

# GRANULAR ACTIVATED CARBON (GAC) BIOFILTER FOR LOW STRENGTH WASTEWATER TREATMENT

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**Abstract** : Biofilter can be a cost-effective alternative treatment unit, especially for low strength wastewater. In this study, detailed experimental investigation of a GAC biofilter was carried out in a laboratory-scale unit using low strength synthetic wastewater. Performance of the biofilter was evaluated in terms of total organic carbon (TOC) removal. The TOC removal efficiency of the biofilter (when acclimatized at the filtration rate of 1 m<sup>3</sup>/m<sup>2</sup>hr) was found to be stabilized at around 55% after 30 days, and remained constant for 77 days of continuous operation of the biofilter. The long-term operational efficiency of the biofilter was predicted by a simple mathematical model, which was developed incorporating both adsorption and biological degradation of the organics. The average biomass retained on the activated carbon ranged from 0.036 to 0.09 g per g of GAC (as dry weight). Filter backwashing provided at 30% bed expansion for 5 min on a daily basis to overcome physical clogging of the filter by attached mass, had no adverse effect on the active biomass attached to the media and thus the organic removal efficiency of the filter remained unchanged. Although, the organic removal efficiency was reduced when hydraulic loading rate of the filter was increased, the organic removal pattern of the filter with time remained unchanged. The results also indicated that the influent organic concentration could have significant effect on the organic removal pattern and thus the biofilter should be operated as close to steady-state conditions as possible to achieve optimum organic removal efficiency.

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**Key Words** : biofilter, biomass, GAC, organics, wastewater

## INTRODUCTION

Wastewater contains significant levels of organic contaminants. A number of organic substances of the wastewater are not removed by the conventional wastewater treatment processes. The conventionally used sewage treatment processes may remove those organics measured by biochemical oxygen demand (BOD<sub>5</sub>) test but are not as effective in removing the so-called refractive organic materials measured by the chemical

oxygen demand (COD) test. The inherent problems associated with the organics are the requirement of excessive amount of disinfectants, odor, unsightly color, foaming, corrosion of pipes, production of carcinogenic and harmful disinfectant-by-products (DBPs), and stimulation of microbial growth in the effluent-discharging watercourse. Advanced wastewater treatment is therefore required to meet the quality of the sewage effluent that can be reused for various purposes. Biofilter can be utilized in the advanced sewage treatment processes to remove majority of organics that are not removed in the secondary treatment processes. Biofilter is a con-

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ventional filter with biomass attached onto the filter media as a biofilm, where the organics are adsorbed and biodegraded by the microorganisms. Since the organic concentration in the secondary effluent is low, biofiltration is the only biological treatment option in the advanced wastewater treatment. The biofiltration process is also economical and environmentally friendly in treating wastewater of relatively small volume (e.g. wastewater from hotel, small industries or small communities). Previous studies on biofilter have shown that it could remove organics and nutrients in significant quantities and produce high quality effluent.<sup>1-3)</sup>

The biological treatment especially with GAC biofilter has been assessed as an essential part of the drinking water treatment as well.<sup>4,5)</sup> It has been found that the biofilter has a high potential in removing pollutants such as biodegradable organic materials and synthetic organic compounds that produce odor and taste, and cause microbial regrowth in water supply lines. Removal of these organic substances not only impairs microbial regrowth but also reduces taste and odors, the amount of organic precursor (available to form disinfection by-products, corrosion potential) and other micropollutants of health and aesthetic concern.

Many studies have been carried out on biofiltration in last decade especially with GAC as filter media. However, theoretically, it is still difficult to explain the behavior of a biofilter. The growth of different types of microorganisms in different working conditions makes it impossible to generalize the microbial activities in a biofilter. It is thus, important to evaluate the biofilter in terms of its operating conditions and the characteristics of the influent feed. The efficiency of a biofilter operated at different filtration rates and influent characteristics can vary significantly for different target pollutants. Besides, some of the operational drawbacks of the biofilter such as performance fluctuation, maintenance of biomass, release of microorganisms, have made the research on it more imperative.

