How to Estimate and Design the Filter Run Duration of a Horizontal-Flow Roughing Filter

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Abstract

Among pre-treatment methods used before slow sand filters (SSF), horizontal-flow roughing filters (HRF) have been found to be the most effective and appropriate for application in developing countries. This is because they are simple, require no mechanical parts, have low capital cost, can be operated for a long time due to their high solids retention capacity, and with a wide variety of raw surface water characteristics. Most research on HRFs has concentrated on turbidity (solids) removal whereas the way to estimate and design the run duration time before filter (HRF) cleaning necessary has received little attention. In this research, a large gravel (size 10-20 mm) filter media were placed as a single package, uncovered and outlet at the top. It was found that the laboratory-scale filters used in this study provided a useful physical model with respect to the estimation of filter run over time, and the results were found to be in reasonable agreement with practical field experience. This model is a reasonable basis for the design of full scale HRFs and is easy to apply.

Keywords: Algae removal, motile algae, HRF (horizontal-flow roughing filter), filter run duration, turbidity

1.Introduction

Under tropical conditions, one possibility which has been used as pre-treatment before slow sand filtration for reducing the algae content of raw water is horizontal-flow roughing filtration (HRF) [1]. HRF is not only used for improving the physical water quality in order to meet the slow sand filter requirements but also for removing some bacteria and viruses ranging in size from approximately 10 to 20 μm and 0.4 to 0.02 μm, respectively [2]. The most common type of HRF, which has been used widely, was developed by Wegelin [3] is shown in Figure 1. Furthermore Sittivate [4] found that the large gravel media (size 10-20 mm) which were used in the filters with the outlet at the top of an HRF (similar to Wegelin [2] ,[3]) produced the best results for algae and turbidity removal (more than 95% and 90% on average, respectively) and sedimentation was considered to be the principal mechanism responsible for the removal of algae and turbidity in raw water at the low filtration rate (0.3 m/h).

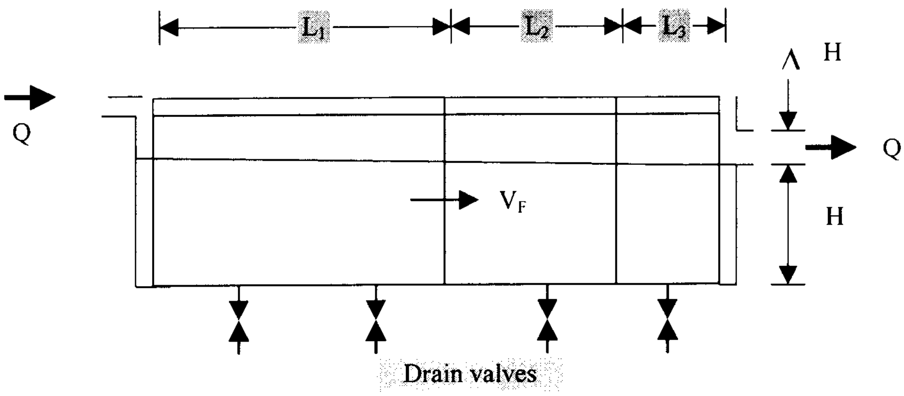
The objective of this research was to devise a simple method by which horizontal-flow roughing filters could be designed for field application under tropical conditions and their long-term performance predicted. This essentially requires an understanding of the process variables, knowledge of the pertinent mechanisms of removal of particulate matter, including algae, and the availability of equations to describe the time-space variation and accumulation of materials inside the filter media.

Many theoretical equations have been developed to describe the filtration process and, particularly, to try to estimate the time of run duration for HRF design However, some parameters and constants in these equations are not universal and will, no doubt, vary with each combination of influent characteristics and filtration conditions [5].

Moreover, when designers have applied such equations they have had to make many assumptions of those parameters for the estimation of results.

It is known that the diversity of removal mechanisms causes the flow of suspended particles through porous media to be a very complex phenomenon. In the present study, the run duration time of the HRF model was rather short. Therefore, it is logical to consider the main removal mechanism is sedimentation of the incoming solids and algal mass in the large gravel media filter [4].

In spite of the difficulty of accounting for all variables, it was decided to use the results obtained in the experiments of this study to develop another approach to design the HRF and estimate the run duration before cleaning is necessary.



