THEORETICAL INVESTIGATION ON USING DIRECT FILTRATION PROCESS FOR TREATING RAW WATER FROM LAKE NASSER IN EGYPT

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Abstract

Following the construction of Aswan High Dam in Egypt, changes in raw water quality occurred with the formation of Lake Nasser. Long detention times resulted in lower turbidity where clearer water favored increased growth of phytoplankton. This study addresses the applicability of Direct Filtration (DF) as a candidate process to produce potable water from Lake Nasser or areas under the influence of the Lake water quality in Upper Egypt. This is conducted through investigating the main characteristics of raw water to identify predominant species and characterize their particle size distribution through power law interpretation, then investigating the single collector efficiency of direct filtration bed material. Breakthrough study of particles was conducted considering the main design parameters for DF and the expected headloss development through filter medium. The study indicated that direct filtration can successfully remove algae existence in the Lake water at the studied particle sizes distribution as long as recommended design ratio of bed length to filter medium effective size (l/d_e) are maintained. Bed lengths shorter than recommended will result in escape of finer particles from each of the studied algal species while larger particles would still be removed. Removal mechanism is mainly attributed to interception with low effect of particle sedimentation, while diffusive effect is insignificant.

1. Introduction

The construction of Aswan High Dam (AHD) led to the formation of Lake Nasser extending over an area of 6,000 km^2 that trapped large amounts of silt. Lakes and reservoirs provide long detention times, allowing for adequate settling of the larger turbidity particles and suspended solids. In general, larger reservoirs or lakes have lower turbidity levels. Algae are common and normal inhabitants of surface waters and are encountered in every water supply that is exposed to sunlight. Algae typically range in size from 5 to 100 microns. Concerns in potable water treatment arising from the presence of algae include; the ability to create large quantities of organic matter; the production of turbidity, tastes and odors in source water, and; the physical impact on the water treatment plant processes. Some species of blue-green algae are known to produce endotoxins that may affect human health (USEPA, 1999).

Suspended matter causing water turbidity or impurities may include clay, silt, finely divided inorganic and organic matter, soluble colored organic compounds, and plankton and other microscopic organisms. Removal of these particles and controlling turbidity is a competent safeguard against pathogens in drinking water as it can provide food and shelter for pathogens and promote regrowth of pathogens in the distribution system, leading to waterborne disease outbreaks. While many microorganisms commonly found in source waters do not pose health risk to humans, others such as *Cryptosporidium* and *Giardia* can be sources of infectious and communicable diseases that can resist chlorine disinfection, thus the importance of achieving highest removal through filtration. *Cryptosporidium* is housed in a hard-shelled oocyst typically 2 to 5 microns in diameter. *Giardia* can exist as ovoid cysts approx. 6 to 10 microns (USEPA, 1999). Therefore, higher emphasis in this study is directed towards smaller particle sizes that also represent the highest percentage of abundance as discussed hereafter.

Filters represent the key unit process for particles removal in surface water treatment. Optimization used prior to the filtration process will control loading rates while allowing the system to achieve maximum filtration rates. Direct filtration is one of several treatment processes that can be applied in combination with others to produce potable water. Low turbidity (<30 NTU) and algae count in the order of 10^6 units/liter among other factors were reported to suit the application of such process (Kawamura, 2000). Water treatment plants in Egypt generally adopt the conventional treatment process using coagulation, flocculation, sedimentation, and rapid sand filtration. Though direct filtration is one of the known applications in water treatment field, there is no large-scale application of direct filtration process for producing potable water in Egypt. Therefore, this study aims towards investigating the compatibility of direct filtration process with Lake Nasser water quality, as a theoretical pre-evaluation of its performance relative to prevailing conditions.

2. Raw Water Quality and Particle Size Distribution

The main changes following the construction of the Aswan High Dam were linked to suspended solids and algae content. These changes are the results of physio-chemical and biological transformations occurring in the reservoir, i.e. sedimentation, evaporation, and primary production. Water released from the reservoir is silt-free and its suspended solids content is mainly due to phytoplankton. Lake Nasser *Flora & Fauna* includes several floating macrophytes that range from few millimeters to centimeters in diameter or size and should be removed by screening. Other species included are phytoplankton and zooplankton where detailed description are reported elsewhere (Saleh and Han, 2002) and are summarized in Table 1 showing the different species found at AHD reservoir, their biomass concentration, and their normal sizes cited in literature. Other physico-chemical parameters concerning raw water quality at AHD are also shown in Table 2 (World Lakes Database, html; Saleh and Han, 2002). It was clear that the phytoplankton concentration is by far larger than that of zooplankton and thus is considered the removal target of direct filter process in this study.

