

# Modeling of bio-sand filter used to remove organic matter from rainwater for predicting sand filter depth and water velocity

## Abstract

Efficiency of bio-sand filter (BSF) must be monitored to ensure the quality of drinking water for consumer health and safety. A common approach to address the monitoring of raw and treated water remained in effective in controlling water quality. Accurate design to achieve an expected efficiency of the drinking water treatment system is still not available to most BSFs since the present physical models were not originally able to calculate any design parameter. The aim of this study was to develop the empirical models for calculating the depth of sand filter and water velocity to be used in operating the BSF treatment system to remove organic pollutants from rainwater. All parameters in equation are physically meaningful, experimental data validation showed the equations remained accurate. The performance of BSFs can be predicted using the models to gain an insight in designing of both depth of sand filter and water velocity.

**Keywords:** bio-sand filter, empirical model, filter depth, organic matter, rainwater, water velocity

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## Introduction

Safe drinking water is very important for everybody but is generally unavailable in most rural and suburban of developing, underdeveloped and often developed countries. Important considerations in the development and maintenance of safe water supplies are the availability and use of efficient, inexpensive and appropriate technology for removing microbial hazards, parasites and toxicants. Sand filtration as one of the filtration techniques is mainly used in combination with other water purification methods.<sup>1-3</sup> Two types of sand filter are commonly used in water treatment i.e., slow sand filter and rapid sand filter. Slow sand systems have recently been adapted to point-of-use systems, especially in developing countries. In this context, they are generally known as “bio-sand filter (BSF)”. The advantages of BSF are: (1) cleaning slow sand filter does not consume any products, (2) the run of BSF treatment system produces virtually no waste water and (3) the use of BSF can be used with surface, well, or rainwater sources. Because of the environmental sustainability aspects of encouraging an integrated water resources management foster river basin boundary approach, filtration technique as one of the alternative technologies offers a water supply treatment process remained reasonable. This is especially addressed to the use of water sources original from rainwater due to harvesting rainwater from a building/housing roof can reduce overflows and could be the path of hydrologic cycle management to control surface runoffs to return back such as in heterogeneous forestry lands regulated water flows. This can have the impact on water resources management to optimize water uses particularly for the regions blessing with abundant rainfall such as in the rainy tropical or temperate countries. Harvesting

rainwater plays the important roles in managing of water resources i.e., to reduce overall water demands of growing cities, to avert the flash floods, to reduce soil erosion and to reduce the cost of urban drainage systems as well.<sup>4</sup> The use of rainwater for drinking water production can help the inland and mountainous people especially in the regions of no providing the public water supply facilities. Other advantages of using rainwater can provide the landscape irrigations, aquacultures, air conditionings, local climatic control, groundwater recharge, and fire fighting.<sup>5</sup>

A study of investigating the performance of BSF with respect to the pause time between filtration runs showed greater removal of total Coliforms when the filter pause period was 12 hours versus 30 hours and the total Coliforms removal by the BSF decreased with an increase in the sample collection volume.<sup>6</sup> Ability of the BSF to reduce concentrations of bacteria, coli phages and human enteric viruses and to modify filter effectiveness with biological ripening and length of operation has been reported to vary ripening process with time due to influent water quality, and the reductions of 95 to 98% E. coli in a ripened filter were verified.<sup>7</sup> A field study of 107 households conducted to evaluate the use and performance of the Manz’s BSF in the Antimonite valley of Haiti showed that an average of BSF efficiency for bacterial removal could be 98.5% for long-term users and 76% for new users.<sup>8</sup> Using two different filters and two different water supplies indicated that an intermittent slow sand filter can remove more than 83% of total heterotrophic bacteria populations, 100% of Giardia cysts, 99.98% of *Cryptosporidium oocysts*, 50-90% of organic and inorganic toxicants when administered in concentrations varying from 10 to 100 times of environmental population levels.<sup>9</sup> The use of BSF would be effective to remove approximately 95% of fecal coliform

and to reduce turbidity to a level of below 1 NTU.<sup>10</sup> Despite of the mathematical models to describe diffusion of oxygen transfer into a bio-layer filter has been developed and supported by experimental data,<sup>2,10</sup> such experiments are still not focused on the modeling of BSF to remove organic matter.