The performance of a biofilter entirely de-

pends on the microbial activities. Therefore, a constant source of substrates (organic substance and nutrients) is required for its consistent and effective operation. The bacterial mass attached onto the filter media as biofilm oxidizes the most of the organics and uses as an energy supply. The microbial activities can vary with seasonal variation. The performance of a biofilter can be better in summer than in winter. It is very important to control and maintain the biomass in the filter for its successful operation. The major factors that affect the performance of the biofilter are the characteristics of filter media, empty bed contact time, backwashing techniques, and the substrate concentration of the feed solution. While selecting the filter media, one should consider the source and concentration of the targeted pollutants. Previous studies with tertiary wastewater and surface water have shown that the GAC (an adsorptive media) is better than anthracite or sand (non-adsorptive media) in removing organic substances from tertiary wastewater and surface water.<sup>6,7)</sup> The microporous structure and irregular surface of the GAC offer more sites appropriate for biomass attachment. It also provides protection from shear loss of biomass. The GAC adsorbs and retains slowly biodegradable organic substances that are biodegraded by the attached microbial mass leading to continuous bioregeneration of the GAC.<sup>8)</sup>

In this study, detailed experimental investigation of a GAC biofilter was carried out using low strength synthetic wastewater. The main objective of the study was (i) to evaluate the long-term performance of the GAC bed filter, (ii) to assess the effect of backwashing on the organic removal efficiency of the filter, and (iii) to estimate the attached biomass on GAC media. A simple mathematical model was also developed to predict the long-term efficiency of the biofilter.

## MATHEMATICAL MODELLING

There are limited numbers of research that predict the long-term performance of a biofilter.

Most of the studies are based on the assumption of steady state condition.<sup>9,10)</sup> Rittmann and McCarty<sup>11)</sup> first introduced a steady-state biofilm model in which the mass transport and the microbial kinetics were expressed by the Monod equation and the Fick's second law respectively. It was assumed that minimum concentration of the bulk substrate ( $S_{min}$ ) is required to maintain the steady state biofilm in the filter. Warner and Gujer<sup>12)</sup> developed a multispecies biofilm model for the wastewater biofilms. The model is very general and can be easily utilized to many types of microbial interactions. Other multispecies biofilm models with similar structures were developed by Namkung and Rittmann,<sup>14)</sup> and Rittmann and Manem.<sup>15)</sup> In these models, the biomass was divided into three categories, heterotrophs, autotrophs, and inert particulate materials. It was also observed that the substrate (organic and nutrients) removal efficiency strongly depends on the factors that confine biofilm growth such as configuration of the bioreactor, and different biomass detachment mechanisms i.e. shear and sloughing. The substrate removal was found to be proportional to the biofilm thickness up to a critical thickness.

Hozalski and Bouwer<sup>16)</sup> developed a non-steady state model (BIOFILT) for the removal of biodegradable organic matter (BOM) from the surface water. The model was successful in simulating the BOM removal in different operating conditions.<sup>17)</sup>

In this study, a simple mathematical model was developed to predict the long-term organic removal efficiency of the GAC biofilter incorporating both adsorption and biological degradation. The model is based on the fundamental mechanisms of transport of substrate in the bulk liquid, biofilm growth, transport, and biodegradation within the biofilm, and adsorption on activated carbon. The schematic representation of the biofilm of GAC particle is shown in Figure 1.

The unsteady-state material balance on the substrate in the bulk liquid is represented by the advection-diffusion equation with adsorption and reaction terms (Eq. 1).

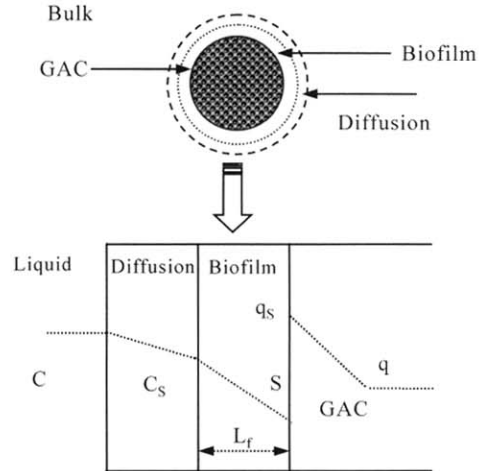


Figure 1. Schematic representation of the biofilm on GAC particle.