Table 1. Water microbiological concentrations, percent composition[1] and typical size at AHD

Biological Species (I)	Size Range (μm)	Ref. in this Study	Biological Species (II)
Phytoplankton (3 – 7 x 10^6 / liter)			**Zooplankton**[2] (15 – 35 / liter)
Cyanophyceae (80%)	4 – 50	*species A (sp. A)*	Daphnia (20%)
Bacillariaceae, Diatoms (15%)	5 – 300	*species B (sp. B)*	Copepoda (80%)
Chlorophyceae (5%)	2.5 – 800	*species C (sp. C)*	Rotifers (2%)

[1] Approximate values subject to changes
[2] Negligible concentration compared with phytoplankton

Table 2. Concentrations of selected parameters in water at AHD

Parameter	Range	Parameter	Range
pH (units)	7.9 – 8.2	TDS (mg/l)	140 - 200
Temperature (°C)	16 - 29	TSS (mg/l)	6 - 12
Phosphorus (mg/l)	0.05 – 0.75	EC (microS/cm)	230 - 330

Particle Size Distribution of Main Species:

The analysis of suspended solids in aqueous solutions has been pioneered in other fields such as geology (sediments in seawater) and wastewater processing. It was noticed that the size distributions appeared to consistently follow a near-hyperbolic pattern and that a very good approximation could be obtained by the relationship:

$$N = K\,(x/x_o)^{-c} \qquad (1)$$

where N is the number of particles larger than a given particle size, x is the particle size parameter (e.g. volume, diameter, surface area), x_o is the base parameter (often set to 1 for simplicity), and K and c are positive constants. This relation was then adjusted to the power law:

$$DN/dl = A\, l^{-\beta} \qquad (2)$$

where N is the particle number density, l is the particle size parameter, and A and β are empirical constants. For a hypothetical suspension with particle sizes from about 1 to approx. 1000 μm, the type of distribution that can be expected for three representative values of β: 2, 3, and 4 are shown in Fig.1 where increase β values indicate more predominant smaller particle sizes. Reviewed data for several natural waters (lakes ad rivers) suggests values for β varying from 1.7 to 4.2, calculated $\log_{10} A$ values ranged from 4.5 to 6.5 (Patterson et al., 1999).

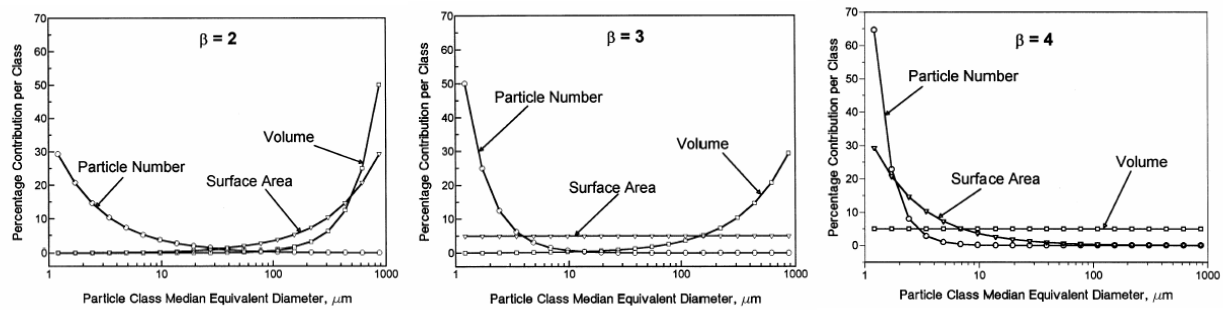


Fig. 1 Typical hypothetical contribution / distribution curves for β = 2, 3, and 4 respectively

Practically, for any class *i*, the following can be derived:

$$\Delta N_i = A\, l_i^{*} \text{-}\, \beta\, \Delta l_i \quad (3)$$

Where ΔN_i is the number of counts in class *i*, l_i^* is the particle size diameter (median of class), and Δl_i is the range of class. This relation was then normalized by researchers to the following form (Patterson et al., 1999):

$$\Delta N_i / N_T = \; l_i^{*(1-\beta)} / \Sigma_i \; l_i^{*(1-\beta)} \quad (4)$$

The constant A is thus normalized out of this expression and the percent distribution will actually depend on the characteristic distribution parameter β. As no precise data about particle size distribution in Lake Nasser were produced, a preliminary estimation of these values is herein conducted for species abundant in the lake using average value for β to identify the most probable particle sizes to be further removed within the treatment process. It is essential that these values be identified through pilot studies and particle counters as to identify real variations in particle size distribution. Patterson et al. (1999) pointed out to the necessity of arranging the class boundaries in ascending geometric progression, such that the ratio of $\Delta l_i / l_i^*$ is a constant, as was also recommended by previous investigators, to ensure statistical reliability in a particle size distribution that is hyperbolic in nature. The best progression was based on volume and then back-converted to the artificial parameter l^* that is the diameter of a sphere whose volume is equal to the volume of particle. In this form, the class boundaries are defined by $l_{i+1} = 1.26\ l_i$, which satisfy the ration conditions. These recommended class ranges were used in this study as shown in Table 3 to calculate particle size distribution for *Species A* shown in Fig. (2), similarly, the particle size distributions for *Species B* and *C* were calculated and plotted in Figs. (3) and (4).