The objectives of this study are as follows: (1) to develop the empirical models of BSF based on the experimental data of removing organic matter from rainwater and to verify physical meanings of the parameter in equations, (2) to define the limitations of filtration rate to be used for BSF treatment systems to feasibility remove organic matter, and (3) to analyze the design parameters of sand filter depth and water velocity to rely with the ability of treatment process to control the efficiency of BSF system.

## Materials and methods

### Organic matter and bio-sand filter

In spite of the parameters of oxidized organic matter consisting of dissolved oxygen (DO), percentage of saturated oxygen (%O<sub>2</sub>), dissolved organic carbon (DOC), permanganate value (PV), biochemical oxygen demands (BOD), chemical oxygen demands (COD), total Kjeldhal nitrogen (TKN) and ammonium (NH<sub>4</sub><sup>+</sup>),<sup>11-14</sup> this work only selected total COD to represent organic matter for the development of the empirical models. The data collected were coming from 15 storm events monitoring to convene via a zinc roof of the pilot building. The experiments conducted to monitor the qualities of raw and treated water treated using three different BSFs during the period of rainy season from February to April 2005. Location of this study was selected within the campus of Universiti Tun Hussein Onn Malaysia at Parit Raja, Batu Pahat, Johor, Malaysia. The values of COD for rainwater vary from 6 to 129 mg/L with an average of 43 mg/L. Three different BSFs used in this work are as follows: (i) bio-sand filter 0.2m (BSF0.2) with filtration rate of 0.3m/h, (ii) bio-sand filter 0.4m (BSF0.4) with filtration rate of 0.6m/h and (iii) bio-sand filter 0.7m (BSF0.7) with filtration rate of 0.91m/h. The performances of the BSF treatment system to remove COD were verified as high as 51, 65 and 84% for BSF0.2, BSF0.4 and BSF0.7, respectively.

### Hypothesis

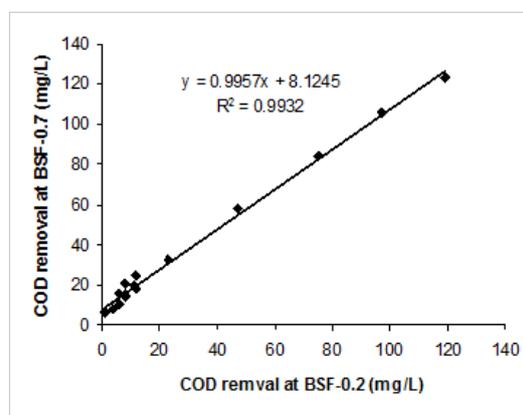
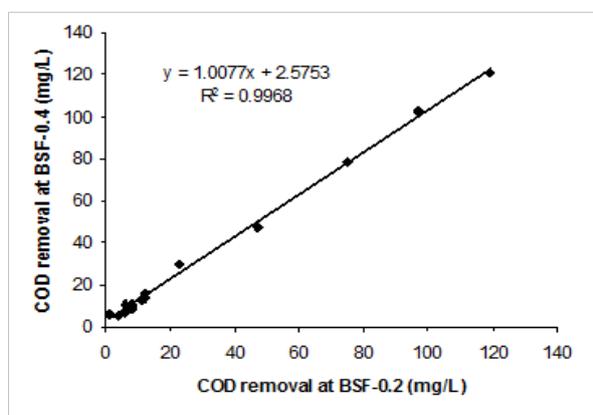
In this work, a BSF filled with sand takes the form of container of less than one meter tall and 30cm in width and in depth. A colloid retention of about 3cm on top of the filter bed was arranged to setting

