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A simple clogging and backwashing efficiency model for filtration of arsenic-contaminated water

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ABSTRACT

Filtration is a very basic and primitive technique of water treatment. For many remote, under-privileged and poor communities, this is the only pre-treatment of drinking water prior to boiling. With the emergence of arsenic contaminations in many groundwater aquifers, the filtration became imperative for many communities around the world. However, after repetitive/continuous uses, clogging of the filter media is obvious, which eventually causes poor performance of the filtration process. Backwashing is a common technique being used for the recovery of the filtration capacity of clogged filter media. This study presents development of a simple clogging and backwashing efficiency model for a special filter media. "3rd generation IHE family filter" was developed by UNESCO-IHE Institute for Water Education and widely used for treating arsenic-contaminated water in many countries including Bangladesh. Several field tests were conducted in three different sites in Bangladesh having different qualities of influent water. Developed model coefficients were derived using the collected data on flow measurements through the device during successive clogging and backwashing periods up to four months. Developed model with the selected model coefficients can simulate field measurements on flow retardation and recovery with good accuracy. Eventually, selected model coefficients for three sites were correlated with the respective influent water quality. It was found that the coefficients are linearly correlated with the iron and ammonium contents of inflow water.

Keywords: Arsenic; Clogging; Backwashing; Filtration; Model

1. Introduction

Arsenic contamination in groundwater has been reported as a serious threat to public health throughout the world. Several works have been done towards the goal of removing arsenic from the groundwater. Conventional technologies such as oxidation/reduction reaction, precipitation, adsorption and ion exchange, and physical exclusion were tried. Alternative safe water options such as clay filters, deep tube wells, surface and rainwater harvesting, and solar distillation were applied in Bangladesh and West Bengal. In the meantime, an alternative technology like SORAS (solar oxidation and removal of arsenic) also

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has been conducted in rural Andes region in Latin America [1]. Moreover, materials such as zeolite, manganese greensand and nanocrystalline magnetite also used to treat arsenic. In a developing country such as Bangladesh, filtration of the contaminated groundwater is widely accepted considering both economic and environmental aspects. Filtration is a necessary step, because without filtration, arsenate removal is only around 30%, but using a 0.1-μm filter, As(V) removal improves to more than 96% [2]. During the filtration process, difficulties often been faced in terms of clogging of filter media and it requires regular attention to be functional for long run. Various physical, biological and chemical processes can enhance the mechanism of clogging. Each of the process can work individually or collectively to reduce infiltration rates. Criteria such as raw water quality, type of sediment, ponding depth, hydraulic loading rate and cycle, and algal or bacterial growth play important role in the development and extent of clogging. Moreover, due to changes in water quality, water depth and basin bottom conditions, these processes can be active at different times [3]. It has been seen that grains of angular shape create more clogging than grains of round shape [4]. Microbial activity can reduce the saturated hydraulic conductivity by clogging soil pores with microbial cells and their synthesized effects called bio-clogging [5]. The largest possible estimate of the biomass is 2% of the mass of soil particle, corresponding to 6% of the volume of soil particle, as the density of the soil particle is three times larger than that of the biomass [6]. On the other hand, sedimentation concentration is the second most important factor affecting the media filter performance. Using high sedimentation, loads of 50 and 100 mg/l affected drastically the removal efficiency [7]. Materials used in filter to treat arsenic are generally sands of wide ranges of sizes, ceramics and other grain particles. Ceramic filtration process is the use of porous ceramic (fired clay) to filter microbes or other contaminants from drinking water which has many potential advantages than sand filters [8]. Comprehensive database of arsenic and iron available for groundwater composition in Bangladesh showed that the average As and Fe concentrations are 199 ± 166 and 5.3 ± 4.8 μg/l, respectively [9]. The result of the bench scale experiment conducted indicated that coagulation with ferric ions followed by filtration is effective in reducing arsenic concentration in the water [10]. To remove the excess arsenic which was unable to adsorb and co-precipitate with the naturally occurring iron in groundwater, additional iron was required.

Most of the works on arsenic filtration were focused on achieving maximum performance on the arsenic removal capacity of particular filter media [7,10–13]. Salient objective of all the previous studies was to trap maximum arsenic and iron. Although in reality, the device, which will trap maximum arsenic/iron, is more likely to clog earlier and will require frequent maintenance/cleaning. In the past operational aspect, such devices did not get enough attention, although without proper and regular maintenance all such filtration devices will be gradually ineffective or inoperative. Very limited works were done on quantitative measurements, i.e., on the flow capacity and reduction of flow capacity through filter media after repetitive use. Moreover, no work was done on modelling such flow reduction as well as flow recovery. This sort of study with operational aspect is very important for the end-users, as through such study end-users will gain awareness on maintenance requirements of such device. Moreover, they will be able to know critical day/time when backwashing is imperative. Backwashing is a process that enhances the performance of filtering media by removing unwanted clogs. This study presents development of a simple model on clogging and backwashing efficiency of a filter media using iron oxide-coated sand for arsenic filtration. Developed model parameters were evaluated through field measurements from several sites using "IHE family filter." Different types of filters for arsenic removal were developed and rigorously tested by UNESCO-IHE. The recent one, "3rd generation IHE family filter" has proven to be very effective in arsenic removal, while being very simple in operation and inexpensive [14].