Table 3 Parameters used in calculating particle size for different class boundaries

Class	l_i	l_{i+1}	Δl_i	l_i*	$\Delta l_i / l_i^*$
1	4	5.04	1.04	4.52	0.23
2	5.04	6.35	1.31	5.70	0.23
3	6.35	8.00	1.65	7.18	0.23
4	8.00	10.08	2.08	9.04	0.23
5	10.08	12.7	2.62	11.39	0.23
6	12.7	16.01	3.30	14.35	0.23
7	16.01	20.17	4.16	18.09	0.23
8	20.17	25.41	5.24	22.79	0.23
9	25.41	32.02	6.61	28.71	0.23
10	32.02	40.34	8.32	36.18	0.23
11	40.34	50.83	10.49	45.59	0.23
12	50.83	64.00	13.22	57.44	0.23

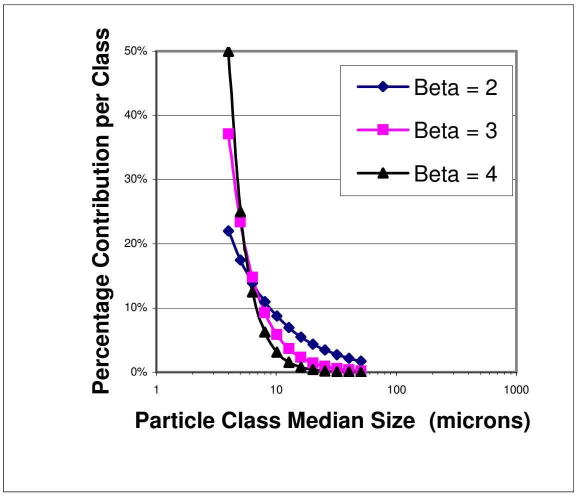


Fig. 2 Hypothetical size distribution of *Sp.A*

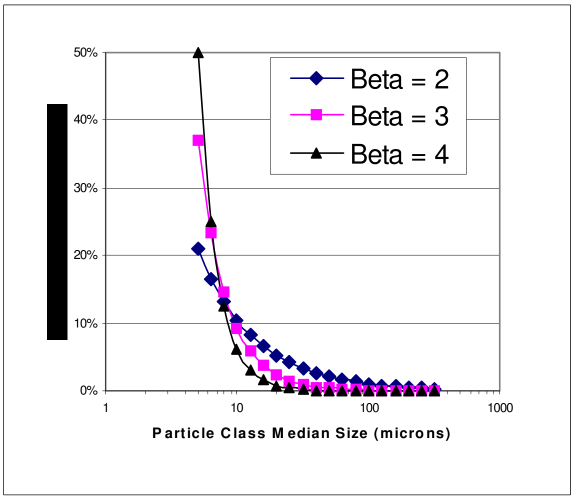


Fig. 3 Hypothetical size distribution of *Sp.B*

Figures for hypothetical contribution of each particle class (2 to 4) show the particle size distribution for the three main species found in Lake Nasser using different values for β ranging from 2 to 4 as found in most natural environments. A general trend suggests that fine particles should be theoretically dominating in the Lake. A calculation of the percentage of particles lower than specified diameters is shown in Fig. R considering an intermediate value of $\beta = 3$, it can be concluded that the majority of particles would have sizes varying from their minimum size (4, 5, and 2.5 µm for *Species A*, *B*, and *C* respectively) to approximately 40µm even when changing the value of β since the most predominating species is *A* (80%) as previously shown. Particles with larger diameters would be easily intercepted within the filter and partially contribute to mass loading of the filter. However, fine pore size particles are of most concern as they tend to escape from the filter material and represent an overburden of downstream disinfection units with the risk of hosting pathogens.