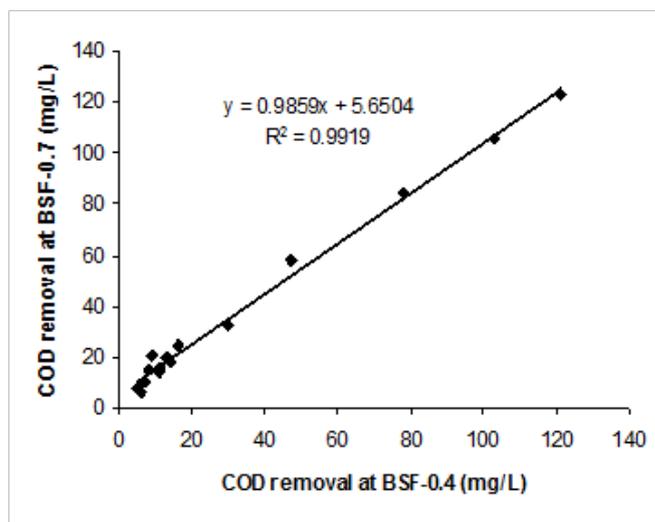
up the level of outlet to collect filtered water and that of inlet to feed raw water remained corresponding. This contains biological activity and therefore often refers as “bio-sand filter”. Since many microorganisms of such as bacteria, viruses and parasites can travel through the sand, they collide with and adsorb onto sand particles.<sup>1,15</sup> A biological active layer, which takes a week or two to fully develop, was maintained at a water level of above the top of the sand, as with slow sand filters, this bioactive layer helps filter, adsorb, destroy, or inactivate the pathogens. Both organisms and particles collected in a greatest density on the top layer of the sand gradually form a biological zone. Biological zone does not really a distinct or cohesive layer but rather a dense population that gradually develops on top layer of the sand. The population of microorganisms could be part of the active food chain that consumes pathogens (disease-causing organisms) as they are trapped in and on the sand surface. The uppermost 1-3cm of this biological zone is sometimes referred to as “*schmutzdecke*” or “filter cake”, which is defined as a layer of the particles deposited on top of the filter bed or biological growth on top of the filter bed.<sup>1,15</sup> A porous plate placed above the sand can prevent disturbance to bioactive layer when water flows. Users simply pour water into the top of the sand and collect treated water from outlet of the BSF. A BSF can be easily cleaned by scraping of bio-film or top sand layer. The empirical models developed in this work systematically adhere with certain parameters of the equation. Physical meanings of each parameter should be verified to describe the behaviors of biological and physical sorption. The empirical models were developed based on the following hypotheses that: (1) bioactive layer of different depths of sand filter contributes no significant difference to filtration process, (2) biological phenomenon, which involves to remove organic matter, can affect the rate of substrate depletion, and (3) physical phenomenon, which involves to collide with and adsorb organic matter onto the sand particles, depends on sand filter depth and water velocity.

### Models development

A plot Figure 1 of COD removal at BSF0.2 versus COD removal at BSF0.4, COD removal at BSF0.2 versus COD removal at BSF0.7 and COD removal at BSF0.4 versus COD removal at BSF0.7 takes a shape of the straight line and gives a mathematical expression of:

$$R_2 = \beta x R_1 + C \quad (1)$$





**Figure 1** Correlation of COD removal between two BSFs of different depth.

Where  $R_1$  is COD removal at first BSF as the horizontal line (in  $\text{mgL}^{-1}$ ),  $R_2$  is COD removal at second BSF as the vertical line (in  $\text{mgL}^{-1}$ ),  $\beta$  is biofilm coefficient relying with capability of filter cake to remove COD (dimensionless) and  $C$  is biophysical adsorption constant relying with depth of sand filter, filtration rate and biochemical fixation onto sand particles during filtration process (in  $\text{mgL}^{-1}$ ). The results (Table 1) show that every shape has a very good correlation with  $R^2 > 0.9918$  and the values of  $\beta$  are all very close to one. This explains that bioactive layer of different depths of sand

filter contributes no significant difference in filtering the rain water hence role of the schmutzdecke to control the performance of BSF to remove organic matter remains comparable.<sup>2</sup>