List of symbols

d_g	(mm)	gravel size
H	(m)	filter depth
$L_{1,2,3}$	(m)	filter length
W	(m)	filter width
A	(m^2)	filter cross-section area
Q	(m^3/h)	flow rate
Qd	(m^3/h)	drainage rate
VF	(m/h)	filtration rate
Vd	(m/h)	drainage rate

design guidelines

$$V_F = \frac{Q}{H \cdot W} = \frac{Q}{A} = 0.3 - 1.5 \text{ m/h}$$

$$Vd = \frac{Q}{(L_1+L_2+L_3) \cdot W} \sim 60 - 90 \text{ m/h}$$

$\Delta H \sim 30$ cm

$H \sim 0.8 - 1.20$ m

$d_g = 12 - 18$ mm, $L_1 \sim 2 - 4$ m

$d_g = 8 - 12$ mm, $L_2 \sim 1 - 3$ m

$d_g = 4 - 8$ mm, $L_3 \sim 1 - 2$ m

Figure 1: Layout and Design of a Horizontal-flow Roughing Filter (Wegelin, 1996)

2. Experimental Procedure

2.1 Pilot Plant

The pilot plant system [4] shown in Figure 2 consisted of the following: (1) A plastic filter box composed of two symmetrical rectangular channels with dimensions of 1.6 m × 0.39 m × 0.195 m each; the lateral walls of the filter box were fitted with sampling ports. (2) Two plastic cylindrical tanks (total volume of one cubic metre) with an internal diameter of 1.60 m and height of 0.50 m; these were the feed tanks which contained algae and clay to simulate tropical surface water. (3) Two stirrers for mixing the suspension in the large tank. (4) A light source constructed from lightweight steel bars to carry fluorescent tubes; this was suspended over the two large tanks. (5) Two peristaltic pumps were used to feed the suspension from the algae inoculation tanks into the filters.

The suspension of turbidity and algae from the large tanks was pumped into the inlet chambers of each filter, passed through the gravel media and discharged into the outlet chambers of each filter. During the filter runs, effluent water samples were analysed following the method of Standard Methods for Examination of Water and Wastewater [6], mainly to determine the DO concentration, turbidity and pH. The chlorophyll *a* concentration was also determined as a measure of the algae concentration. The pilot study plant was installed in a specific room where the temperature was controlled between 19 and 23° so as to maintain good environmental condition for algal growth in the large tanks [4].

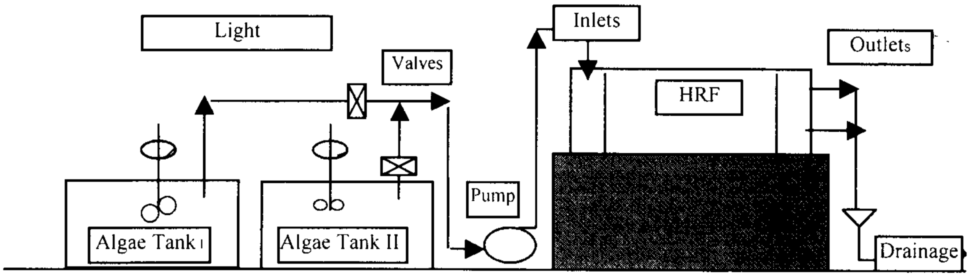


Figure 2: A schematic diagram of filtration equipment (not to scale)

2.2 Design of Synthetic Raw Water

To prepare a medium with a high algae content in the preparation of an appropriate raw water, one factor which was considered was turbidity. High turbidity in water inhibits photosynthesis and thus reduces the production of oxygen by algae as well as algal growth [7]. Two types of motile green algae (*Euglena gracilis* and *Chlamydomonas reinhardtii*) were chosen as representative algae for this research [4]. Wegelin [3] suggested that the possibility of annual turbidity maximum in raw water sources in tropical areas is normally not higher than 100 NTU. As a result, it was decided to set the turbidity of the synthetic raw water at 100 NTU for every run in this research. Algae inoculation in the large tank used the methods suggested by The Institute of Freshwater Ecology (Ambleside, UK). The required turbidity was achieved by the addition of a known weight of clay, which would produce turbidity 100 NTU in the water in the large tank and maintained in suspension by continuous stirring [4]. The type of clay used was kaolin clay (Speswhite china clay) supplied by ECC International Ltd, Cornwall, England.

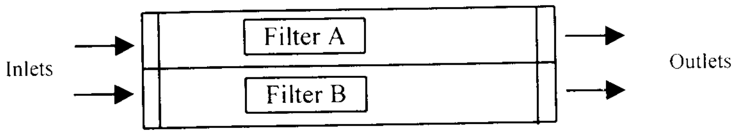
2.3 Experimental Planning

Experiments as shown in Table 1 and in the Filter diagram (Figure 3) were performed on the 1.60 m long channel. The filtration rate was 0.3 m/h throughout the study.

