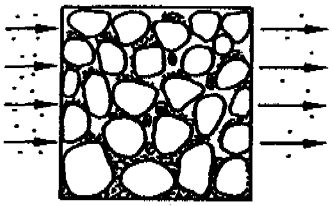
(i) due to addition of coagulant particles agglomerate and form bigger ones. The first coarse media compartment can be described as a multi-storied sedimentation basin with a very large total surface area where the



HRF acts as a multistore sedimentation tank



Accumulation of solids on the upper collector surface



Drift of separated solids to the filter bottom

Fig.3 Schematic diagram showing drifting in HRF [7].

agglomerated particles settle easily;

(ii) in-pore flocculation along the filter bed assists in agglomeration of particles which can settle faster;

(iii) the deposited flocs (together with coagulant) build up a layer of deposits with reduced surface charge over the filter media. Therefore preferential adsorption over the already deposited particles is likely to occur.

Fig 4a-d illustrates the variation of turbidity along the filter length for different time intervals and for different flow rates (runs 21 to 24). It can be observed that a clogging front is created in the second media which moves progressively forward. At the lower filtration rate of 1 m/h the clogging front is more pronounced. The finer media in the second (and third) compartment(s) can be explained to act as a number of vertical filtration layers, perpendicular to the flow direction. These layers become progressively clogged implying continuing filtration activities in the still unclogged layers in a mode similar to common vertical filtration.

The typical pattern of turbidity removal along the lengths of coarse and finer media compartments of all DHRF runs are schematized in Fig 5. In the first coarse compartment there is a gradual decrease of turbidity along the length which resembles the pattern of partial removal in a sedimentation basin. As the filter run time increases the filter pores are gradually filled up with deposits and the particle removal capacity decreases. At the end of the run the coarse media compartment almost losses its removal