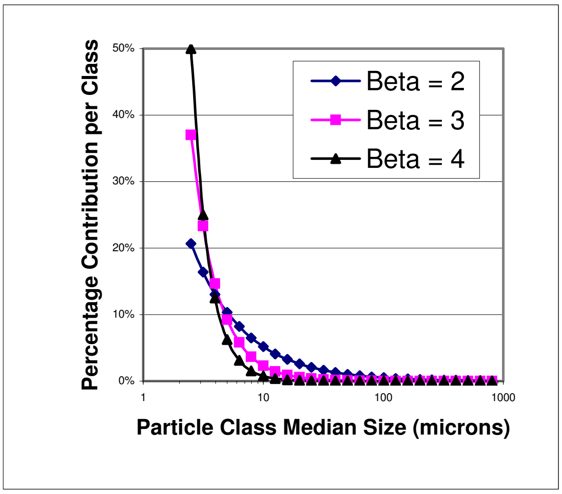


Fig. 4 Hypothetical size distribution of *Sp.C*

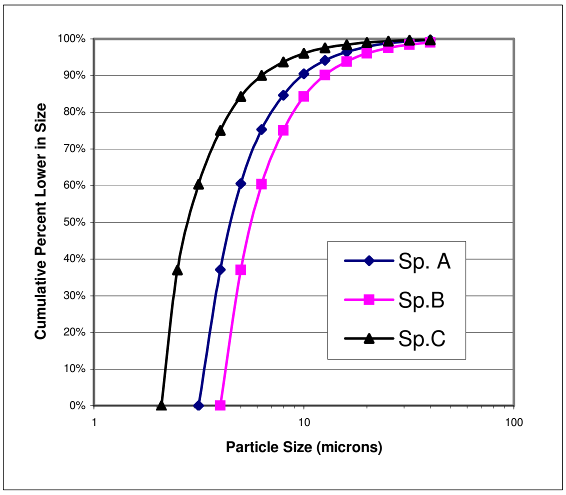


Fig. 5 Percent particles lower in size at $\beta = 3$

3. Applicability of Direct Filtration Process

Direct Filtration (DF) is one of several processes used worldwide in water treatment plants. The selection of the process is related to the nature of raw water to be treated. Unlike conventional rapid sand filters (RSF) that deals with remainder flocs after coagulation and sedimentation, direct filters are subjected to particles with different sizes directly from raw water and shall be designed for successful removal of these varieties. Other differences between these filtration processes are encountered in the rate of filtration, size and type of filtrating media, depth of filter medium and other factors as illustrated in Table 4. It is clear that direct filtration design is based on tolerating higher rate of filtration through coarser media, thus the importance to verify the small particle sizes shall not escape the system due to shorter bed design or at shorter filtration run. In addition, particles charge destabilization is also a pre-requisite for Direct Filtration to ensure successful removal of particles. Higher filtration rate allow for a smaller footprint of the filtration units within the plant and subsequent savings in construction costs.

The general description of the temporal and spatial variation of particle concentration for a spherical particle of filter media was developed by (Yao et al., 1971) where the temporal variation of particles concentration C was correlated with the effects of advection, diffusion, and gravitational force. Yao et al. (1971) provided analytical solution of this relation adding factors to account for contact and collision efficiencies, bed porosity and length as shown in Fig. 6. Removal of particle sizes lower than 1μm was attributed to diffusive effect, while larger particles removal mechanisms is mainly through interception and sedimentation. Experimental data shows higher removal efficiency as theoretical approach ignores effects of neighboring particles, non-sphericity, etc.; thus provides conservative values. Figure 7 shows recommended ranges for selected water treatment processes relative to particle diameters and their initial numbers and mass concentration in raw water (Montgomery, 1985). By implying these limits to lake Nasser water quality having particle concentration 10^3 to 10^4 per cm^3 and most dominant particle sizes from 2.5 to 40μm, it is shown that direct filtration highly suits these conditions, additional investigations on particles breakthrough are herein conducted.

Table 4 Main differences between conventional Rapid Sand Filtration and Direct Filtration

Parameter	**Rapid Sand Filter**	**Direct Filtration**
Rate of Filtration (m/hr)	5.0 – 7.5	12.5 – 30.0
Filtering media		
Type	Monotype sand	Mono, dual, or multi-media
Sand effective size - mm (d_e)	0.45 – 0.65	0.8 – 2.0
Medium depth - m (l)	0.60 – 0.75	0.8 – 2.0
U.C.	1.4 – 1.7	1.4 – 1.7
l / d_e (recommended)	1000	1250 – 1500
Influent	Settled effluent	Raw water
Particles charge destabilization	Accomplished in previous units	Needed

(Source: Kawamura, 2000).

