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# Modifications of a simple clogging and back-washing efficiency model for arsenic filters

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**After continuous use of any filtration device, clogging of the filter media becomes apparent, which eventually causes poor performance of the filtration process. Back-washing is a common technique that is used for the recovery of the filtration capacity of clogged filter media. This paper presents the development of a simple clogging and back-washing efficiency model for a special filter medium. The 'third-generation IHE family filter' was developed by the Unesco-IHE Institute for Water Education and is widely used for treating arsenic-contaminated water in many countries, including Bangladesh. Several field tests were conducted at three different sites in Bangladesh having different qualities of influent water. The model coefficients developed were derived using the collected data on flow measurements through the device during successive clogging and back-washing periods of up to 4 months. The developed model with the selected model coefficients can simulate field measurements on flow retardation and recovery with good accuracy. Eventually, selected model coefficients (clogging factors) for the three sites were correlated with the respective ammonium and iron contents in the influent water. It was found that the clogging factor linearly varies with the ammonium and iron contents of the inflow water.**

## Notation

| | |
|---|---|
| $C_f$ | clogging factor |
| $K$ | exponential clogging factor |
| $n$ | number of additional non-washing periods beyond normal non-washing period |
| $Q_1$ | original flowrate before clogging |
| $Q_2$ | flowrate after 1 week of operation |
| $Q_3$ | flowrate after back-washing |
| $R_f$ | recovery factor |
| $t$ | time step |
| $X_{model}$ | modelled flow-rate value |
| $X_{obs}$ | measured flow-rate value |
| $\Delta C$ | clogging factor reduction constant |

## 1. Introduction

Arsenic contamination in groundwater has been reported as a serious hazard to public health in many countries around the world. Several methods and techniques such as oxidation/reduction reaction, precipitation, adsorption and ion exchange, and physical exclusion have been developed for the removal of arsenic from drinking water. A relatively new alternative technology termed Soras (solar oxidation and removal of arsenic) has also been used in a rural region of the Andes in Latin America (Duarte *et al*., 2009). Moreover, in some countries, materials such as zeolite, manganese greensand and nanocrystalline magnetite are also used to treat arsenic. In many developing countries a commonly used practice is filtration of the contaminated water, owing to its simplicity and cost effectiveness. In fact, filtration is a very fundamental and primitive method, which has been in practice for centuries for the treatment of many contaminants, including arsenic. Screening, sedimentation and filtration are primary steps even for many higher level commercial, government-regulated water-treatment plants, as through these primary treatments the effectiveness of subsequent secondary and tertiary treatments can be increased significantly. Filtration through sand or ceramic media enables the trapping of arsenic or other inorganic contaminants through adsorption action. In the presence of calcium and ferric chloride, the removal efficiency of arsenic is significantly increased, due to the additional coagulation effect caused by the ferric chloride and calcium (Hering *et al*., 1996). A common issue of any such filtration system is the clogging of filter media over the course of time, which can be recovered to some extent through a back-washing process.

Various physical, biological and chemical processes can enhance the mechanism of clogging. Each of the processes can work either individually or collectively to reduce infiltration rates. Criteria such as raw water quality, ponding depth, hydraulic loading rate and cycle, as well as algal/bacterial growth, play an important role in the development and extent of clogging. Moreover, owing to changes in water quality, water depth and basin bottom conditions, these processes can be active at different times (Recz *et al*., 2012). It has been observed that grains of angular shape create more clogging than grains of round shape (Benaman *et al.*, 2007). Microbial activity can reduce the saturated hydraulic conductivity by clogging soil pores with microbial cells and their synthesised effects, called bio-clogging (Lee *et al.*, 1998). Furthermore, sedimentation concentration is the most important factor affecting the performance of filter media. EL Awady *et al.* (2008) conducted a detailed study on the hydraulic behaviour and clogging problems of different filter media under different filter depths and sediment loadings. They found that using high sediment loads of 50∼100 mg/l drastically affected the removal efficiency. Finally, they concluded that filter media such as crushed silica and crushed basalt, with a filter depth of 50 cm, under a moderate sediment load of 10–20 mg/l, provided the best performance. Nevertheless, any filter medium requires regular attention and/or back-washing to keep it functional for longer periods. In a commercial set-up, such back-washing is implemented in a regulated way with proper monitoring. However, this is often an issue in a domestic set-up, where regular back-washing depends on the users' awareness and availability. In particular, in remote village areas, where people are mostly illiterate, regular back-washing is often neglected.

