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Development of analytical chart for design of granular mono media (sand) deep-bed water treatment filters

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Abstract

This research focuses on the development of an analytical chart for design of granular mono-media deep-bed (depth) sand filters. Evaluation of filter efficiency for granular media deep-bed filters was carried out using data acquired from pilot filter test runs. Variables, such as grain size distribution (GSD), media depth, filtration rate, turbidity and filter run length were found to dictate the efficiency of filters measured by the quality and quantity of treated water produced.An effluent quality model relating filter media depth with quantity of suspended solids (turbidity) removed and a filter resistance model relating head loss with filter run time were applied in determining the limiting values for the chart. Filter media can be designed using beds of uniform or non-uniform grain sizes. The chart developed in this research allows for the selection of beds of uniform or non-uniform grain sizes for deep-bed filters. The results from the study show that a large number of filters of various configurations can be designed, constructed and operated at economic cost in time and money. The chart will facilitate the work of designers and managers of potable water treatment plants in developing and developed countries of the world.

1. Introduction

Filter materials can be mono, dual or multi-media. The effectiveness of using sand alone in filters is dependent on the initial raw water quality, the characteristics of the sand used and the filtration rate applied during filtration. Mono-media (sand) filters compete favourably with dual-media (anthracite/sand, pumice-sand or similar) filters with a coarse lightweight material on top of a fine heavier sand layer.

Solids removal during filtration through granular media filters involves a combination of complicated processes. Some of the processes include (i) physical straining (ii) transport (iii) attachment (iv) detachment (v) chemical and (vi) biological activity.

Fig 1.1 is an illustration of transport mechanisms applicable to depth filtration (AWWA, 1999). These mechanisms that affect filter performance are interactive and therefore constitute an important feature in the development of filtration models.

Filter hydraulics is made up of two components, the filtration process by which water is purified and the backwashing operation by which the filter is cleaned. The rate of flow through a filter is directly proportional to the driving force and inversely proportional to the filter media resistance and the solids retained by the media. This can be expressed as:

Flow rate (Q)$\propto$driving force / media resistance .. . .(1.1)

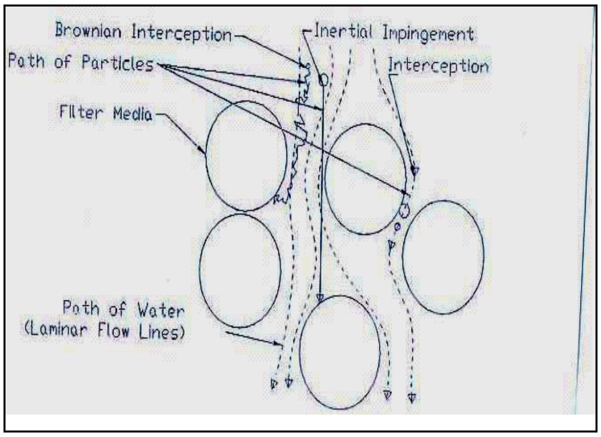

Fig.1.1. Transportation mechanisms in deep-bed filtration.

In gravity filtration, the driving force is a measure of the water head or pressure drop for overcoming the filter resistance. The pressure drop is measured as the difference in water level above the filter media and in the clear well to which the effluent discharges.

This investigation on development of analytical chart for design of deep-bed (depth) filters focuses on the use of mono-media (sand) filter material.
Turbidity, suspended solids concentration and particle count were applied in the computation of removal efficiencies for selected pilot filters. These efficiencies indicate the relative performance of the pilot filters as regards effluent quality and water production per cycle (WPPC) of filter run.

The results obtained from efficiency studies and hydrodynamic modelling of filters were used as tools for development of an analytical chart for design and dimensioning of sand filters. The chart will facilitate the work of design, construction and operation engineers who carry out water purification for domestic, commercial and industrial uses with the objective of achieving set goals of effluent quality standards at optimum costs in temporal and economic terms.

2. Materials and methods

2.1. Materials

Filter media used was silica sand, a bulk filtration media, which is porous with pores, used as particulate collectors. Grain size for silica sand (specific gravity 2.65, uniformity coefficient (uc) 1.5) is in the range 0.4 mm to 1.7 mm.

The raw waters used were of low turbidity (< or = 20.0 NTU). Pilot scale deep-bed filters constructed to operate identically with full-scale granular media filtration plants were used for the study.