If we recognize that the value of  $\beta$  is one, rearranging eqn (1) yields:

$$R_2 = R_1 + C \tag{2}$$

**Table 1** Values of  $\beta$ ,  $C$  and  $f$  obtained from the difference in depth between two BSFs

Curve of	$\Delta H$ (m)	$\beta$	$C$ ( $\text{mg L}^{-1}$ )	$F$ ( $\text{mg L}^{-1}\text{m}^{-1}$ )	$R_2$
BSF-0.2 vs BFS-0.4	0.2	1.0077	2.5753	12.9	0.9968
BSF-0.4 vs BFS-0.7	0.3	0.9859	5.6604	18.9	0.9919
BSF-0.2 vs BFS-0.7	0.5	0.9957	8.1245	16.2	0.9932

The main removal mechanisms for BSF treatment process are metabolic breakdown, bacterioivory, death of influent bacteria, adsorption of pollutants and biomass onto the sand and mechanical straining.<sup>16,17</sup> They may be hypothetically encapsulated into both biological and physical adsorption. We suggest that constant  $C$  to rely on capability of the BSF to remove organic matter depends sand depth and water velocity. Biological adsorption of organic removal can simultaneously occur in filter cake and sand filter; however, substrate depletion rate varies dependent on the depth of sand filter. The value of  $C$  as shown in Table 1 increases with increasing of the difference in depth between two BSFs ( $\Delta H$ ). The influence of sand filter depth on  $C$  can be analyzed with the help of a pertinent correlation. A plot Figure 2 of  $\Delta H$  versus  $C$  gives a linear equation intercept at zero that:

$$C = f \times \Delta H \tag{3}$$

Where  $C$  is biophysical adsorption constant (in  $\text{mgL}^{-1}$ ),  $\Delta H$  is the difference in depth between two BSFs (in m),  $f$  is biochemical fixation coefficient relying with biological and chemical fixations onto sand particles during filtration process (in  $\text{mgL}^{-1}\text{m}^{-1}$ ).

Flow rate of sand column could be proportional to cross-sectional area of sand and pressure head (hydraulic loading) of water on top of the sand. This could be affected by length of sand column as well as by fluid properties (viscosity, density and raw water quality) and sand characteristics. Flow rate ( $F$ ), called also water velocity or filtration rate, for slow sand filter would be around  $0.1 \text{mh}^{-1}$  even though it can increase until  $0.4 \text{mh}^{-1}$ . Note that unit is the compaction of  $\text{m}^3\text{m}^{-2} \text{h}^{-1}$  and sometimes mentioned in d not h. Using eqn (3) permits us to compute the value of  $C$  at any  $\Delta H$  when value of  $f$  has been verified. Figure 2 shows that  $C$  increases with increasing of  $\Delta H$  due to the BSF efficiency increases with depth of the sand filter. It is suggested that  $C/\Delta H$  ratio refers to biochemical fixation coefficient ( $f$ ), which is

dependent on physical adsorption. A high  $f$  value of  $18.9\text{mgL}^{-1}\text{m}^{-1}$  can be obtained from a curve of plotting COD removal at BSF0.4 versus COD removal at BSF0.7 with  $\Delta H=0.3\text{m}$ , comparing with that of  $12.9\text{mgL}^{-1}\text{m}^{-1}$  for the curve of BSF0.2 versus BSF0.4 with  $\Delta H=0.2\text{m}$  and that of  $16.2\text{mgL}^{-1}\text{m}^{-1}$  for the curve of BSF0.2 versus BSF0.7 with  $\Delta H=0.5\text{m}$  Table 1. This signifies that deeper sand filter can induce the fixation of organic matter onto the sand particles remained more effective.