The majority of studies on arsenic filtration have focused only on the arsenic removal capacity of different filter media. Several studies, such as Oyanedel-Craver and Smith (2008), Seki (2013), Khan (2004), Wickramasinghe *et al.* (2004) and Petrusevski *et al.* (2008), were done on quantitative measurements – that is on the flow capacity and reduction of flow capacity through filter media after repetitive use. Very few studies have been done on modelling such flow reduction as well as flow recovery. A mathematical model is often necessary for the purpose of prediction of the extent of clogging and/or expected level of recovery through back-washing. Among the modelling works, Vandevivere *et al.* (1995) proposed a mechanistic model to simulate microbial clogging of saturated soils and aquifer materials. Through comparing experimental results with their model and other existing models, they concluded that none of the existing models can satisfactorily predict saturated hydraulic conductivity reductions, especially for fine sands. Mays and Hunt (2007) proposed an empirical model to quantify clogging and conducted experiments with destabilised suspensions of sodium- and calcium-montmorillonite to quantify the hydrodynamic and chemical factors responsible for clogging. Ozis *et al.* (2007) developed a numerical biofilm growth-percolation model for biofilters to be used for air pollution control. The model predicts biomass accumulation, head loss and treatment efficiency as a function of time, as well as total time to form a complete blockage. Through conducting bio-clogging experiments with sand columns, Seki (2013) concluded that the reduction of hydraulic conductivity (i.e. flow) can be better explained by 'microcolony models' of Vandevivere (1995), compared to 'biofilm models' of Clement *et al.* (1996).

From previous modelling studies on bio-clogging, it is evident that complex, data-intensive models are not necessarily producing accurate results. Imteaz *et al.* (2016) presented a simple clogging–back-washing efficiency model, developed with a series of experimental data conducted at three different locations in Bangladesh using the 'IHE family filter', which is made from iron-oxide-coated sand for arsenic filtration, developed by the United Nations Educational, Scientific and Cultural Organization (Unesco)-International Institute for Hydraulic and Environmental Engineering (IHE), as presented in Khan (2004). The simple linear model developed simulated clogging and back-washing behaviour of the device for 27 different series of repeated clogging and back-washing with good accuracies for a time step of 1 week (i.e. back-washing is performed after an operation period of 1 week). This paper presents validation of the same linear model for another set of data conducted with a filter made from Skye sand at Monash University in Australia. Skye sand is a specialised mineral sand found at Skye, Melbourne, Australia. Owing to the presence of crystalline goethite as a coating on the silica sand, this sand possesses a higher arsenic adsorption capability. Moreover, in the earlier sets of data with the 'IHE family filter', on three occasions the filters were not back-washed for prolonged periods, causing an accumulated clogging of the filters; the model was unable to simulate this accumulated clogging with good accuracy. Thus, the present paper presents improved models to simulate accumulated clogging during prolonged periods of non-back-washing.

## 2. Methodology

The original data collection was based on measurements of concentrations of the contaminants in both inflow and outflow samples, as well as flows for an entire operational period of 4 months, details of which are reported by Khan (2004) and Petrusevski *et al.* (2008). Based on flow measurements before and after clogging (within 1 week) as well as after back-washing, the following models for linear clogging (Equation 1) and back-washing efficiency (Equation 2) were proposed

$$Q_2 = Q_1 \times (1 - C_f) \tag{1}$$

$$Q_3 = Q_2 \times R_f \tag{2}$$

where, $Q_1$ is the original flow rate before clogging; $Q_2$ is the flowrate after 1 week of operation; $Q_3$ is the flow rate after back-washing; $C_f$ is the clogging factor; and $R_f$ is the recovery factor. After 1 week of operation following back-washing, the calculated $Q_3$ becomes the $Q_1$ for the following time step. The same process is repeated until the last measurement.