Table 1: Planning of experiments

Run no.	Filter	Algae type	Influent turbidity (NTU)	Influent algae content during the run (μg/l)	Gravel size (mm)	Outlet position
1	A	E	125 to 195	6.49 to 37.66 μg/l	L	T
	B	E	125 to 195	6.49 to 37.66 μg/l	M	T
2	A	E	230 to 235	19.48 to 151.95 μg/l	L	T
3	A	C	145 to 198	86.10 to 363.12 μg/l	L	T
4	A	E & C	150 to 260	238.83 to 360 μg/l	L	T

Notes: A = Filter A, B = Filter B. E = *Euglena gracilis*, C = *Chlamydomonas reinhardtii*.
L = Large gravel, sized 10 - 20 mm. M = Medium gravel, sized 5 - 10 mm.
T = Outlet at the top, 0.16 m from the bottom of the filter bed.
Clogged filter volume = Filter volume accumulated by suspended solids (SS) and gravel media.
Inlet turbidity (NTU) = Clay turbidity + turbidity produced by algae [4].



Run nos.1 to 4.

Figure 3: Plan view of filter showing flow of synthetic raw water pass through filters

3. Results

Throughout the study, the filter volumes in which suspended solids and microorganisms accumulated in the pore spaces of the filter media over time were measured. Linear measurements of the dimensions of the clogged area profile along the side of both filters were made at various times in every run and converted into volumes of the filter by multiplication of the filter width (0.195 m). These data are given in Tables 2 to 6. Note that this total volume is composed of the volume of gravel media and solids particles (microorganisms and clay) occupying the filter media pore spaces.

Table 2: Accumulation of solids mass in the large gravel media (size 10-20 mm) filter volume in Run No.1: Algal culture = *Euglena gracilis*

Accumulated time (h)	Clogged filter volume (cm^3)	Time difference (h)	Clogged filter volume difference (cm^3)	Clogged filter volume difference / difference time (cm^3/h)	Influent turbidity (NTU)
33	4,095.00	-	-	-	195
56	7,020.00	23	2,925.00	127.17	170
96	9,740.25	40	2,720.25	68.01	140
126	13,308.75	30	3,568.50	118.95	170
242	14,820.00	116	1,511.25	13.03	-
365	22,985.63	123	8,165.63	66.19	120
484	28,255.50	119	5,269.87	44.28	145
557	35,012.35	73	6,756.75	92.56	125
			average =	**75.77**	**152.14**

Table 3: Accumulation of solids mass in the medium gravel media (size 5-10 mm) filter volume in Run No.1: Algal culture = *Euglena gracilis*

Accumulated time (h)	Clogged filter volume (cm^3)	Time difference (h)	Clogged filter volume difference (cm^3)	Clogged filter volume difference / difference time (cm^3/h)	Influent turbidity (NTU)
33	3,968.25	-	-	-	195
56	6,313.13	23	2,344.88	101.95	170
96	6,669.00	40	355.87	8.90	140
126	11,407.50	30	4,738.50	157.95	170
242	14,430.00	116	3,022.50	26.06	-
365	17,788.88	123	3,358.88	27.31	120
484	21,498.75	119	3,709.87	31.18	145
557	23,751.00	73	2,252.25	30.85	125
605	26,822.25	48	3,071.25	63.98	120
			average =	**56.02**	**148.13**

Table 4: Accumulation of solids mass in the large gravel media (size 10-20 mm) filter volume in Run No.2: Algal culture = *Euglena gracilis*

Accumulated time (h)	Clogged filter volume (cm^3)	Time difference (h)	Clogged filter volume difference (cm^3)	Clogged filter volume/ difference time (cm^3/h)	Influent turbidity (NTU)
28	25,072.13	-	-	-	235
52	32,048.25	24	6976.12	290.67	-
82	44,850.00	30	12,801.75	426.73	230
97	49,530.00	15	4,680.00	312.00	225
145	61,161.75	48	11,631.75	242.33	230
			average =	**317.93**	**230**

Table 5: Accumulation of solids mass in the large gravel media (size 10-20 mm) filter volume in Run No.3 : Algal culture = *Chlamydomnas reinhardtii*

Accumulated time (h)	Clogged filter volume (cm^3)	Time difference (h)	Clogged filter volume difference (cm^3)	Clogged filter volume difference / difference time (cm^3/h)	Influent turbidity (NTU)
53	16,321.50	-	-	-	198
79	21,674.25	26	5,352.75	205.88	145
127	29,250.00	48	7,575.75	157.83	150
223	33,783.75	96	4,533.75	47.23	145
319	38,288.25	96	4,504.50	46.92	145
415	55,282.50	96	16,994.25	177.02	145
487	60,094.13	72	4,811.63	66.83	150
			average =	**116.95**	**154**