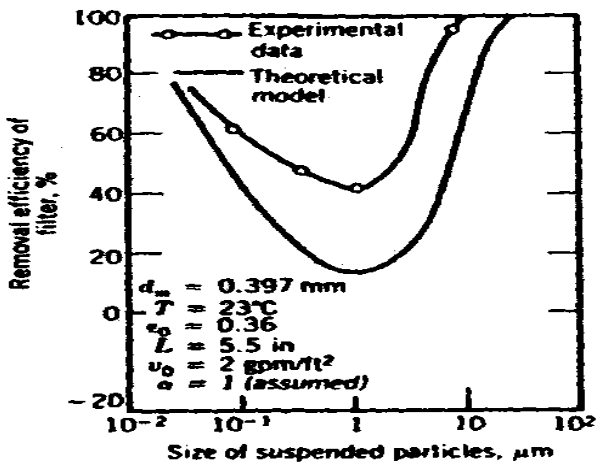


Fig. 6 Particle removal within filtering medium

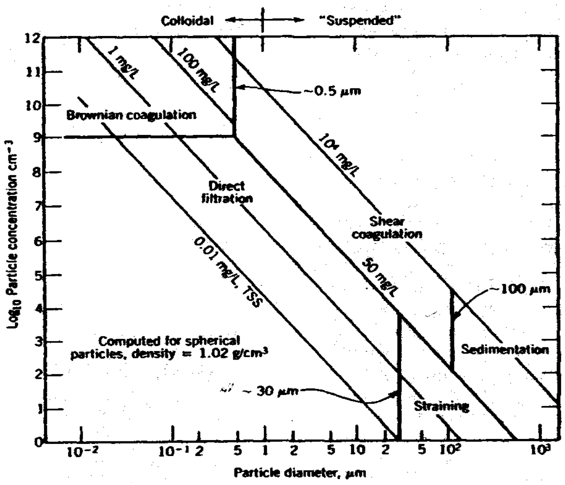


Fig. 7 Process compatibility with Lake Nasser Water Quality

Single Collector Efficiency:

In this study, two main mechanisms are considered responsible for particle removal within the filtering medium namely interception and sedimentation. Diffusive effect will not be considered in this study as particle sizes of concern are higher than 1μm. The filtering medium is assumed to be mono-layer sand as widely applied in other filtering processes in Egypt. The quantitative estimates of the single collector efficiency for the main mechanisms can be expressed as follows:

$$\eta_i = \frac{3}{2}\left(\frac{d_p}{d_m}\right)^2 \qquad \textit{(for interception)} \tag{5}$$

$$\eta_s = \frac{\Delta\rho g d_p^2}{18\mu V_o} \qquad \textit{(for sedimentation)} \tag{6}$$

where η_i and η_s are the single collector efficiencies due to interception and sedimentation respectively, d_p and d_m are particle diameter and filter medium effective size, μ is the water viscosity, $\Delta\rho$ is the difference in densities between particles to removed and water, g is the gravitational acceleration, and V_o is the superficial velocity (Montgomery, 1985). Figure 8 shows the different values for single collector interception efficiency for the most dominant algae of concern (Cyanophyceae – *Species A*), where three diameters namely 4, 10, and 40µm were investigated representing the minimum diameter of the species, the diameter covering approx. 90% of the species population, and the diameter covering almost all population. It is clear that the chance of intercepting particles by individual collector drastically decreases with decreased particle size thus the higher the possibility of escaping from filter material. Therefore, only the minimum size of each species was considered for calculating efficiency of interception as shown in Fig. 9 denoting lower possibility to retain species C due to its smaller size.