A new filter device using Skye sand was developed and rigorously tested at Monash University, Australia by Cashion *et al.* (2017). In addition to evaluating arsenic removal efficiency, flow rates were also measured for the evaluations of clogging and back-washing efficiency. For these flow measurements, flow rates were collected daily up to 1 week without back-washing, then one measurement was made after back-washing, and this was repeated for a period of 3 weeks. The linear models developed earlier (Equations 1 and 2) were validated with this new set of data.

As was mentioned earlier, in the original 27 sets of data from Bangladesh, in three cases the devices were not back-washed for a prolonged period. The original linear model presented by Imteaz *et al.* (2016) was unable to accurately predict flow clogging during prolonged non-back-washing periods, as the root mean square error (RMSE) values of the model-predicted results during prolonged non-back-washing periods varied from 0·35 to 0·64, whereas during regular back-washing periods the RMSE values varied from 0·12 to 0·16. Prediction of clogging after this type of prolonged non-back-washing is important, as it will reveal the period of non-back-washing after which the device will be inactive (or very poorly active) with regard to outflow. In order to achieve better accuracy of clogging prediction during such prolonged non-back-washing periods, this paper presents two more models (exponential and semi-conceptual). In addition, actual measured back-washing efficiencies after such prolonged non-back-washing periods were highly divergent from the model-predicted efficiencies using the original linear model. As such, this paper presents a semi-conceptual model to predict clogging removal through back-washing after such a prolonged period.

Proposed exponential clogging model

$$Q_2 = Q_1 \times \mathrm{e}^{-kt} \tag{3}$$

where $Q_1$ is the original flowrate before clogging; $Q_2$ is the flowrate after 1 week of operation; $k$ is the exponential clogging factor; and $t$ is the time in weeks. A time step of 1 week was selected for the sake of comparison, as in the original linear model (Equations 1 and 2) the time step was also 1 week. After 1 week of operation, the calculated $Q_2$ becomes the $Q_1$ for the following time step. The same process is repeated until the last measurement.

The proposed semi-conceptual clogging model works such that it follows linear decay as the original linear model (Equation 1); however, the initial clogging factor does not remain constant. Rather, the initial clogging factor is reduced by a step-like constant ($\Delta C$), for every additional non-washing period beyond the normal non-washing period (i.e. 1 week). Such reductions continue until the 'reduction constant' becomes equal to or more than the initial clogging factor. The equation can be expressed as

$$Q_2 = Q_1 \times [1 - (C_\mathrm{f} - n \times \Delta C)];\ n \times \Delta C \leq C_\mathrm{f} \tag{4}$$

where $Q_2$, $Q_1$ and $C_\mathrm{f}$ are as defined earlier; $n$ is the number of additional non-washing periods beyond the normal non-washing period – in other words, after two non-washing cycles (i.e. 2 weeks), $n$ would be equal to 1.

To evaluate the performance of the developed models – namely, the differences between the measured and predicted values – the following RMSE criterion is used

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n} (X_{\mathrm{obs},i} - X_{\mathrm{mo\,del},i})^2}{n}} \tag{5}$$

where $X_\mathrm{obs}$ denotes the measured values; $X_\mathrm{model}$ is the modelled values at time step $i$; and $n$ is the total number of data/ observations.

## 3. Results

### 3.1 Validation of the original linear model

The arsenic removal efficiency through a custom-made filter device using Skye sand was rigorously tested at Monash University, Clayton (Melbourne) campus. In addition to testing the arsenic removal efficiency, the clogging and back-washing efficiency were also tested for the same device. As mentioned earlier, flow measurements were conducted on a daily basis for a period of 3 weeks, where at the end of each week back-washing was performed. As expected, the initial flowrate kept on decreasing until back-washing, and after back-washing the flow was increased again. However, as had been found in the earlier measurements (conducted in Bangladesh), after back-washing the flowrate never returned to its original magnitude, but rather it was lower than the original initial flow rate prior to commencement of the operation. The same pattern was seen in the subsequent cycles. In the original linear model, clogging was calculated for a weekly time step, whereas for the current experiment, it was measured on a daily basis. As such, the original model was adjusted for a daily time step.