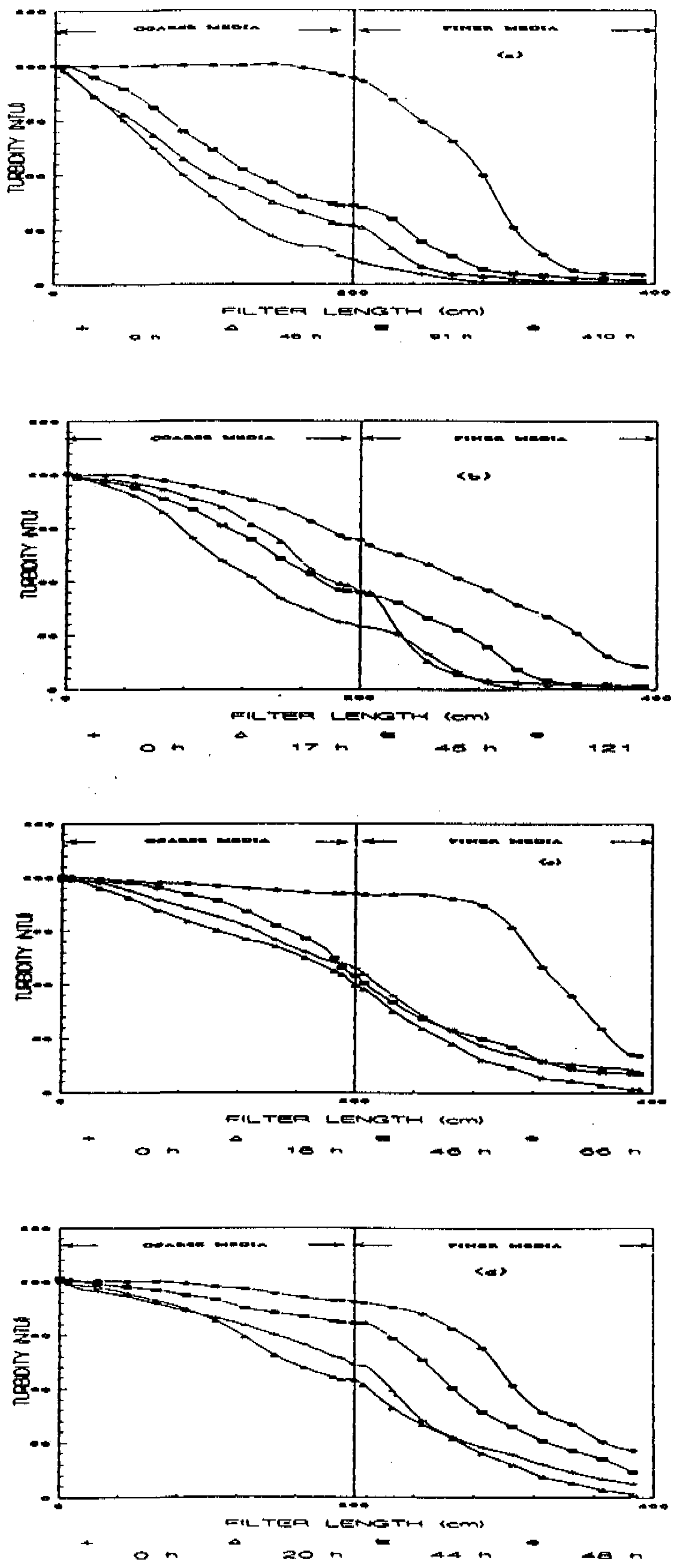


Fig.4 Variation of turbidity along the length of filter for different flow rates. Length of first compartment = 2 m, media size = 20 mm, length of second compartment = 2 m, media size = 8 mm. Coagulant dose [Al] = 1 mg/L. Initial turbidity = 200 NTU. Filtration rate (a) 1 m/h (b) 3 m/h (c) 5 m/h (d) 7 m/h.

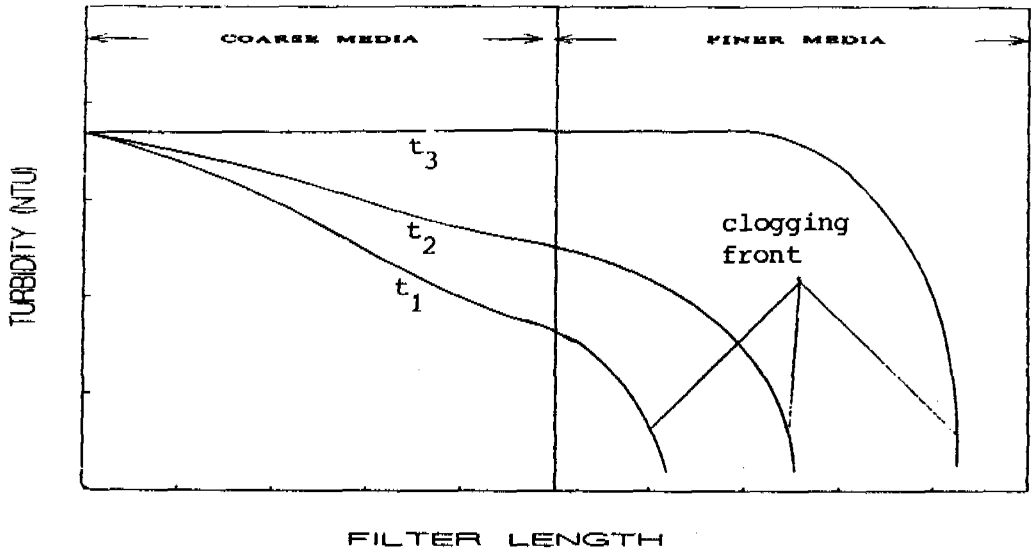


Fig. 5 Schematic pattern of turbidity removal in DHRF.

capacity. In the finer media compartment the progressive clogging front withfilter run time is shown. This pattern is similar to vertical deep bed filtration.

Coagulant dose

For the experiments involving 160 NTU influent turbidity coagulant dosing was varied from 0 to 4 mg Al/L (runs 1 to 4)(Fig.6). Maximum efficiency of 98% is achieved for Al dose of 1 mg Al/L. It can also be observed that the efficiency varied only 2% (96 to 98%) within a wide band of coagulant dose of 0.5 to 2 mg Al/L. Therefore, from the trend of the curve it appears that around the optimum dose of 1 mg Al/L, the dosage need not to be adjusted very precisely and also regular adjustment is not required. It has also been observed that DHRF can tackle moderate increase in influent turbidity without affecting the effluent quality significantly. The coagulant dose requirement for DHRF is much lower compared to the conventional flocculation-sedimentation process where dosages around 4-20 mg Al/L are generally required.

The right ordinate shows the corresponding filter run time with coagulant doses. The filter run time however does not seem to vary much with increasing dosage, highlighting again the excellent floc removal and accommodation capacity of the first compartment.

Filtration rate

Fig. 7 illustrates the dependency of the overall average efficiency in turbidity removal, and of the filter run time on the filtration rates (runs 21 to 24). The maximum effluent turbidity allowed in these cases is 20 NTU.