Table 6: Accumulation of solids mass in the large gravel media (size 10-20 mm) filter volume in Run No.5: Algal culture = *Euglena & Chlamydomonas*

Accumulated time (h)	Clogged filter volume (cm^3)	Time difference (h)	Clogged filter volume difference (cm^3)	Clogged filter volume difference / difference time (cm^3/h)	Influent turbidity (NTU)
78	23,868.00	-	-	-	260
105	29,401.13	27	5,533.13	204.93	210
130	42,237.00	25	12,835.88	513.44	200
150	47,580.00	20	5,343.00	267.15	185
191	61,161.75	41	13,581.75	331.26	150
			average =	**329.20**	**201**

4. Discussion

4.1 Progression of Filter Volume Occupied by Suspended Solids and Filter Media

In HRFs, the filtration rate is assumed to remain constant throughout a filter run and the type of flow in filter media is **plug flow** [3].Tchobanoglous [8] suggested that, in general, the mathematical characterisation of the time-space removal of particulate matter within the filter is based on a consideration of the equation of continuity, together with an auxiliary rate equation. The equation of continuity for the filtration operation may be developed by considering a suspended solids mass balance for a section of filter of cross-sectional area, and of the thickness, measured in the direction of flow. The mass balance would be as follows:

a) General word statement:

Rate of accumulation of solids within the volume element = Rate of flow of solids into the volume element – Rate of flow of solids out of the volume element (1)

b) Simplified word statement:

Accumulation = [inflow - outflow] - degradation (2)

However, it was found that the degradation in HRF occurred very little [4]. Hence, the last term in equation (2) is negligible.

c) Symbolic representation of equation (1) [8]:

$$dV \frac{\partial C}{dt} = -Q\,\partial C \frac{dx}{\partial x} \quad (3)$$

where,

dV = differential volume of reactor or filter (L^3)

$\partial C/dt$ = rate of change of suspended solids concentration within the container or filter ($ML^{-3}T^{-1}$)

Q = volumetric rate of flow into and out of the reactor or filter ($L^3\,T^{-1}$)

$\partial C/\partial x$ = change in concentration of suspended solids in fluid stream with distance ($ML^{-3}.L$)

dx = differential distance of filter (L)

C = concentration of suspended solids in reactor or filter (ML^{-3})

If $A\ dx$ is substituted for dV, the resulting expression is

$$A\,dx\,\frac{\partial C}{dt} = -Q\,\frac{\partial C}{\partial x}\,dx \qquad (4)$$

where; A = cross-sectional area of filter (L^2)
Therefore, equation (4) may be rewritten:

$$A\,\partial x\,\frac{\partial C}{dt} = -\,Q\,\partial C \qquad (5)$$

It can be said that the first term of equation (5) is the different weight of solids accumulated in the pore space of the filter media over the different time. Hence, equation (5) may be rewritten as an ordinary differential equation:

$$\frac{dP}{\Delta t} = -\,Q\,dC \qquad (6)$$

where;

P_t = weight of suspended solids retained in the filter media at any time (M)
Δt = different time (T)

Therefore, equation(6) can be rewritten in a form suitable for numerical analysis:

$$\frac{\Delta P_t}{t_2 - t_1} = Q\,\Delta C. \quad \text{or}$$

$$\frac{P_{t2} - P_{t1}}{t_2 - t_1} = Q\,[(C_{SSt2} - C_{SSOt2}) - (C_{SS\,t1} - C_{SSOt1})] \qquad (7)$$

where;
P_t = weight of suspended solids retained in the filter media at any time (g)
Q = flow rate through the cross-sectional area of filter (m^3/h)
$C_{SS\,t1}$ = concentration of suspended solids in the influent at time t_1 (g/m^3)
$C_{SS\,t2}$ = concentration of suspended solids in the influent at time t_2 (g/m^3)
C_{SSOt1} = concentration of suspended solids in the effluent at time t_1 (g/m^3)
C_{SSOt2} = concentration of suspended solids in the effluent at time t_2 (g/m^3)
A = cross-sectional area of filter (m^2)
v_F = filtration rate (m/h) , t = time (h)