The model's parameters ($C_\mathrm{f}$ and $R_\mathrm{f}$) were calibrated to fit the measured flow rates. Figure 1 shows the comparison of measured and simulated flow rates. From the figure it is evident that the model's simulated flow rates were very close to measured flow rates. A basic measure of the model error is the RMSE, which was found to be 0·04 for the current set of data, whereas for the earlier set of data (from Bangladesh), RMSE values were within the range of 0·09–0·20. For the earlier models, for three different locations (having three different levels of water quality), the average $C_\mathrm{f}$ values obtained were 0·23, 0·26 and 0·27. For the current model, with water from the Melbourne supply network, a $C_\mathrm{f}$ value of 0·19 was obtained. Table 1 shows the values for the inflow samples' iron content, as well as clogging and recovery factors for all the three sites in Bangladesh and the current experiment.

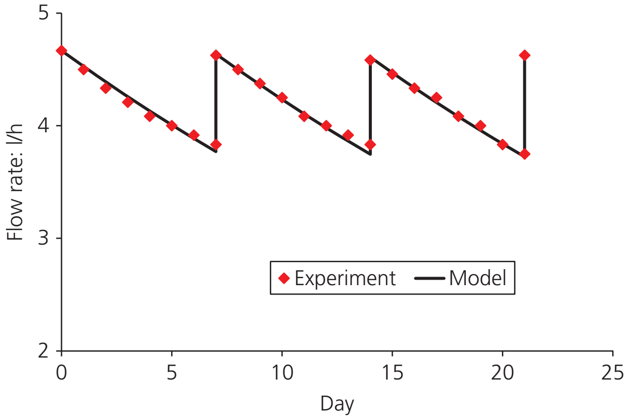


Figure 1. Comparison of measured and simulated flow rates for Monash experiment

A comparatively lower value of $C_f$ for the current filter/experiment is reasonable, as the current filter was tested with Melbourne water, which has low iron and total dissolved solids (TDS) concentrations, whereas the IHE filters were tested with Bangladesh's rural water that had higher values of iron and TDS concentrations. Higher concentrations of iron cause more clogging (Nyerges *et al.*, 2010); also higher concentrations of TDS are likely to cause more physical clogging.

### 3.2 Modified clogging model

As the linear model developed earlier was unable to simulate the measured data closely for the cases of prolonged non-back-washing, to explore a better model, two more models were investigated: exponential and semi-conceptual. To be able to visualise clearly the discrepancies between the model results and the measured data, the models are split into two phases: phase 1, initial weekly alternate clogging and back-washing cycles for many weeks, and phase 2, continuous prolonged clogging without back-washing.

Phase 1 models: for the initial phase, only two models were investigated: (*a*) the linear model developed earlier (Equations 1 and 2) and (*b*) the current exponential model (Equations 3 and 2). Figures 2(a)–2(c) show the comparisons between measured data and the simulated results from the two different models for the periods of weekly alternating clogging and back-washing. Through visual inspection it is difficult to assess the differences between the performances of the models as the continuous lines were very close to each other. However, from the RMSE values, it can be concluded that the exponential model is slightly better than the earlier linear model, because the RMSE values for the linear model are 0·12, 0·14 and 0·16, whereas the corresponding RMSE values for the exponential model are 0·11, 0·13 and 0·11, respectively.

In the exponential model, the exponential clogging factor ($k$) can be defined as a degradation rate, as it is used in the case of some decay functions, including the biochemical oxygen demand (BOD) decay equation. In this particular case, $k$ is the degradation of the flow rate through the filter medium. The $k$ values from the three locations were plotted with the corresponding iron and ammonium ($NH_4$-N) concentrations of the inflow water. Figure 3 shows the relationship between $k$ and the ammonium concentration in the inflow water. It was found that the exponential clogging factor ($k$) linearly varied with the inflow water's ammonium concentration. As ammonium concentration increases algal growth, as well as the growth of certain bacteria (e.g. *Methylocystis*), it is likely to cause enhanced bio-clogging, as mentioned by Nyerges *et al.* (2010). Figure 4 shows the relationship between $k$ and the iron concentration in the inflow water. It was found that the exponential clogging factor ($k$) linearly varied with the inflow water's iron concentration. This finding is in line with the finding of Hasselbarth and Ludemann (1972), who reported that a higher concentration of iron enhances certain bacterial growth, especially 'iron bacteria', which is likely to cause higher clogging.