The influence of water velocity on the performance of BSF can be analyzed using its relevant correlation. A plot Figure 3 of  $V$  versus  $C$  gives us a linear expression of:

$$C = -\phi x V + \chi \quad (4)$$

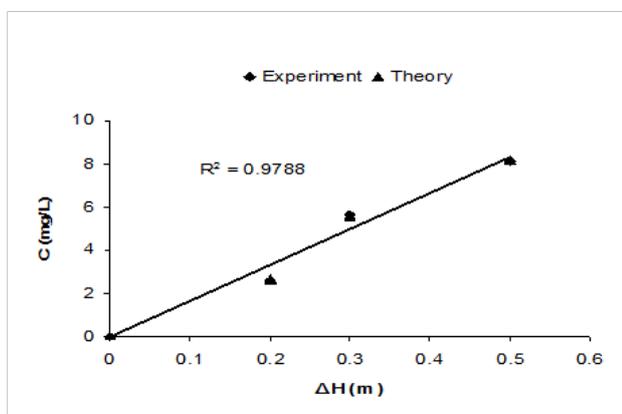


Figure 2 A plot of  $\Delta H$  versus  $C$ .

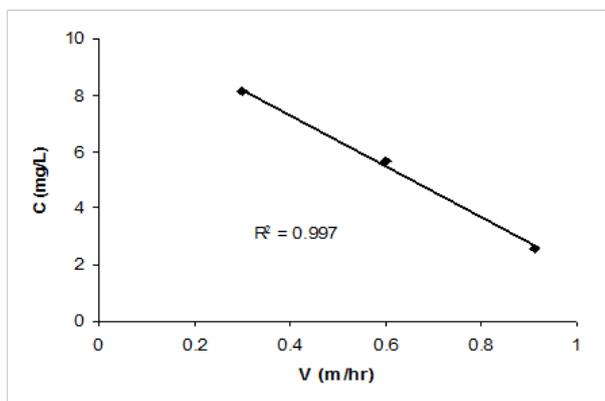


Figure 3 Linear expression of  $C = -\phi.V + \chi$

Where  $C$  is biophysical adsorption constant (in  $\text{mgL}^{-1}$ ),  $V$  is water velocity (in  $\text{mh}^{-1}$ ),  $\phi$  is velocity coefficient (in  $\text{mg h L}^{-1}\text{m}^{-1}$ ) and  $\chi$  is physical adsorption constant relying with water velocity and sand filter depth (in  $\text{mgL}^{-1}$ ). With its appropriate range water velocity does not significantly affect bacteriological effluent quality; therefore, the use of filtration rate at  $0.25$  and  $0.45\text{mh}^{-1}$  without any marked difference in the effluent quality has been reported in Netherlands.<sup>1</sup> A research in India reported that continually operated sand filters found no significant difference in faecal coliform reduction with the

flow rates of  $0.1$ ,  $0.2$  and  $0.3\text{mh}^{-1}$ .<sup>18</sup> It is still reasonable to increase filtration rate of BSF when supported with effective pretreatment and effective disinfection stage followed the filtration process.<sup>19</sup> In spite of bacteriological quality of filtered water in a BSF does not get fully qualified with high filtration rate rather than a conventional figure, the removals of turbidity and color can achieve with high water velocity to having a filtrate quality remained reasonably good for much of this system. A water velocity of higher than conventional one can therefore be implemented in a BSF when the quality of raw water is good.<sup>20</sup> As a limitation of this study is that the empirical models only allow the  $C$  value ranged from  $0$  to  $10.9\text{mgL}^{-1}$  conforming to good engineering practice of using the water velocity ranged from  $0$  to  $1.2\text{mh}^{-1}$ . This interprets that sand filtration cannot be classified as slow sand filter when a water velocity of higher than  $1.2\text{mh}^{-1}$  is used to solve for the maximum overall preference for a design parameter set. According to eqn (4) the performance of BSF treatment system to remove organic matter will increase with decreasing of water velocity as  $C$  value increases.