$$\frac{\partial C}{\partial t} = D_{ax} \cdot \frac{\partial^2 C}{\partial z^2} - v \cdot \frac{\partial C}{\partial z} - \gamma_{bio} - \gamma_{ads} \tag{1}$$

With initial and boundary conditions,

$$C = C_0$$

$$D_{ax} \frac{dC}{dz} = -v \cdot (C|_{z=0^-} - C|_{z=0^+}) \text{ at } z = 0$$

$$\frac{dC}{dz} = 0 \text{ at } z = L$$

where  $\gamma_{bio}$  and  $\gamma_{ads}$  are the substrate removal rates by biodegradation and adsorption respectively and can be calculated using Eq. 2.

$$\gamma_{bio} = k_{max} \cdot \frac{C}{K_s + C} \cdot X_s \text{ and}$$

$$\gamma_{ads} = (1 - \epsilon) \cdot \frac{3N}{4 \cdot \pi \cdot a_p^3} \tag{2}$$

The suspended biomass in the bulk liquid, and biofilm diffusion and biodegradation are given by Eq. 3 and 4 respectively.

$$\frac{\partial X_s}{\partial t} = \left( Y \cdot \frac{k_{max} \cdot C}{K_s + C} - K_d - \frac{\beta}{\theta \cdot \epsilon} \right) \cdot X_s + \frac{1 - \epsilon}{\epsilon} \cdot a_f \cdot X_f \cdot \sigma \tag{3}$$

with initial and boundary conditions,

$$X_s = X_{s0}$$

$$X_s = X_{s0} \quad \text{at} \quad Z = 0$$

$$\frac{\partial S}{\partial t} = D_f \cdot \frac{\partial^2 S}{\partial x^2} - X_f \cdot \frac{k_{\max} \cdot S}{K_s + S} \quad (4)$$

with initial and boundary conditions,

$$S = S_0$$

$$D_f \cdot \frac{\partial S}{\partial x} = \left( \frac{a_p}{3} \right) \cdot \rho_s \cdot k_s \cdot (q_s - \bar{q}) \quad \text{at} \quad x = 0$$

$$D_f \cdot \frac{\partial S}{\partial x} = k_f \cdot (C - S) \quad \text{at} \quad x = L_f$$

It is assumed that the substrate diffuses through biofilm where it is biodegraded by the microorganisms. Since the biofilm growth rate is directly related to the biological activity, the cell growth rate, which is the sum of the cell production, degradation, and decay rates, can be written as in Eq. 5.

$$\frac{dL_f}{dt} = \int_0^{L_f} \left( \frac{Y \cdot k_{\max} \cdot S}{K_s + S} - b_{tot} \right) \cdot dr \quad (5)$$

$$\text{At } t = 0,$$

$$L_f = L_{f0}$$

The change in bed porosity and the specific surface area of the biofilter due to the growth of biofilm are given by the Eq. 6 and 7 respectively.

$$\varepsilon = 1 - (1 - \varepsilon_0) \cdot \left( \left( 1 + \frac{L_f}{a_p} \right)^3 - n \cdot \left( \frac{L_f}{a_p} \right)^2 \cdot \left( 2 \frac{L_f}{a_p} + 3 \right) \right) \quad (6)$$

$$a_f = \frac{3(1 - \varepsilon_0)}{2 \cdot a_p} \cdot \left( 1 + \frac{L_f}{a_p} \right) \cdot \left( (2 - n) \cdot \frac{L_f}{a_p} + 2 \right) \quad (7)$$

The support-phase substrate balance of the biofilter was carried out by the linear driving

force approximation (LDFA) model and the Freundlich isotherm.

$$\frac{\partial \bar{q}}{\partial t} = k_s \cdot (q_s - \bar{q}) \quad (8)$$

Here,  $q_s = f(S|_{y=0})$  and  $S|_{y=0} = C_s$

$$q_s = K_f C_s^{1/n_f} \quad (9)$$

It is almost impossible to solve analytically the sets of the coupled parabolic second-order partial differential equations. Numerical methods are generally employed to solve the complex equations. In this study, the partial differential equations were first discretized by orthogonal collocation method (OCM) to form a set of first-order ordinary differential equations (ODEs). The resulting set of ODEs was then solved using the subroutine DVODE.<sup>18)</sup>