In addition, for the earlier linear model, the clogging factor was found to be linearly related with the inflow water's iron concentration. However, it should be noted here that these linear relationships were observed with only three datasets. To ascertain such a conclusion, it is recommended that further investigation should be done with more data having different inflow iron concentrations.

Phase 2 models: for the later phase (i.e. prolonged non-back-washing period), three clogging models were investigated without applying any back-washing. The models were: (*a*) the linear model developed earlier (Equation 1); (*b*) the current exponential model (Equation 3); and (*c*) a modified/semi-conceptual model (Equation 4). Figures 5(a)–5(c) show the comparisons between the measured data (from three different sites of Bangladesh) and the simulated data from three

Table 1. Comparison of the model coefficients, inflow water qualities and RMSE values

| Prototype | As: $\mu$g/l | Fe: mg/l | NH4-N: mg/l | $C_f$ | $R_f$ | RMSE |
|---|---|---|---|---|---|---|
| Current filter with Skye sand | 500 | 3·00 | — | 0·192 | 1·23 | 0·04 |
| Unesco-IHE filter, site 1 | 425 | 3·94 | 0·65 | 0·23 | 1·3 | 0·14 |
| Unesco-IHE filter, site 2 | 280 | 20·5 | 5·15 | 0·27 | 1·35 | 0·18 |
| Unesco-IHE filter, site 3 | 544 | 15 | 4·25 | 0·26 | 1·34 | 0·17 |

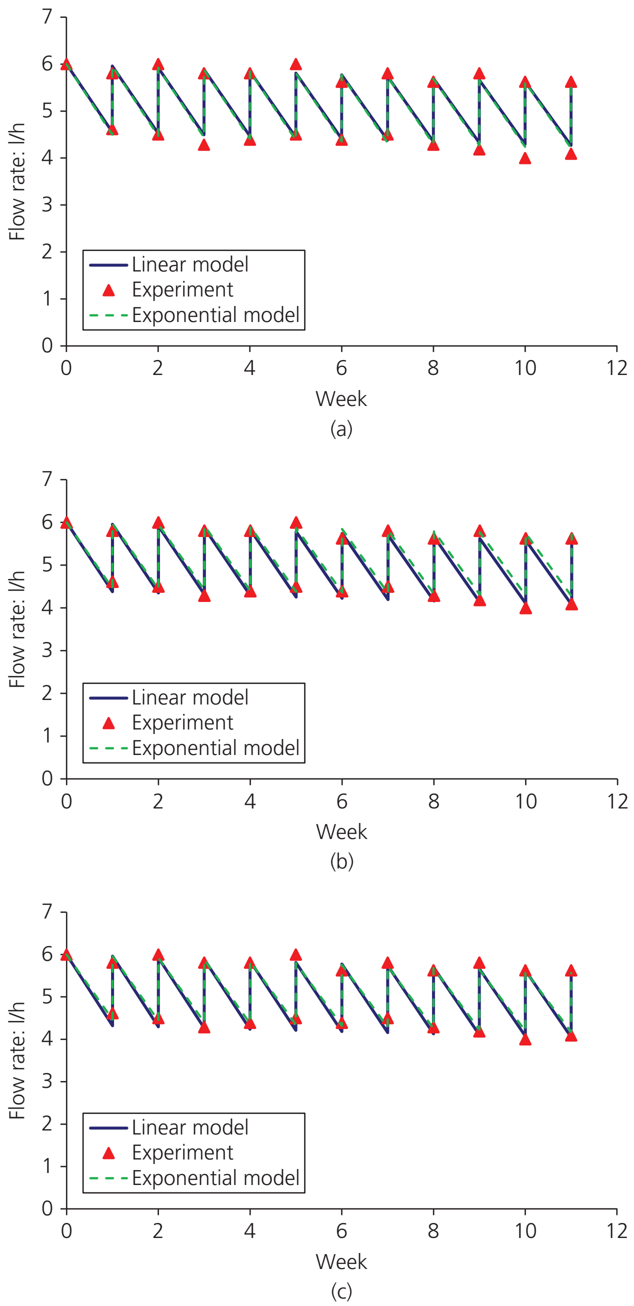


Figure 2. Comparisons of measured and simulated flow rates for the periods of regular weekly back-washing : for: (a) site 1; (b) site 2; (c) site 3