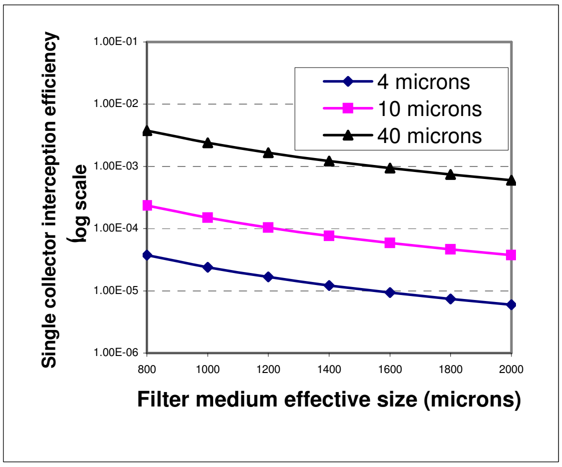


Fig. 8 Interception efficiency (η_i) for *Sp.A* vs. size

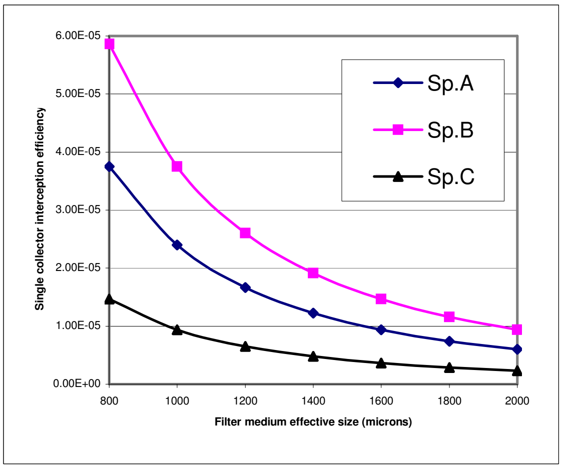


Fig. 9 Interception efficiencies for minimum S*p.* sizes

An estimation of the single collector sedimentation efficiency was also conducted considering the minimum sizes of the different species in study. Values of various superficial velocities of 2, 4, 6 and 8 cm/s (7.2, 14.4, 21.6 and 28.8 m/hr) were used to representing typical operation of RSF, besides minimum, average and maximum flows in direct filtration respectively. The results shown in Figure 10 denote that varying superficial velocities has an impact on removal through sedimentation mechanism. However, the overall value of the efficiency was very low compared to interception efficiency. Thus, interception mechanism that is dependent on filter medium particle size plays the major role in particles removal, and changes in filtration rates would have minimal effect on particles removal efficiency. For the remainder section of this investigation the superficial velocity was kept at 6 cm/s (21.6 m/hr) as an average rate of filtration typically used in direct filtration processes.

Breakthrough of Minimum Size Particles:

Removal of algae, as reflected in the filter medium capability to retain a certain particle size, and the particles breakthrough from the filter were investigated through several runs through which a combination of filter medium effective size and medium depth were altered within the minimum and maximum recommended values for direct filtration design as shown in Table 5.

Table 5 Different runs conditions for evaluating algae removal*

Typical filter depth 0.8 - 2.0 m and Typical medium effective size 0.8 - 2 mm							
Runs maintaining minimum (l/de) and typical design values							
effective size (mm)	0.8	1	1.2	1.4	1.6	1.8	2
depth of medium (m)	1	1.25	1.5	1.75	2	2	2
l/de	1250	1250	1250	1250	1250	1111	1000
Runs maintaining maximum (l/de) and typical design values							
effective size (mm)	0.8	1	1.2	1.4	1.6	1.8	2
depth of medium (m)	1.2	1.5	1.8	2	2	2	2
l/de	1500	1500	1500	1429	1250	1111	1000

* where different design values are encountered similar investigations can be carried out

The investigation was conducted through estimating the single collector overall efficiency, then predicting the particles breakthrough using the following equation:

$$\frac{N}{N_o} = \exp\left[\frac{-\psi(1-\varepsilon_o)}{d_m} L\eta\right] \qquad (7)$$

where N/No represents the fraction of the particulate removed for a certain size, ψ is a shape factor defined as the ratio of area and volume shape factors for granular media (ψ=6 for spherical media), ε_o is the initial pore volume (porosity of the granular medium was considered 0.4), η is the overall single collector efficiency ($\eta = \eta_i + \eta_s$), d_m is filter medium effective size, μ is the water viscosity, $\Delta\rho$ is the difference in densities between particles to removed and water ($\Delta\rho$ is taken 0.05 kg/cm^3 as the practical value for aglae density is 1.05 kg/cm^3), g is the gravitational acceleration, and V_o is the superficial velocity which was variably selected as illustrated hereafter (Montgomery, 1985).

Recommended l/de values for most coarse deep mono-medium beds range from 1250 to 1500 (Kawamura, 2000). An investigation of particles breakthrough was conducted through estimating N/N_o using equation (7), and maintaining both minimum and maximum recommended values for l/de as previously noted in Table 5. Runs for investigating breakthrough, having l/d_e valued ranging from 1250 to 1500, showed successful removal of the minimum diameter of the three different species of concern. Additional runs using values of l/de lower than the previous possible breakthrough.