## EXPERIMENTAL INVESTIGATION

Detailed column experiments were conducted using low strength synthetic wastewater at Environmental R&D Laboratory, University of Technology, Sydney (UTS). Six filter columns (each with a diameter of 2 cm and a height of 50 cm) were employed. The columns had ports for influent feed, effluent collection, and back-washing. The columns were packed with 5 g (bed depth 4 cm and porosity 0.65) of granular activated carbon (GAC). The GAC used in the experiments was washed with distilled water and dried in an oven at 103.5°C for 24 hr. It was kept in desiccators before packing into the column. The physical properties of the GAC are shown in Table 1. The GAC bed was fully acclimatized at a constant filtration rate of 1 m<sup>3</sup>/m<sup>2</sup> hr. The filters were backwashed at 30% bed expansion for approximately 5 min every 24 hr of filtration run. Total organic carbon (TOC) was measured on a daily basis using the UV-persulphate TOC analyzer (Doh

Table 1. Physical properties of GAC used

Specification of the GAC	Estimated Value
Iodine number, mg/(g.min)	800
Maximum ash content	5%
Maximum moisture content	5%
Bulk density, kg/m <sup>3</sup>	748
BET surface area, m <sup>2</sup> /g	1112
Nominal size, m	$3 \times 10^{-4}$
Average pore diameter, Å	26.14

Table 2. Constituents of the Synthetic Wastewater used

Compounds	Weight (mg/L)	Compounds	Weight (mg/L)
MnSO <sub>4</sub>	0.125	KH <sub>2</sub> PO <sub>4</sub>	1.250
CaCl <sub>2</sub>	0.925	NH <sub>2</sub> .NH <sub>2</sub> .H <sub>2</sub> SO <sub>4</sub>	3.500
NaHCO <sub>3</sub>	0.875	Glucose	16.500
NaCl	2.500	Yeast Extract	1.750
MgSO <sub>4</sub> .7H <sub>2</sub> O	3.750	Peptone	1.750

rmann, Phoenix 8000). Total adsorbed biomass (as dry weight) was calculated on a weekly basis. To measure the biomass, after a week of continuous filtration, the GAC was taken out of the filter column and washed with distilled water to remove the suspended mass. The GAC with the retained biomass was then dried in an oven at 103.5°C for 24 hr and desiccated prior to the measurement of the total adsorbed biomass (as dry weight).

The chemical composition of the synthetic wastewater used is shown in Table 2. The synthetic wastewater was representative of the secondary effluent from a biological treatment plant, Sydney in terms of TOC concentration (TOC = 3.5 mg/L). The TOC contribution of the glucose, peptone, and yeast extract with inorganics are 79%, 11%, and 10% respectively.

## RESULTS AND DISCUSSION

### Attached Biomass

The performance of a biofilter depends on the biomass attached to the filter media. The biomass growth and its maintenance over the surface of the filter media, on the other hand, depend mostly on the surface characteristics of the filter media itself. As mentioned earlier,

Table 3. Measures of biomass<sup>19)</sup>

Parameter	Method
Colony forming units	Van der Kooij, Kemmy et al., USEPA
Turbidity	Werner
ATP	Jago-Stanfield
Cell numbers and volume	Billen-Servais

different media can have different biomass growth rate and biomass retention capacity. The GAC, sand, anthracite, blast-furnace slag, and the floating polypropylene pellets are some of the common biofilter media used in the water and wastewater treatment. Other factors that can affect the biomass accumulation are the filtration rate, filter backwashing techniques, and the organic content of the influent wastewater.

Several methods have been adopted in practice to measure the biomass attached to the filter media depending on the availability of the analytical facilities. Usually for the biofilter used in water treatment facilities, the amount of biomass is relatively small (in microgram) and hence a precise method for the measurement of the biomass is required (Table 3).