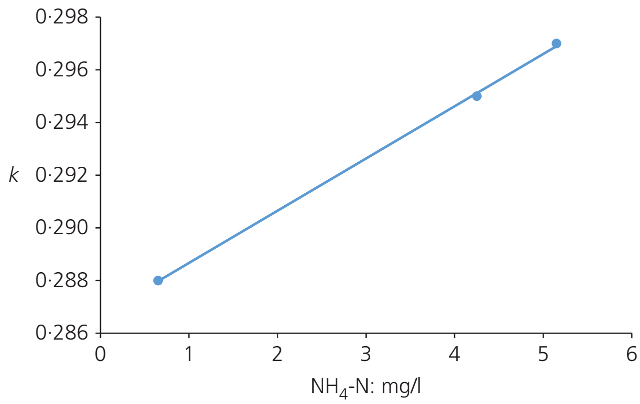


Figure 3. Relationship between $k$ and ammonium concentration in the inflow water

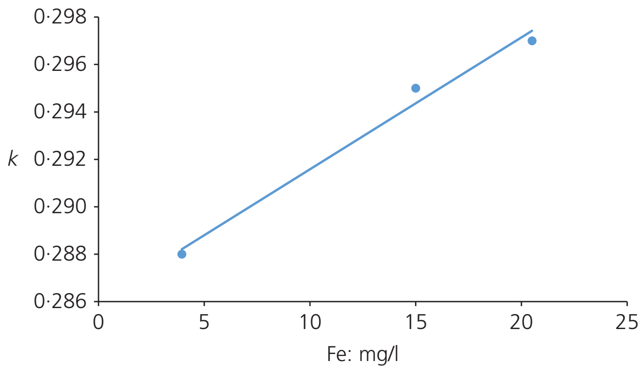


Figure 4. Relationship between $k$ and iron concentration in the inflow water

different models for the prolonged non-back-washing periods. From these figures, it is clear that the semi-conceptual model performed better than the other two models. The RMSE values of the models' simulated values compared to the measured values for the three models studied at three different sites are shown in Table 2. From the table it can be found that the RMSE values for the linear model varied from 0·35 to 0·64, whereas the RMSE values for the semi-conceptual model varied from 0·12 to 0·24, revealing a significant improvement over the linear model developed earlier with regard to simulating the flow rates during a prolonged non-back-washing period. In addition, it was found that the semi-conceptual model's clogging factor reduction constant ($\Delta C$) was the same for all of the three sites, with a value of 0·015. It is interesting that this clogging factor reduction constant turned out to be same for all the three sites, which is mainly due to the use of the same filter medium with the same dimensions.

## 4. Conclusion

An earlier developed simple, linear clogging and back-washing efficiency model was validated with a new set of data from experimental measurements conducted at Monash University (Melbourne) with an arsenic filter made from Skye sand. Model parameters (i.e. clogging and recovery factors) were selected to fit the experimental measured flow rates for 3 weeks. It was found that the model can accurately simulate the laboratory measurements of flows through the filter media after accumulated clogging (for 1 week) and after subsequent back-washing. While comparing the model factors with the