This can be rewritten;

$$V_2)(\gamma_{t2})\,f_o - (V_1)(\gamma_{t1})\,f_o = A\ v_F\ X$$

$$[(C_{SST2} - C_{SSOT2})\,t_2 - (C_{SST1} - C_{SSOT1})\,t_1] \qquad (8)$$

where;

V_1 = filter volume occupied by suspended solids and filter media at time t_1 (cm^3)
V_2 = filter volume occupied by suspended solids and filter media at time t_2 (cm^3)
γ_{t1} = total unit weight of solids mass accumulated in the pore space of filter media at time t_1 (g/cm^3)
γ_{t2} = total unit weight of solids mass accumulated in the pore space of filter media at time t_2 (g/cm^3)
f_o = porosity of the bed when clean (V_o / V_f)

The time difference between t_1 and t_2 is not much. Hence, it can be said that $\gamma_{t2} \approx \gamma_{t1} = \gamma_t$
Therefore, equation (8) may be rewritten;

$$\frac{f_o(\gamma_t)\,[V_2 - V_1]}{t_2 - t_1} = A\ v_F\,[(C_{SST2} - C_{SSOT2})\,t_2 - (C_{SST1} - C_{SSOT1})\,t_1] \qquad (9)$$

where;

γ_t = total unit weight of solids massaccumulated in the pore space of filter media

The filter volume (V_2, V_1) and porosity (f_o) are easily measured but it is very difficult to measure the total unit weight of solids mass accumulated in the pore space of filter media (γ_t). This is because the suspended solids content will be different at any depth or at any length in the pore space of the filter media of the HRF, and at any time as influenced by the drag force of fluid, velocity of flow through the pore space of the filter media, gravity and the characteristic diameter of the solids particles (Fair *et al.*, 1968) during the run duration. So the first term of equation (9) cannot be used to estimate the solids mass retained in the filter. However, all parameters in the last term of equation (9) can be measured and used to estimate the solids mass retained in the filter media

Hence, it follows that $(V_2 - V_1)$ is occupied by gravel media and solids mass A v_F $[(C_{SSt2} - C_{SSOt2})\, t_2 - (C_{SSt1} - C_{SSOt1})\, t_1]$. Therefore, the rate of filter volume occupied by gravel media and solid mass, per time, is equivalent to the difference in weight of suspended solids mass accumulated in the pore space of filter media over the time change, divided by porosity of gravel media and total unit weight of solids mass accumulated in the pore space of filter media. Hence, equation (9) after rearranging the terms, yields;

$$\frac{V_2 - V_1}{t_2 - t_1} \cong \frac{A\ v_F\,[(C_{SSt2} - C_{SSOt2})\, t_2 - (C_{SSt1} - C_{SSOt1})\, t_1]}{f_o\,(\gamma_t)} \qquad (10)$$

Sittvate [4] indicated that under the same operating conditions as adopted for the large gravel media filter, the medium gravel (size 5-10 mm) filter with less pore space than the large gravel media filter, was blocked faster than the large gravel media filter. This resulted in the duration of a filter run for a medium gravel media filter becoming shorter than that for a large gravel media filter. Furthermore, because taking many samples along the bed of the large gravel filter over time drew out clay from the pore spaces, as observed in the first run it was decided, therefore, not to use the result from Table 2 and 3 in this analysis. For the large gravel media filter model, the filter volume occupied by suspended solids and filter media at different times, from tables 4 to 6, were 317.93, 116.95 and 329.20 cm^3/h, respectively. In addition, Sittivate [4] found that the patterns of the removal characteristics for *Euglena gracilis* and *Chlamydomonas reinhardtii* in HRF were similar. Hence, the average filter volume occupied by suspended solids and filter media at different times

$$= \frac{317.93 + 116.95 + 329.20}{3}$$

$$= 254.69 \sim 250 \text{ cm}^3/\text{h}$$

Hence, with the outlet at the top and a filtration rate of 0.3 m/h (**at average influent turbidity = [230 + 154 + 201] / 3 = 195 NTU**), the average change of filter volume over time accumulated by gravel media and suspended solids mass (clay and algal mass) in the large gravel media (size 10-20 mm) filter is 250 cm^3/h. Hence, the average change of filter volume accumulated by gravel media and suspended solids mass (clay and algal mass) in the large gravel media filter pore space over time (See equation (10)) is **110 cm^3/h** (=250 cm^3/h × porosity of gravel media = 250 cm^3/h × 0.4372)

This rate could be the basis of both the design of HRFs, and estimates of the run duration times for scaled up HRFs.