Ahmad et al.<sup>5)</sup> however, used heterotrophic plate count (HPC) to represent biomass growth in the biofilter. Wang et al.<sup>7)</sup>, and Carlson and Amy<sup>20)</sup> used phospholipid analysis to estimate the biomass in the biofilter. In this study, since the biomass growth with synthetic wastewater was significantly large, the total dry weight of the attached mass was measured as the active biomass. This method is simple and more practical.

As shown in Figure 2, after 6 weeks of continuous filtration operation, a decline in the biomass was observed. The maximum biomass was 0.09 g per g of GAC after 42 days, and the minimum biomass was 0.036 g per g of GAC after 63 days of continuous operation. The amount of biomass accumulation was found to be dependent on hydraulic loading rate (HLR) and the organic concentration. Another set of experiments conducted with filtration rate of 2.5 m/hr showed a biomass concentration of 0.1 g per g of GAC in 30 days of continuous filter run.

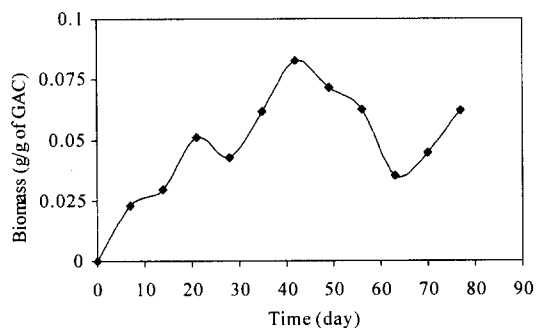


Figure 2. Biomass accumulation in the GAC biofilter (Filtration rate =  $1 \text{ m}^3/\text{m}^2\text{hr}$ , GAC = 5 g, average influent TOC = 3.5 mg/L).

Carlson and Amy<sup>20)</sup> also found the biomass concentration profile as a function of HLR. The higher the loading rate, the greater was the initial biomass and deeper the penetration into the filter bed. The biomass concentration profile thus appears to be the most critical parameter in the design of biofiltration system. Servais et al.<sup>21)</sup> observed 13 - 34 % decrease in biomass after 100 days of operation of the GAC biofilter at Neuilly-sur-Marne (France) water treatment plant. Ong et al.<sup>22)</sup> used high strength wastewater ( $\text{BOD}_5 = 389 \text{ mg/L}$ ) in an ultra-compact biofilm reactor, and observed 52.5 % and 32.8 % decrease in biomass after 38 days and 94 days of filter run respectively. These studies indicate that the decrease in the biomass during the continuous operation of the biofilter is unavoidable. The decrease in the biomass may be due to the die-off of microorganisms and its subsequent removal in backwashing. In this study, despite the decrease in the biomass during the 7<sup>th</sup> to 9<sup>th</sup> week of the continuous operation of the biofilter, the organic removal efficiency of the biofilter remained unaffected.

### Long-term Performance of the Biofilter

The TOC removal efficiency of the biofilter in a long run is presented in Figure 3. The performance of the biofilter was predicted using the model discussed earlier. The model parameters used to predict the experimental results are presented in Table 1. This result shows that the GAC biofilter can be operated for a long

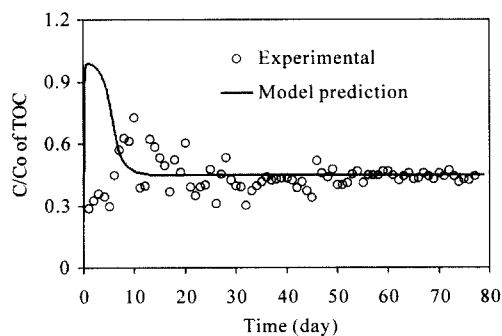


Figure 3. TOC removal efficiency of the GAC biofilter and model prediction (Filtration rate =  $1 \text{ m}^3/\text{m}^2\text{hr}$ , GAC bed depth = 4 cm, average influent TOC = 3.5 mg/L) ( $X_s = 1 \times 10^{-8} \text{ mg/L}$ ,  $K_d = 5 \times 10^{-6} \text{ 1/s}$ ,  $L_f = 1 \times 10^{-6} \text{ m}$ ,  $\sigma = 1.16 \times 10^{-6} \text{ 1/s}$ ,  $\beta = 10000$ ,  $Y = 0.34$ ,  $X_f = 6.44 \times 10^3 \text{ mg/L}$ , Effluent was taken after filter backwash considering influent residence time. C and  $C_0$  are the effluent and influent TOC concentration).