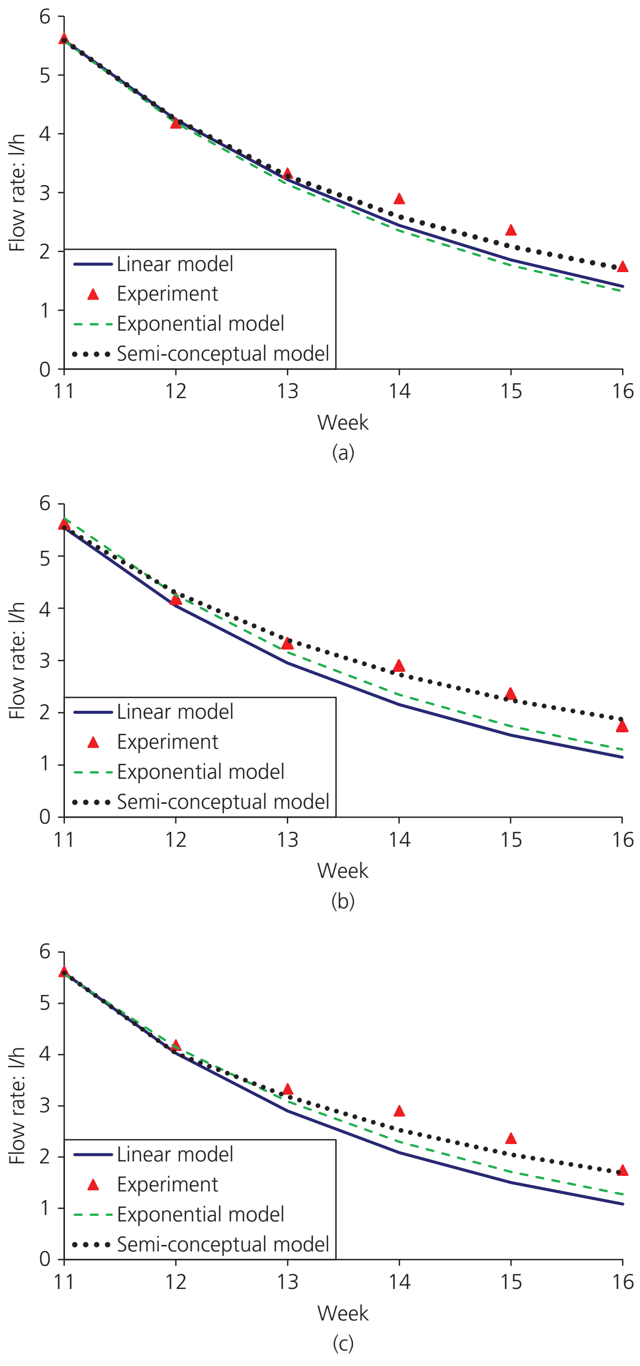


Figure 5. Comparisons of measured data and simulated flow rates for prolonged non-back-washing periods for: (a) site 1; (b) site 2; (c) site 3

earlier calibrated linear model factors, it was found that the current clogging factor obtained from the Monash University experiment was lower than the clogging factors obtained through the linear model, which is mainly due to the lower concentrations of iron and TDS in the current water sample. To achieve a better accuracy compared to the linear model developed earlier in simulating alternating clogging and back-washing efficiency, an exponential clogging model was proposed. It was found that, with the earlier set of data, the exponential model performed better than the linear model. In addition, the exponential model's exponential clogging factor was found to be linearly related with the inflow samples' iron concentrations, which is in line with the relationship between the linear model's clogging factors and the inflow samples' iron concentrations. Again, to achieve better accuracy in simulating continuous clogging for a prolonged period without back-washing, two more models were investigated: an exponential model and a semi-conceptual model. Experimental measurements were compared with the simulated results for all the three models – the linear model, exponential model and semi-conceptual model. It was found that the proposed semi-conceptual model performed much better than the other two models in matching the experimental flow measurements.

It should be noted that the factors derived are valid only for the particular type of filter media used for the data collection. Moreover, these factors will be different for different types of inflow water or water source. However, this type of simple model can be developed and calibrated for any filtration process to predict the flow behaviour of the system. To achieve better accuracy, it is proposed that the regular (alternate clogging and back-washing) flow modelling should be performed using the exponential model, whereas flow modelling under continuous or prolonged clogging should be performed using the proposed semi-conceptual model. This type of model is very useful for filter users, as many of them forget or become negligent regarding regular cleaning or back-washing of the filter media. Without regular cleaning, after a long period of operation, the efficiency of any such filter is expected to become very low. This type of model can provide an indication as to how long a particular filter medium will be effective without regular cleaning. As the clogging is related to the inflow water's ammonium and iron concentrations, it is possible to try to develop a more robust model incorporating the concentrations of ammonium and iron in the inflow water.

Table 2. RMSE values of different models for three different sites

| Prototype | Linear model | Exponential model | Semi-conceptual model |
|---|---|---|---|
| Unesco-IHE filter, site 1 | 0·64 | 0·47 | 0·24 |
| Unesco-IHE filter, site 2 | 0·59 | 0·43 | 0·12 |
| Unesco-IHE filter, site 3 | 0·35 | 0·42 | 0·19 |

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