4.2 Confirmation of Results

Checking this value (110 cm^3/h) was achieved by estimating the run duration time of the large gravel filter model which normally failed by solids blocking along the filter length in 10 days [4];

The effective volume pore space of filter model occupied by large gravel media

$= 19.5 \times 20 \times 153 \times 0.4372$

$= 26{,}087.72 \text{ cm}^3$

$\therefore$ Run duration time $= 26{,}087.72/110 \times 24$

$= 9.88$ days~10 days

4.3 Scale-up Considerations

As shown in Section 4.2, for the conditions of filtration velocity (v_F) = 0.3 m/h and with the filter outlet at the top, it was calculated that:

$$R\,(\text{day}) = \frac{(\text{Volume of filter model occupied by gravel media (cm}^3)\,(f_o))}{110\,(\text{cm}^3/\text{h}) \times 24} \qquad (11)$$

where;

R = Run duration (days) before filter cleaning is necessary.

Let,

A_m = The cross-sectional area of filter model (= 19.5×20 cm^2)
L_m = The length of filter model (internal)
W_m = The width of filter model (internal)
D_m = The depth of filter model (internal)
f_o = porosity of the bed when clean(V_o / V_f)

Hence, equation (11) will be;

$$R = \frac{A_m.L_m\ (f_o)}{110\ (\text{cm}^3/\text{h}) \times 24}$$

$$\text{or} = \frac{(W_m.\ D_m.) \times L_m\ (f_o)}{2{,}640\ (\text{cm}^3/\text{h})} \qquad (12)$$

This filter model will also fit the prototype (the large-scale design for field application), on the basis of an implied confidence in the principles of geometrical and dynamical similarity. Henderson [9] suggested that the detailed interpretation of model measurements requires that scale ratios be available for translating model values for various quantities, e.g., velocity, discharge, etc., into the corresponding prototype values. Scales can be deduced for all physical quantities if scales are known for mass, length, time, and the physical properties of prototype and model fluids.

The prototype will have conditions similar to the filter model in this study, for instance the low filtration rate (0.3 m/h), position of the outlet, gravel media size, and influent turbidity. The scale ratio of this model and the prototype can be obtained from the cross-sectional area of the prototype divided by the cross-sectional area of the model. This is because the filtration rate (v_F) in the design of the prototype is equal to that in the model and the depth of the filter is not significant in the filter behaviors [10]. Hence, this scale model ratio can be calculated as follows:

From $Q = Av$ (13)

therefore, $Q_p = A_p.v_F$ (14)

and, $Q_m = A_m.v_F$ (15)

where;

Q_p = flow-rate through the cross-sectional area of filter prototype (m^3/h)
Q_m = flow-rate through the cross-sectional area of filter model (m^3/h)

Equation (14) / Equation (15) gives,

$$\frac{Q_p}{Q_m} = \frac{A_p.v_F}{A_m.v_F} = \frac{A_p}{A_m}$$

therefore;

$$Q_p = (A_p/A_m).\ Q_m \qquad (16)$$

$$A_p/A_m = m_1 \qquad (17)$$

where;

m_1 = scale ratio of prototype and model

Hence, for the large scale of HRF (prototype) with the same conditions as in the model, the run duration can be estimated by;

$$R = \frac{A_p.L_p\,(f_o)_p}{2{,}640\ (m_1)} \qquad (18)$$

where;

L_p = the length of filter prototype (m)
$(f_o)_p$ = porosity of the bed of filter prototype when clean (V_o / V_f)

It was found that $R \propto 1/\ v_F$ and $R \propto 1/$ influent turbidity (NTU) [2], therefore, equation (18) could be modified by these proportional relationships for use in the design of a HRF, as follows [9]:

$$R = \frac{A_p.\ L_p\,(f_o)_p}{2{,}640\ m_1(v_F)_p/(v_F)_m\ (NTU)_p/(NTU)_m} \qquad (19)$$

when;

$m_2 = (v_F)_p\ /\ (v_F)_m$

$m_3 = (NTU)_p\ /\ (NTU_m$

Equation (19) becomes,

$$R = \frac{A_p . L_p . (f_o)_p}{2,640. m_1 . m_2 . m_3} \qquad \textbf{(20)}$$

4.4 Model validation

From equation (20), it can be said that the filtration rate and turbidity are the main parameters which affect the run duration and turbidity removal efficiency as Wegelin [2] found. If the gravel media is chosen as in Wegelin [3]'s design guidelines, the porosity of the gravel media size 10-20 mm will not affect this equation. As a result, this model is valid for use in HRF design, for the filtration rate adopted and up to the influent turbidity of raw water used in the study.