2.2. Methodology

The methodology for the research is outlined as follows:
(i) Procurement and collation of pilot filter test data.
(ii) Filter efficiency analysis and evaluation
(iii) Analysis for development of analytical chart

2.2.1. Evaluation of filter efficiency

The evaluation of efficiency of granular media depth filters was carried out with operational data from twenty-seven (27) filter runs obtained from selected sources. The sources include doctoral theses, renowned journals, project reports on existing water treatment works, and research findings in current literature (Kebreab, 2004; Al-Khalili et al., 1997; Hart, 2004; Huisman, 1984).

For the purpose of this research, the data procured were collated, analyzed and plotted for efficiency analysis and evaluation.

Efficiency for a filter was principally assessed from the quality and quantity of the effluent produced by a given filter configuration. The quantity of effluent is a function of filtration rate and filter run length (FRL).
Filters with turbidity (suspended solids) removal efficiencies in the range 85 to 100 percent are considered as performing to acceptable standards.

Filter efficiency is directly related to the characteristics of the influent liquid (water) and the design of the filtering material. Grain size constitutes the principal filter medium characteristic in the operation of filters. It affects the clear-water head loss and the head loss rise due to clogging of media during filter operation. Filtration rate is primarily a function of filter plant size, influent water characteristics and the type, size and depth of the filtering material.The results obtained for 15 pilot filters that exhibited high efficiency are displayed in Table 2.1.

Table 2.1
Depth filters of high efficiency

S/No	*Media Type*	*Grain Size (mm)*	*Media Depth (cm)*	*Influent Turbidity (NTU)*	*Filtration Rate (m/hr)*	*FRL (hr)*	*WPPC (m^3/m^2)*	*Rem Eff. (%)*	*HLR (cm)*	*Ter H L (cm)*
1.0	Sand	0.67	90	3.52	3.0	31.7	95	91.0	70	80.6
2.0	Sand	0.67	90	3.9	5.5	14	77	94.2	70.8	84.5
3.0	Sand	0.67	90	2.85	7.5	16	120	92	80.2	95.9
4.0	Sand	0.5-1.0	70	10.0	5.0	50	250	98.6	210	240
5.0	Sand	0.85-1.7	70	10.0	5.0	55	275	97.0	140	150
6.0	Sand	0.7	80	8.0	7.2	50	360	98.3	145	195
7.0	Sand	0.8	80	8.0	7.2	55	396	97.6	105	150
8.0	Sand	0.9	80	8.0	7.2	65	468	96.7	100	135
9.0	Sand	0.8	100	8.0	10.8	45	486	97.3	55	130
10.0	Sand	0.8	120	8.0	10.8	60	648	98.7	80	170

11.0	Sand	0.8	150	8.0	10.8	65	700	98.7	80	200
12.0	Sand	0.75	90	8.0	9.0	30	270	90.0	67	137
13.0	Sand	0.5 – 1.0	70	20	20	6.5	129	83	16	36
14.0	Sand	0.85 – 1.7	70	20	20	13	134	80	33	43
15.0	Sand	0.85	150	8.0	12.6	28	353	91.0	145	210

Filtration parameters shown in table 2.1 are substantially within limits specified in conventional criteria. For mono-media sand filters, the ranges of values conform to measured values in published literature provided below:

Grain size (mm): Sand : 0.35 to 1.0 (Peavy et al., 1985); 0.5 to 1.5 (Tebbutt, 1988);
Media depth (cm): up to 180.0 (Tchobanoglous and Burton, 1991); 50 to 250 (Tebbutt, 1988).
Filtration rate (m/hr): 2.5 to 20.0 (Peavy et al., 1985); up to 21.5 (Baumann, 1978);
Filter run length (hr): up to 72.0 (Tebbutt, 1988); up to 65.0 (Huisman, 1984).
Max head loss (cm): up to 250 (Tebbutt, 1988; up to 360 (Baumann, 1978).
Water production per cycle (m^3/m^2): 360 to 700 (Huisman, 1984)

2.2.2. Analysis for development of analytical chart

An analysis of filtration data obtained from efficient pilot filter test runs was carried out. Filter averaged data calculated by summation of individual parameter values and dividing by the number of data used were tabulated for filtration rate (loading rate), run length (time), and media grain size. Terminal head loss was the controlling parameter for this exercise.

Mathematical models of effluent quality and filter resistance developed from filtration research for granular media deep-bed (gravity) filters were applied in defining and delimiting applicable ranges and boundaries for the design chart.