time without regeneration of carbon. Even after 77 days of continuous run, the biofilter maintained the organic removal efficiency of 50-55 %. The daily backwash adopted to avoid the physical clogging of the biofilter did not affect the organic removal efficiency of the filter. Some of the biomass may naturally be lost during backwashing of the filter but the loss of biomass can create more sites for adsorption of organics and thus impairment is balanced. Adsorption of organics and biological degradation of the organics adsorbed onto the activated carbon can be the two major mechanisms for the consistent removal of organics in the GAC biofiltration system.

### Effect of Filtration Rate and Influent Organic Concentration

In this study, the filter column was acclimatized with relatively low concentration of organics (TOC of 3.5 mg/L) and low filtration rate of 1 m/hr for the gradual growth of biomass in the filter media. The effects of both influent organic concentration and filtration rate on the organic removal efficiency of the biofilter were experimentally investigated. As can be seen from

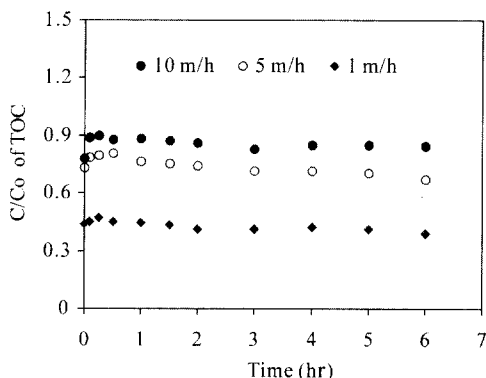


Figure 4. Effect of filtration rate on the performance of GAC biofilter (Acclimatization period = 77 days, average influent TOC = 3.5 mg/L, GAC = 5 g, C and  $C_0$  are the effluent and influent TOC concentration).

Figure 4, with increased filtration rates, the effluent quality became inferior to that with lower filtration rate (at which the filter was acclimatized) but the organic removal pattern remained unchanged with time. The drop in the organic removal efficiency of the biofilter with the increase in the hydraulic loading rate was because of the decrease in the EBCT of the biofilter. Previous researchers have also observed the decreases in the organic carbon removal with decreased EBCT.<sup>6,23</sup> LeChevallier et al.<sup>6</sup> found an increase in TOC removal from 29 to 51.2 percent when EBCT was increased from 5 to 20 min. However, Carlson and Amy<sup>20</sup> have reported from their pilot scale experimental studies that organic removal in a biofilter was limited either by biodegradable organic matter (BOM) formation or biomass concentration, not by filter operating parameters. They also found that optimum organic removal efficiency of the biofilter was at the loading rate to which the filter was acclimatized, and if the steady-state biomass conditions were allowed to develop, even at higher hydraulic loading rate, the removal efficiency of biofilter would increase to that found at the lower hydraulic loading rate (at which the filter was first acclimatized).

As shown in Figure 5, the removal efficiency of the filter improved slightly when the influent

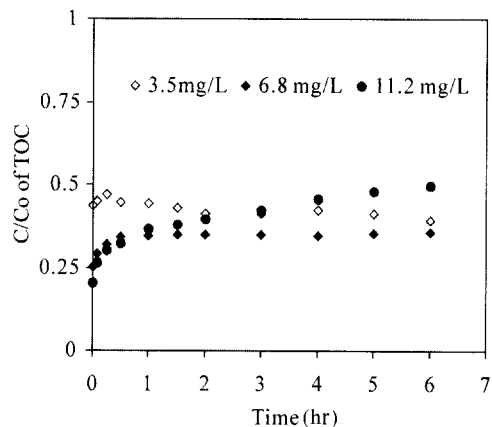


Figure 5. Effect of influent organic concentration on the performance of the GAC biofilter (Acclimatization period = 77 days, average influent TOC = 3.5 mg/L, GAC = 5 g, C and  $C_0$  are the effluent and influent TOC concentration).