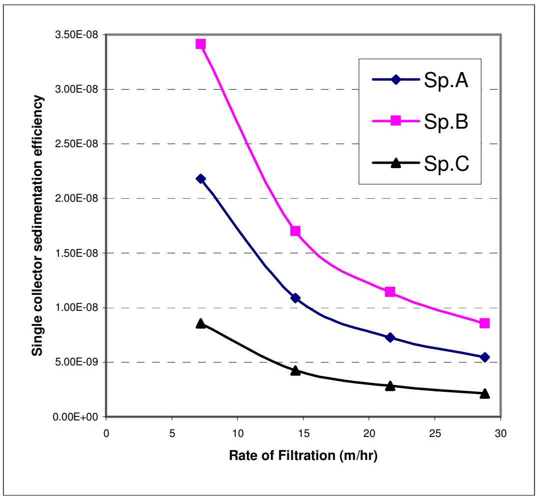


Fig. 10 η_s estimates for minimum *Species* size

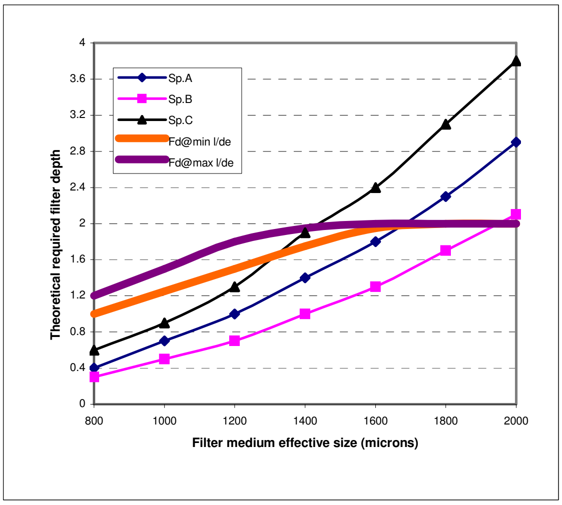
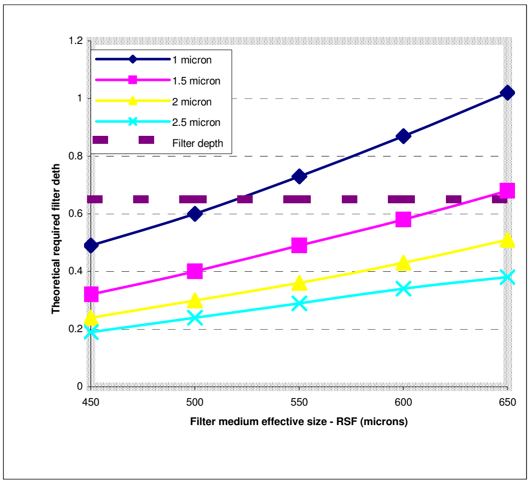


Fig. 11 Particles breakthrough vs. design parameters

Consequently, a theoretical minimum filter depth at which breakthrough can be eliminated was developed as shown in Figure 11. From Table 5 and Fig. 11 it is clear that the ranges recommended for filter media size and depth does not fully allow the fulfillment of a desired l/d_e value. In areas fulfilling this requirement, the filter media covers the need to satisfy removal of the concerned species. On the contrary, lower l/d_e values will allow for particles breakthrough from filter medium. *Species C (Chlorophyceae)* is the most subject to breakthrough in this study as it has the smallest size among concerned species.

Filters are used for the removal of a variety of particle sizes shall take into consideration particles that are mostly difficult to remove, i.e. within 1μm in size as discussed above. Though it is not the case in this study but any future variation may introduce some new particles with varying diameters, Fig. 12 shows the theoretical bed depths that would prevent particles breakthrough in a critical particle size range (from 1 to 2.5 μm) for both DF and RSF noting that RSF data is considered the lower side extension of DF data.



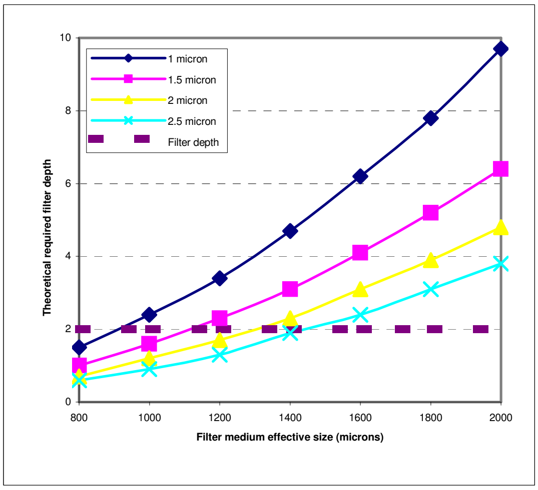


Fig. 12 Theoretical filter depth for removal of critical particle sizes DF (right) & RSF (left)

The figure shows that both RSF and DF require deeper filter media for effective removal of particle sizes within the range of 1µm in size, however, as filter medium in DF often has larger size allowing for higher rate of filtration, there is much higher possibility for particles breakthrough especially in the range of 1 to 2.5 µm. This case is less accentuated in RSF where the smaller medium particle size use helps increasing the efficiency of interception mechanism. Therefore, careful considerations should be given to removal of lower particle sizes that are not addressed in this study, meanwhile, using filter medium with lower particle size will strongly minimize chances of particles breakthrough.