3. Analysis and results

3.1. Development of analytical chart for design of mono-media (sand) deep-bed filters.

3.1.1. Introduction

The design of rapid filters requires an optimal selection of a wide range of operational parameters to ensure functionality and reliability when the plant is constructed and put into operation. The performance of the plant would determine the quality and quantity of treated water produced per cycle (WPPC) of filter run. To maximize these requirements, it is necessary to carry out an analysis for filtration parameters using a wide range of data obtained from reliable sources. This will take into account particle removal efficiency in the filter and filter hydraulics related to head loss development. The development of head loss in a filter is a complex process that has to be modeled in relation to media grain size distribution (GSD), which is crucial to the performance of depth filters.

The turbidity of surface waters fluctuates continuously during the rainy season but shows little variation in dry periods of the year. In practice, influent raw water characteristics vary for different sources. Granular filters should therefore be designed to function under a wide range of operating conditions because of the multiple number of the variables that dictate their efficiency and enhance the quality and quantity of treated water produced for small, medium and large populations.

3.1.2. Analytical chart

3.1.2.1. Analysis of filtration data

Curves were plotted for removal efficiency (Rem Eff) and head loss rise (HLR) as functions of filter run length (FRL). Also, curves for turbidity and head loss as functions of filter run length were plotted**.** Some of these curves are shown in Figures 3.1, 3.2, 3.3, and 3.4. (Appendix A).

A comparative analysis of these curves was carried out with a view to extracting optimal data for varying critical operational parameters.

Filter averaged data obtained from pilot filter test runs adjudged to be of high efficiency (Table 2.1) were used for plotting graphs (Fig 3.5) for filtration rate, filter run length, media depth and media grain size as functions of fixed terminal head loss values in sand media filters. This was facilitated through interpolation and extrapolation of data. The development of this chart took into consideration limiting parametric boundary conditions for functional filter design and operation. Limits obtained from filter efficiency studies include: turbidity removal efficiency of 85 to 100 percent, filtration rate of 2.5 to 17.0 m/hr, 1.0 to 15.0 NTU of influent turbidity, 0 to 1.0 NTU of effluent turbidity, terminal head loss of 30 to 240 cm, filter run length of

10 to 70 hours, and media size of 0.4 to 1.7 mm. Terminal head loss is defined as the sum of clear water head loss and the head loss rise at the point of turbidity break through during filtration of influent water. Table 3.1 shows filter averaged data obtained from this analysis.

3.1.2.2. Use of mathematical models

When solids begin to accumulate during filtration through a clean porous filter medium, the porosity of the bed decreases resulting in an increase in head loss. The rate of solids accumulation, and therefore the rate of head loss change is a function of the nature of the suspension, the characteristics of the media, and filter operation methods.

The classical deep-bed filtration model (CDBFM) originally proposed by Iwasaki (1937) assumes that the rate of particle deposition is directly proportional to the number of particles available for capture by the porous medium. This is a statement of Fick's law (Huisman 1984). The clean bed filter coefficient λ_o was evaluated from experiments based on first order deposition kinetics and step-input curve resulting from continuous input of dilute colloidal suspension.

For steady-state flow conditions, flow of water through a packed-bed composed of porous granular media can be described by considering a suspended solids mass balance for a section of filter (Tchobanoglous and Burton, 1991).
In words, this is:

Inflow – Outflow = Storage + Deposition (3.1)

The simplified form of the materials balance equation when the storage term is zeroed, can be written as:

$$- v\, \partial c/\partial x = \partial q/\partial t \qquad (3.2)$$

where v = filtration rate (velocity) in filter media (m/hr)
$\partial c/\partial x$ = change in concentration of suspended solids in water with distance (g/m^3)
$\partial q/\partial t$ = change in quantity of solids deposited within the filter element with time (g/m^3 hr).

This is the equation of continuity, which is used in studies of filtration theory.

Two empirical models, an effluent quality model relating filter media depth with quantity of suspended solids (turbidity) removed and a filter resistance model relating head loss with filter run time for sand filters (Ekenta, 2006) were also applied in determining the limiting values for the chart.

The semi-logarithmic plots of filter averaged data for media depth as a function of turbidity ratio resulted in a straight line indicating that the relationship was exponential of the form: -

$$x = 157 * 10^{-1.494\, tr} \qquad (3.3)$$

The empirical model expressed in semi-logarithmic form can be written as: -

$$\text{Log } x = 2.196 - 1.494\, t_r \qquad (3.4)$$

The log-log graphical plot for head loss rise and filter run length was a straight line indicating that the desired relationship is logarithmic of the form:

$$h_t = 2.371\, t^{1.01} \qquad (3.5)$$

Expressed in logarithmic form it can be written as :

$$\text{Log } h_t = 0.375 + 1.01 \log t \qquad (3.6)$$

where
x = depth from inlet surface in filter media (cm)
t_r = turbidity ratio (t_e/t_o)
t_e = effluent turbidity (NTU)
t_o = influent turbidity (NTU)
h_t = head loss rise in filter (cm)
t = filter run length (hr)