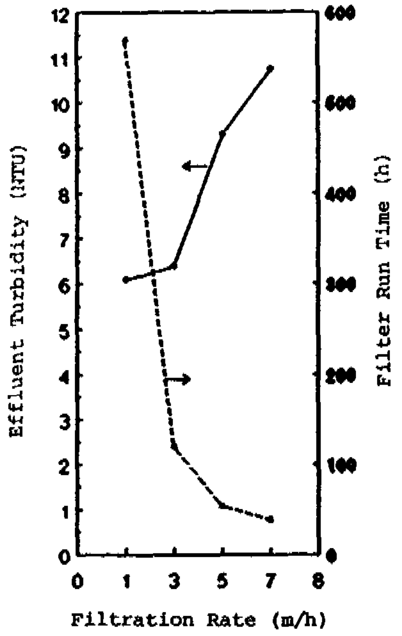


Fig.7 Relationship of effluent turbidity filtration rate.

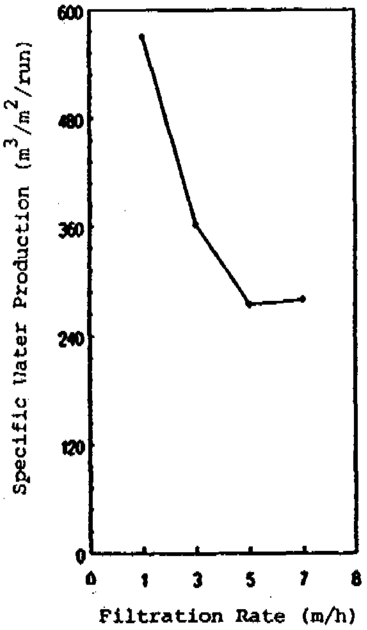


Fig.8 Relation between specific water and production per and with filtration rate.

turbidity of 510 NTU and at 5 m/h filtration rate, removal efficiency also increased (13 to 39%) as well as filter run time (0 to 127%).

Therefore it can be concluded tentatively that the filtration rate of DHRF can be at least twice that of HRF, yet yielding much higher turbidity removal. A preliminary cost estimate of DHRF (including a small coagulation basin of 4 min detention time and a constant-dosing system of the alum) indicates that the construction cost of DHRF per m^3 of produced water could be in the order of magnitude of 2 times lower than HRF (or conventional flocculation-sedimentation). The operation cost is a little higher than HRF as about 1 mg AL/L coagulant dose is required; of course it is much lower than the flocculation-sedimentation process which requires more chemicals and stricter process control. The DHRF can be constructed using locally available materials and manpower in developing countries.

The feasibility of DHRF prior to SSF would be restricted to rural or urban areas where coagulants are regularly available. The existing HRFs can easily be modified to DHRFs by constructing a small coagulation basin before the HRF. This could solve the problem of high effluent turbidity or short filter runs. DHRFs can also be used to increase the discharge of HRFs by applying a higher filtration rate, and/or to improve the quality of effluent to SSF.

CONCLUSIONS

The work reported herein intended to be exploratory in order make a first attempt at the optimization of the Direct HRF process and to gain insight in its underlying mechanisms. An important matter that will be studied in subsequent experiments is the optimization of sludge removal. Preliminary evidence shows that DHRF sludge can be more easily mobilized during hydraulic flushing than not flocculated sludge. The results so far indicate that coagulation in HRF is an effective process modification which can combine the better turbidity removal properties of Direct Filtration with the very high suspended solid storage capacity of HRF. Some of the limitations of HRF with high influent turbidity or higher filtration rate could be overcome in the DHRF mode. From the results of the study the following conclusions could be made :

1. Comparing the performance of DHRF with HRF it was found that DHRF systematically yields longer filter runs (approx. 160% more) with better removal efficiencies (approx. 40% more). DHRF can be applied at a higher filtration rate (3-5 m/h) than HRF (1 m/h).

2. The mode of particle/floc deposition in DHRF could be that the coarse media in the first compartment act as a gross particle collector in which sedimentation is the main process. The finer media in the second (and third) compartment(s) can be considered to act more similar to common deep-bed filtration.

3. By consequence, to optimise the DHRF, the first compartment should be optimized as settler, and the finer media compartment(s) as a deep-bed filter.

4. The optimum dose of Al for average presettled river water (160 NTU) is in the range of 0.5 to 2 mg/l. The optimum dose appears not to depend much on the filtration rate. This relatively low dose leads to considerable saving in chemical costs as compared to alternative conventional process of flocculation followed by sedimentation.

5. At low filtration rate (< 2 m/h) DHRF produced better effluent quality, longer filter runs and higher specific water production. However, by optimizing the DHRF compartments, it is expected that better performance can be achieved.

6.The cost of construction of DHRF per m^3 produced water is in the order of magnitude of 2 times lower than for HRF or conventional flocculation-sedimentation process. Thanks to its relatively low investment and operating cost, simplicity in operation and maintenance, DHRF could be an attractive low cost technology for township and urbanised areas in the developing countries.

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