<u>Headloss through Filter Bed:</u>

As the smaller filter medium particle diameters show the best removal efficiency of particles in raw water, one other issue of concern would be the headloss through filter bed. Therefore, the flow pattern within the porous media should be first check for being either laminar flow or transition flow as to calculate the total headloss thereafter. Reynold's number in porous media is defined by the following equation:

$$N_{\mathrm{Re}} = \frac{d_m V_o \rho L}{\mu(1-\varepsilon_o)} \qquad (8)$$

Minimum value of Reynold's number was first calculated using values minimizing the equation product as: effective size = 0.8mm, bed depth = 1.0m (l/d_e=1250), minimum superficial velocity used in DF process (approx. 14m/hr). The resulting N_{Re} was 53 (>10), thus the flow should be considered as transition flow rather than laminar flow and two terms should be used to estimate headloss through the filter accounting for porous media effect and velocity effect. Equation *(9)* is used to calculate the resulting headloss (Montgomery, 1985), and the predicted hydraulic gradient through the filter due to effects of porous media and velocity is shown in Fig. 13 where they have considerable effect on headloss development especially with the use of lower size filter medium.

$$\frac{\Delta H}{L} = \frac{180\mu V_o}{\rho L g d_m^2} \frac{(1-\varepsilon_o)^2}{\varepsilon_o^3} + \frac{1.75 V_o^2}{d_m g} \frac{1-\varepsilon_o}{\varepsilon_o^3} \tag{9}$$

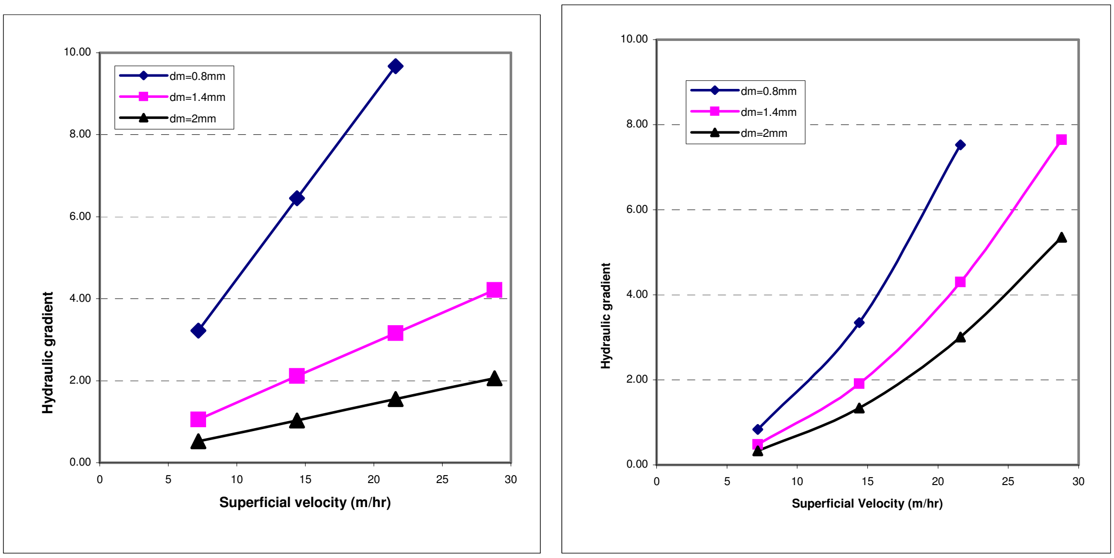


Fig. 13 Hydraulic gradient affected by: porous media (left) & superficial velocity (right)

4. Conclusions

This study investigated the applicability of direct filtration process to treat raw water from Lake Nasser in Egypt characterized with increased algae concentration. The size characterization of the three main algal species found in lake water showed that: (i) minimum particle sizes of each species (4, 5, and 2.5µm for *sp. A, B* and *C* respectively), represent approx. 37% of each category, (ii) approx. 90% of the particles have less than 10µm equivalent diameter, and (iii) approx. 99% of the particles have less than 40µm equivalent diameter, according to power law distribution and using average β value of 3. In view of this size distribution, single collector efficiency was estimated; assuming adequate particle charges destabilization prior to filter, and revealed that the removal mechanism is mainly through interception that was decreasing with decreased particle size. Particle sedimentation effect had little impact while diffusive effect was insignificant. Minimum particle sizes were of concern in subsequent interpretations as they have higher breakthrough potential from filter medium.

Breakthrough study predicted successful removal for various sizes of different studied species including minimum expected particle diameters when maintaining l/d_e ratio of 1250 to 1500. Shorter bed lengths resulted in breakthrough of finer particle sizes from each species; algal species having the lowest particle size will be subject to the highest breakthrough events. When high rate of filtration is applied, transition flow will dominate rather than laminar flow and estimates for clean bed headloss were developed. Both porous medium size and velocity have considerable effect on headloss development especially with lower filter medium particle size. Particles with certain critical sizes (approx. 1µm), though not encountered during the study, have the highest potential for breakthrough from filter bed material, thus adequate design parameters should be considered providing adequate removal efficiency while maintaining reasonable filtration rate and headloss through the filter. Selected design parameters shall further be verified through pilot plants investigations.

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