TOC concentration was increased to 6.8 mg/L. The obvious reason for this improvement is the increased biological activity of the microorganism. The first order steady-state model developed by Huck et al.<sup>24</sup> also showed that the organic removal efficiency of the biofilter was approximately directly proportional to the influent organic concentration. However, when the influent concentration was increased from 6.8 mg/L to 11.2 mg/L, the removal efficiency of the filter was higher initially and then decreased with time.

These experimental results thus indicated that the biomass profile is the most critical parameter in the design of a biofiltration system, and that the biofilter should be operated as close to the steady-state conditions as possible to achieve optimum organic removal efficiency. The sudden increase in the flow rate and influent concentration can change the efficiency of the biofilter temporarily, and if the steady state condition of the biomass is allowed to develop at the changed hydraulic or organic loading rate, the organic removal efficiency of the biofilter would be equivalent to that of the organic or hydraulic loading rate at which the filter is first acclimatized.

## CONCLUSIONS

1. GAC biofilter can effectively be used in an economical manner to produce better quality of effluent due to its consistent TOC removal efficiency, long operational life, and simplicity in operation.
2. The biological activity led to consistent effluent organic concentrations over a long period. The daily backwash adopted did not affect the biological mass growth thus the effluent quality. Its performance however, was affected by the filtration rate and the influent organic concentration, suggesting that the biofilter should be operated in the same conditions at which it was acclimatized for its optimum and consistent organic removal efficiency.
3. Although higher filtration rates led to inferior effluent quality, the TOC removal efficiency was maintained constant with filtration time. A correct choice of filtration rate and GAC medium depth with an appropriate backwash can lead to a long-term operation with consistent and superior effluent quality.
4. The mathematical model proposed in this study could predict the long-term organic removal efficiency of the biofilter reasonably well.
5. It is however important that the biofilter parameters should be estimated at different operating conditions (such as acclimatization filtration rate and initial organic concentration) to verify the versatility and adaptability of the model in practice.

## ACKNOWLEDGEMENTS

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## NOMENCLATURE

- $a_f$  = Specific surface area ( $m^2$ )  
 $a_p$  = Pellet radius (m)

- $b_{tot}$  = Total shear and decay loss (1/sec)  
 $C$  = Liquid phase concentration (mg/L)  
 $C_S$  = Concentration at the liquid solid interface (mg/L)  
 $D_{ax}$  = Axial dispersion coefficient ( $m^2/sec$ )  
 $D_f$  = Molecular diffusivity within biofilm ( $m^2/sec$ )  
 $k_f$  = Interphase mass-transfer coefficient from liquid to biofilm (m/sec)  
 $k_s$  = Solid phase mass-transfer coefficient (1/sec)  
 $k_{max}$  = Maximum rate of substrate utilization (1/sec)  
 $K_d$  = Decay constant (1/sec)  
 $K_F$  = Freundlich equilibrium constant  
 $K_S$  = Monod half velocity coefficient (mg/L)  
 $L_f$  = Biofilm thickness (m)  
 $n_F$  = Freundlich exponential constant  
 $N$  = Substrate uptake rate of biofilm  
 $q$  = Adsorbed-phase concentration (mg/g)  
 $\bar{q}$  = Average concentration of  $q$  (mg/g)  
 $q_S$  = Value of  $q$  at pellet surface (mg/g)  
 $S$  = Concentration of the substrate in the biofilm (mg/L)  
 $x$  = Film coverage defined as volume of film per unit volume of clean pellet (m)  
 $X_f$  = Cell density of biofilm (mg/L)  
 $X_S$  = Suspended cell concentration (mg/L)  
 $Y$  = Yield coefficient (mg/mg)  
 $\sigma$  = Biofilm shear loss coefficient (1/sec)  
 $\beta$  = Filtration efficiency  
 $\gamma_{ads}$  = Rate of removal of the substrate from the liquid phase by adsorption (mg/L/sec)  
 $\gamma_{bio}$  = Rate of removal of the substrate from the liquid phase by biodegradation (mg/L/sec)  
 $\epsilon$  = Bed porosity  
 $\epsilon_0$  = Initial bed porosity  
 $\nu$  = Superficial velocity (m/sec)  
 $\theta$  = Empty bed contact time (sec)  
 $\rho_s$  = Solid density ( $kg/m^3$ )

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