## Results and discussion

### Correlation between $\Delta H$ and $V$

Combining eqn (4) and eqn (3) yields a new equation valid for calculating  $\Delta H$  values when a  $V$  value has been verified, such that:

$$\Delta H = \frac{-\phi.V + \chi}{f} \quad (5)$$

Using eqn (5) permits us to calculate the depth of sand filter for operating the BSF treatment system pursuant to the water velocity since the values of  $\phi$ ,  $\chi$  and  $f$  from a pilot BSF have been verified see Figure 4. As an example that in keeping the results of physical model BSF0.2 with an average efficiency of  $51\%$  retained for the BSF baseline data set, the depth of a BSF system should be extended to around  $0.53\text{m}$ , modifying from  $0.20$  to  $0.73\text{m}$ , when a water velocity of the expected BSF treatment process has been decided to change from  $0.2$  to  $1.0\text{mh}^{-1}$ . A water velocity should be regulated to comply with the rate of water demands to a quotidian familial use or communal water provision.

### Analysis of $\Delta H$ for the BSF treatment process

By substituting eqn (3) into eqn (2) and redefining  $R_1$  to  $R_{\text{pil}}$  and  $R_2$  to  $R_{\text{prop}}$ , this can summarized using the following equation:

$$R_{\text{prop}} = R_{\text{pil}} + f.\Delta H \quad (6)$$

Where  $R_{\text{prop}}$  is COD removal at the proposed BSF (in  $\text{mgL}^{-1}$ ),  $R_{\text{pil}}$  is COD removal at the pilot BSF (in  $\text{mgL}^{-1}$ ),  $f$  is biochemical fixation coefficient (in  $\text{mgL}^{-1}\text{m}^{-1}$ ) and  $\Delta H$  is depth of sand filter to be modified to the proposed BSF (in  $\text{m}$ ).

Using eqn (6) permits us to define the performance of a proposed BSF after modified the depth of sand filter since the performance of a pilot BSF and the biochemical fixation coefficient have been verified. The efficiency of the proposed BSF can be calculated by

$$\theta = \frac{R_{prop}}{COD_{in}} \cdot 100\% \quad (7)$$

By substituting eqn (7) into eqn (6) yields eqn (8) that can be used to calculate  $\Delta H$  in accordance with the performance of the proposed BSF, such that:

$$\Delta H = \frac{\theta \cdot COD_{in} - R_{pil}}{f} \quad (8)$$

Where  $\Delta H$  is depth of sand filter to modify for the proposed BSF (in m),  $\theta$  is performance of proposed BSF (in %),  $COD_{in}$  is COD in raw water or initial COD (in mg L<sup>-1</sup>),  $R_{pil}$  is COD removal at the pilot BSF (in mg L<sup>-1</sup>) and  $f$  is biochemical fixation coefficient (in mg L<sup>-1</sup>m<sup>-1</sup>).

The modification of sand filter depth ( $\Delta H$ ) for operating the proposed BSF treatment system can be calculated using eqn (8). This needs to conform to any performance of the proposed BSF such as 80, 85, 90, 95 or 100%. As an example that in keeping the results of the pilot BSF0.2 to refining rain water with an initial COD concentration of 43mgL<sup>-1</sup> have shown to be proficient to remove COD of about 22mg L<sup>-1</sup>. A plot Figure 5 of  $\Delta H$  versus  $\theta$  gives us a straight line of intercept at 51%, which is the efficiency of BSF0.2 without modification of sand filter. Experimental data validation shows the results calculated using eqn (8) are still accurate; therefore, an efficiency of 100% can be achieved for a BSF treatment process since the depth of sand filter is higher than 1.3m Figure 5.

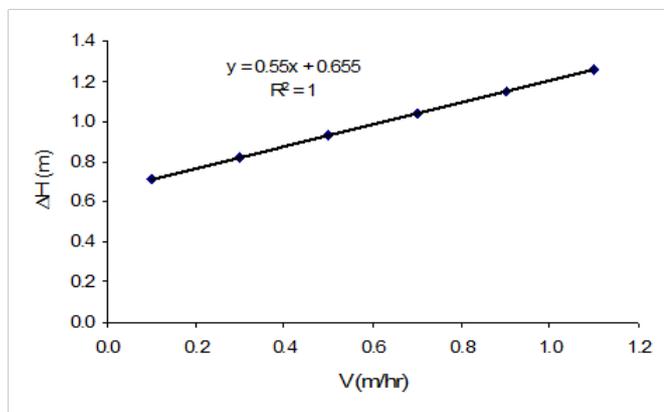


Figure 4 A plot of  $\Delta H$  versus  $V$ .