Table 3.1
Filter averaged data computed from pilot filter studies

Terminal Head Loss (cm)	*Filtration Rate (m/hr)*	*Filter Run Length (hr)*	*Media Depth (cm)*	*Media Grain Size (mm)*
30	3.0	30	85	0.9
30	5.0	14	95	0.75
30	10.0	12	120	0.45
50	5.0	30	95	0.9
50	7.5	25	107.5	0.75
50	9.0	20	115	0.65
50	10.5	17.5	122.5	0.57

90	5.0	35	95	1.03
90	7.5	27.5	107.5	0.88
90	9.0	25	115	0.77
90	10.5	20	122.5	0.65
130	5.0	40	95	1.15
130	7.5	32.5	107.5	0.95
130	9.0	27.5	115	0.85
130	10.5	25	122.5	0.77
160	5.0	42.5	95	1.2
160	10.5	27.5	122.5	0.85
160	12.5	25	132.5	0.77
210	3.0	55	85	1.52
210	5.0	46	95	1.3
210	10.5	32.5	122.5	0.95
210	12.5	28	132.5	0.85
240	3.0	62.5	85	1.7
240	5.0	56	95	1.55
240	10.5	37.5	122.5	1.1

Note: Influent turbidity is limited to 1.0 to 15.0 NTU
Effluent turbidity is in the range 0 to 1.0 NTU
Turbidity removal efficiency of is in the range 85 to 100 percent

4. Results and discussion

To demonstrate the application of this chart for design of deep-bed granular media sand filters a filtration rate of 5.0 m/hr is used. From the chart it can be observed that by applying a constant filtration rate of 5.0 m/hr to a filter with media depth of 95 cm, the water production per cycle will be 275, 240, 215, 200, 175, and 150 m^3/m^2 for filter run length of 55, 48, 43, 40, 35, 30 and 24 hours using media grain size of 1.55, 1.35, 1.25, 1.15, 1.05, 0.90, and 0.75 mm to a terminal head loss of 240, 210, 160, 130, 90, 50, 30 cm respectively.

From the example provided above, it is evident that a large number of filters of various configurations can be designed, constructed and operated at economic cost in time and money.

A summary of the results obtainable for filtration rates of 5.0, 10.0, and 15.0 m/hr from this analytical chart for design of sand media depth filters is presented in Table 4.1.

Table 4.1
Summary of results from analytical chart

Filtration Rate (m/hr)	*Terminal Head Loss (cm)*	*Filter Run Length (FRL) (hr)*	*Media Depth (cm)*	*Media Grain Size (mm)*	*Water Production Per Cycle (WPPC) (m^3/m^2)*
5.0	30	24	95	0.75	120
5.0	50	30	95	0.9	150
5.0	90	35	95	1.05	175
5.0	130	40	95	1.15	200
5.0	160	43	95	1.25	215
5.0	210	48	95	1.35	240
5.0	240	55	95	1.55	275
10.0	30	12	120	0.45	120
10.0	50	18	120	0.6	180
10.0	90	22	120	0.7	220
10.0	130	26	120	0.8	260
10.0	160	29	120	0.88	290
10.0	210	34	120	1.0	340

10.0	240	39	120	1.15	390
15.0	50	9	145	0.38	135
15.0	90	13	145	0.48	195
15.0	130	16	145	0.55	240
15.0	160	19.5	145	0.58	293
15.0	210	23	145	0.75	345
15.0	240	27	145	0.85	405

Filter media can be designed using beds of uniform or non-uniform grain sizes. The chart developed in this research allows for the selection of an optimum uniform grain size for the filter. Bed expansion during backwash will not result in stratification of media.

The use of non-uniform grain size media results in stratification with small grains and smaller pore openings on top of the filter bed and vice-versa at the end of wash cycle. This means that most removal of suspended solids (turbidity) and a greater portion of head loss rise will occur at the upper layer of the filter bed, resulting in a reduction in filter run time.

It can be observed from the analytical chart that filters of high efficiency could be designed using non-uniform grain size media for the indicated filtration rates as follows: filtration rates of 5.0, 10.0, 12.0 m/hr with media depths of 95, 120 and 130 cm for grain size ranges of 0.45 to 1.5, 0.45 to 1.15, and 0.45 to 1.0 mm respectively.