Lebcir [10] also found that:

- Particles are removed mainly by sedimentation and the removal is slowed by increasing the filtration rate or Reynolds Number.
- Laminar flow conditions prevailed when the filtration rate was less than 1 m/h and 2 m/h for large gravel media filter (LGF) and small gravel filter (SGF), respectively (both outlet at the top).
- The pattern of the turbidity distribution inside the bed is in conformity with that of the sedimentation tanks at flow velocities between 0.5 - 1 m/h. This is because these flow velocities are low enough to not cause turbulence in the gravel filter media.
- For the depth of bed channel, studies to date merely state the problems of structural constraints that can be faced with deep channels and they do not give any indication of whether the depth will influence filter behaviour.

Hence, equation (20) could be valid if the filtration rate does not exceed 1 m/h for the large and medium gravel filter media and the other conditions are as in this study. This is because within this range the conditions inside the filter media are assumed to not change. This equation should be used with the low filtration rate of 0.3 m/h for the scaled up design as in this study, because it was found that, with these filters used in this study, both algae and turbidity removal were more than 90% at this filtration rate. Moreover, this filtration rate was found to be suitable for operation and has produced turbidity removal efficiencies more than 80% in field installations ([3] and [11]).

4.5 Confirmation of the Physical Modelling

Although equation (20) has been developed to be a simple tool for the design and estimation of the run duration time of a HRF, it is still not proven on the larger scale. However, the horizontal-flow roughing filters used in the Blue Nile Health Project in Sudan [12], were similar to this model and the results reported by Brown can be used to confirm the applicability of equation (20). A plan view of the HRF series used in the Sudan is shown in Figure 4.

Brown (1988) reported on two runs where the run duration of the filter (Figure 4) was terminated when solids accumulated in the filter media pore spaces to the point of breakthrough. In the first run, with a filtration rate of 0.4 m/h and average influent turbidity 300 NTU, the run duration time was 20 days. In the second run (after cleaning), with average filtration rate 0.45 m/h and average influent turbidity 312 NTU, the run duration time was 14 days.

From equation (20); for the first run,

$$R = \frac{A_p . L_p . (f_o)_p}{2,640\ m_1 . m_2 . m_3}$$

$$A_p = 1 \times 0.95 \times 10,000\ cm^2$$

$$m_1 = \frac{0.95 \times 1.00 \times 10,000}{19.5 \times 20} = 24.36$$

$$m_2 = (V_F)_p / (V_F)_m = 0.4 / 0.3 = 1.33$$

$$m_3 = (NTU)_p / (NTU)_m = 300 / 195 = 1.54$$

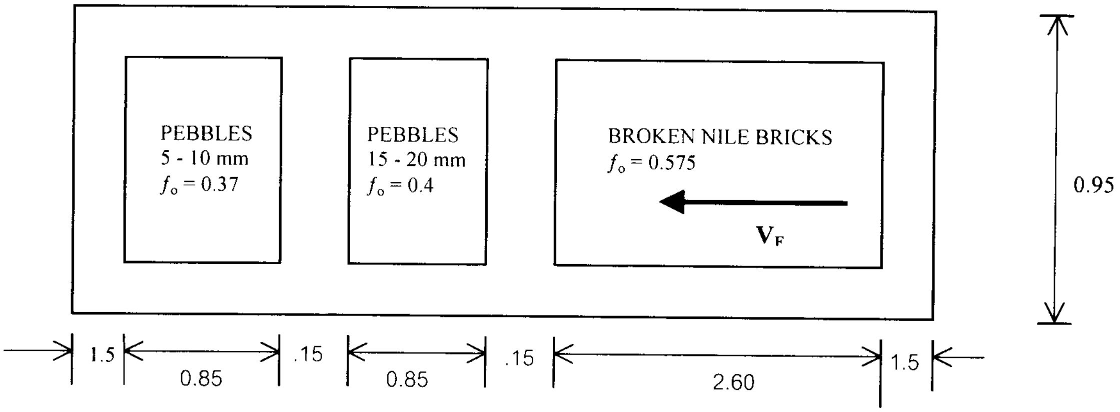


Figure 4: Plan View of the Horizontal Flow Roughing Filter used in Blue Nile Health Project in Sudan [12] (not to scale)
Note: The depth of this filter was 1 m.