### Analysis of $V$ dependent on $\theta$ and $\Delta H$

Combining eqn (8) and eqn (5) yields an equation valid for calculating the  $V$  value pursuant to the performance of proposed BSF treatment system that:

$$V = \frac{R_{pil} + \chi - \theta \cdot COD_{in}}{\phi} \quad (9)$$

Using eqn (9) permits us to control water velocity for operating the BSF treatment process in accordance with an expected performance

of such proposed BSF since the concentration of organic matter in raw water, efficiency of the pilot BSF, velocity coefficient and physical adsorption constant have been verified. The results Figure 6 show that the water velocities of 0.16; 0.40, 0.63, 0.87 and 1.10mh<sup>-1</sup> as conforming to the performances of 80, 85, 90, 95 and 100% were verified since the depths of sand filter of 0.75; 0.88; 1.01; 1.14 and 1.27m, respectively, were used to a proposed BSF. There is because of the increase in water velocity can reduce the depth of sand filter in retaining the efficiency of BSF remained consistent, as shown in eqn(5).

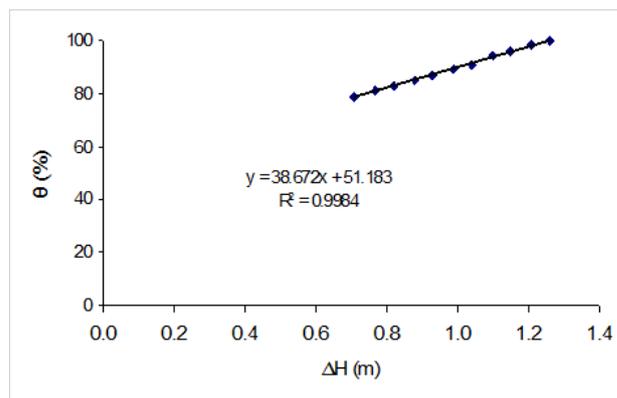


Figure 5 A plot of  $\Delta H$  versus  $\theta$ .

Every  $\Delta H$  value calculated using eqn (8) equals to that calculated using eqn (5) since the  $V$  value calculated using eqn (9) is applicable. Therefore, the values of  $\phi$ ,  $\chi$  and  $f$  are all constant because of the physical model designed to fix across-sectional area of the BSF has remained consistent. This implies that the design parameters technicality act upon the performance of the proposed BSF. As a conclusion, the depth of sand filter designed to a proposed BSF treatment system could conform to the water velocity. The efficiency of the proposed BSF to remove organic matter can be regulated through a modification of either sand filter depth or water velocity, or through a modification of both sand filter depth and water velocity in the same time.

### Conclusion

This study used the data monitored three physical models to develop the empirical models of BSF to remove organic matter from rainwater. The models developed could be feasible for use of calculating the design parameters of  $\Delta H$  and  $V$ .  $C$  values ranged from 0 to 10.9mgL<sup>-1</sup> have been verified using the models to this conform the water velocity ranged from 0 to 1.2mh<sup>-1</sup>, respectively. Functional filtration equations accounting for bio-film, biophysical sorption, biochemical fixation, water velocity and physical adsorption have been developed to showing the parameters in equation are all physically meaningful. Experimental data validation shows all empirical equations remained accurate. A new methodology of calculating the design parameters has been proposed to BSF treatment process. An appropriate engineering design of the proposed BSF to remove organic matter can be calculated using the models since the quality of raw water and the respected parameters in equations have been verified. The application of the models may be alternated of calculating either sand filter depth or water velocity, or both and filter depth and water velocity in the same time.

## Acknowledgements

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## Conflict of interest

The author declares no conflict of interest.

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