5. Conclusion

Filter efficiency analysis coupled with studies related to modelling of deep-bed (depth) filters constitute the foundation for the conception and development of an analytical chart that would ensure a fast-track, top-down, reliable and sustainable approach to the design and operation of granular media deep-bed filters.

The efficiency of depth filters is dependent on their capacity to remove suspended solids namely colloids, micro-organisms and other particulates from influent water and is measured in terms of turbidity or suspended solids removal efficiencies, the quantity of treated water that is produced per cycle of filter run and filter run time.

Removal efficiency increases with depth of media and run time but peaks faster at low-to-medium than high filtration rates when the same influent water and media are used.

Extrapolation and interpolation of results from efficient pilot filter test runs provide for reliability in estimation of filter design parameters.

Analytical chart incorporating filtration rate, filter run length, media depth, and media grain size as functions of terminal head losses ensure optimal design of a wide range of filter configurations as stipulated by indicated limiting conditions.

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APPENDIX A

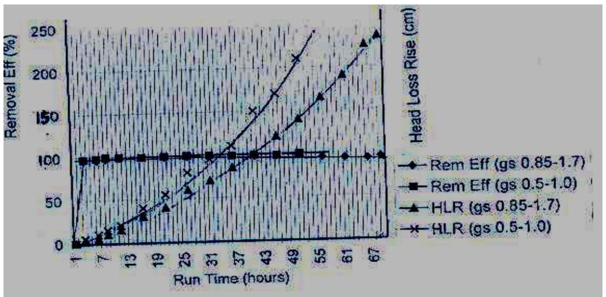

Fig 3.1. Removal efficiency and heat loss rise as functions of run time for mono-media (sand) at filtration rate of 5.0 m/hr.

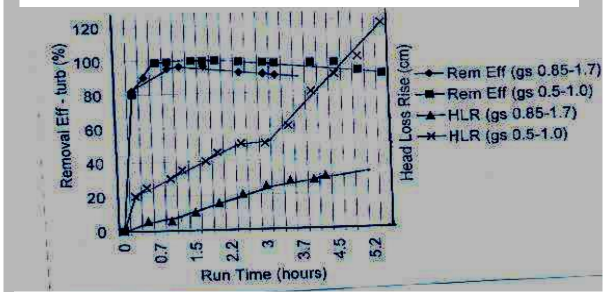

Fig 3.2. Removal efficiency and heat loss rise as functions of run time for mono-media (sand) at filtration rate of 10.0 m/hr.

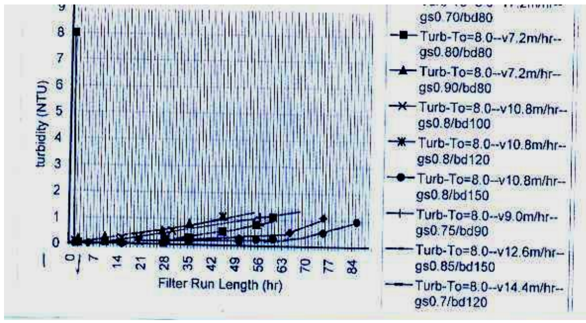

Fig 3.3. Turbidity as a function of filter run length for sand filter (Influence Turbidity – 8.0 NTU).

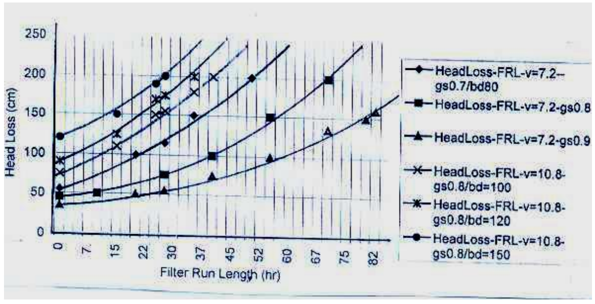

Fig 3.4. Head loss as a function of filter run length for sand media filters (influent turbidity – 8.0 NTU).

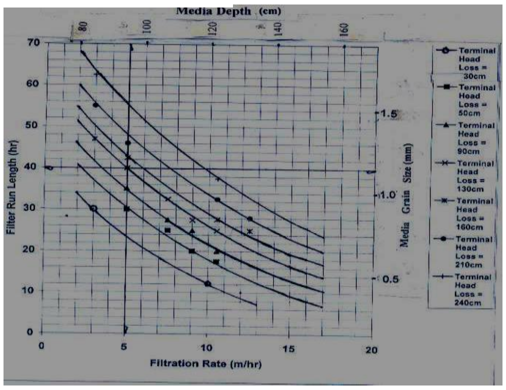

Fig 3.5. Analytical chart for design of granular media deep-bed sand filters.