Substituting these values in equation (20), provides the estimated run duration time for the first run;

$$R = \frac{1 \times 0.95 \times 1{,}000{,}000 \times (2.9 \times 0.575 + 1 \times 0.40 + 1 \times 0.37)}{2{,}640 \times 24.36 \times 1.33 \times 1.54}$$

= 17.58 days (cf. 20 days in Brown's results)

For the second run,

$m_2 = (V_F)_p / (V_F)_m = 0.45 / 0.3 = 1.5$

$m_3 = (NTU)_p / (NTU)_m = 312 / 195 = 1.6$

Substituting these values in equation (20), provides the estimated run duration time for the second run;

$$R = \frac{1 \times 0.95 \times 1{,}000{,}000 (2.9 \times 0.575 + 1 \times 0.40 + 1 \times 0.37)}{2{,}640 \times 24.36 \times 1.5 \times 1.6}$$

= 15 days (cf. 14 days in Brown's results)

It would appear that equation (20) gives a reasonable agreement with practical field experience and the estimation of HRF run duration obtained from the equation is a reasonable basis for design. As a result of this, Figure 5 was constructed in order to provide some guidelines for design and estimation of the run duration for the large gravel media (10-20 mm) HRF operating under the conditions as shown in Figure 5. For each given turbidity and filter length, the run duration in days can be read off. For example, with input turbidity (including algae and suspended solid particles) 150 NTU and a filter length of 7 m, the corresponding run duration time is sixty days (Figure 5).

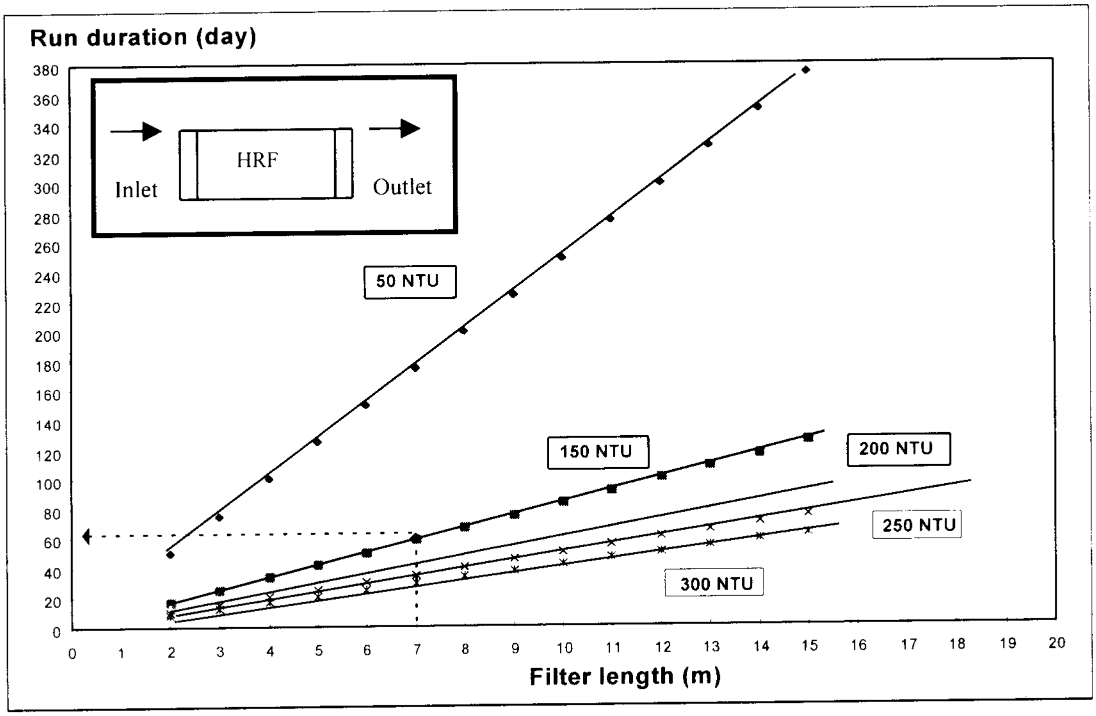


Figure 5: Design guidelines for large gravel media filter (size 10-20 mm) with outlet at the Top, porosity (f_o) = 0.43, filtration velocity = 0.3 m/h, depth of water level = 1.0 m, gravel media filter depth ~ 1.05 m, and width of the filter = 1.00 m.

5. Conclusion

Due to the fact that there was not sufficient time over the period of the experimental programs to cover a full statistical evaluation of all design variables such as filtration rate, cross-section area of the filter, the length of the filter media, the size of the filter media, the influent characteristics of raw water (turbidity) etc., a comprehensive design model is not possible. However, based on experimental findings and theoretical considerations, the physical models which have been developed in this study can provide significant improvement on previous design and could be used in the design and to estimate the run duration time of HRFs.

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