2. Methodology

Fig. 1 shows the photo and schematic diagram of experimental set-up of "3rd generation IHE family filter" as it is used in the field (i.e. house). Detailed field experiments and data collections were conducted by UNESCO-IHE in collaboration with the Department of Public Health Engineering, Bangladesh. Three sites were selected on the basis of ground water quality, i.e. iron, arsenic, ammonium and manganese concentrations. The concentrations of the contaminants in inflow and outflow samples as well as flows were measured for entire operational period of four months and details are reported in [14,15]. This study focused on the clogging behaviour of the filter media and as such analysed only the flow measurements before and after clogging (within one week) as well as after backwashing. It was observed that performance of the filter decreased with time. It happened as intermolecular pores among the sand grains started to be clogged. However, after backwashing, the flow rate reached

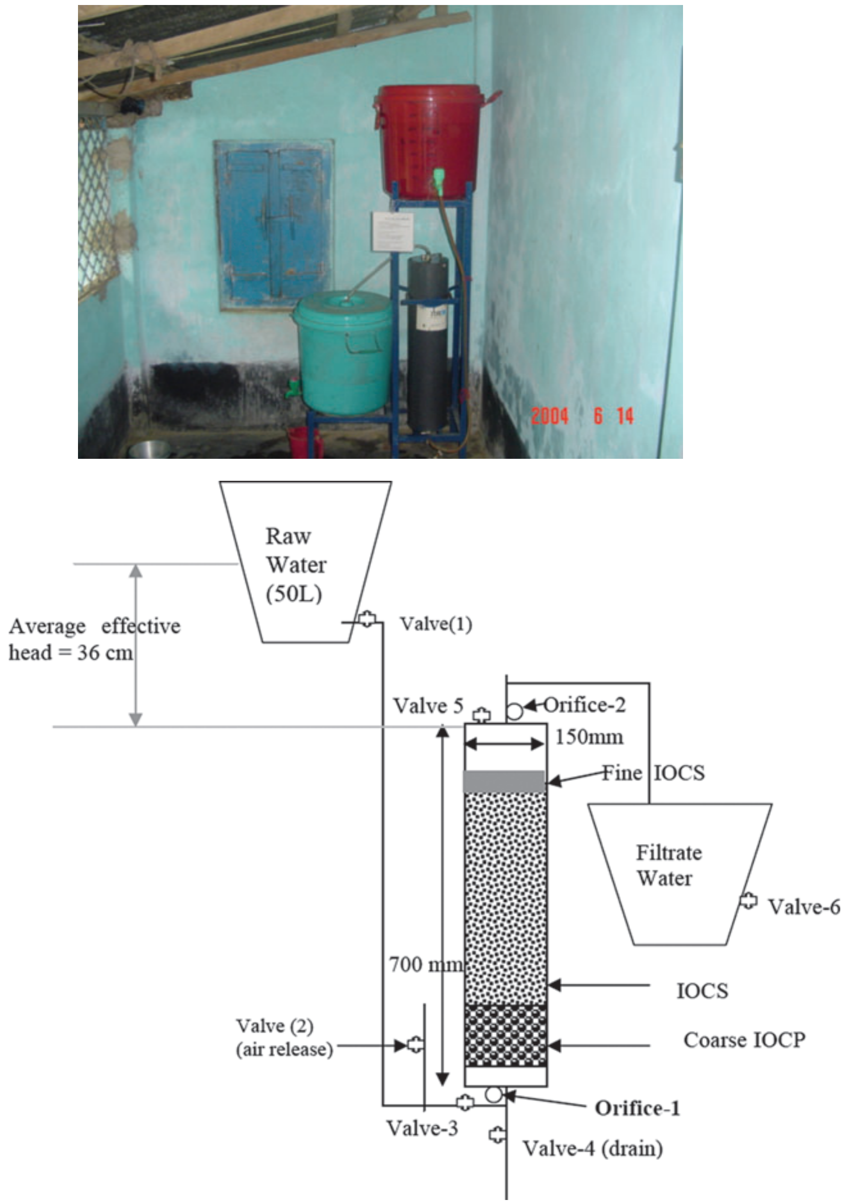

Fig. 1. Photo and schematic diagram of IHE family filter.

almost to its original level, although there were small differences between the flowrates before and after backwashing. Also, it is unlikely that the flowrate will be recovered to its original level.

Based on the field measurements, two simple equations are proposed: one for the clogging process and the other for the backwashing efficiency. The equations are expressed as follows:

$$Q_2 = Q_1 \times (1 - C_f) \quad (1)$$

$$Q_3 = Q_2 \times R_f \quad (2)$$

where Q_1 is the original flowrate before clogging, Q_2 is the flowrate after one week operation, Q_3 is the flowrate after backwashing, C_f is the clogging factor, and R_f is the recovery factor.

After one week operation following backwashing, the calculated Q_3 becomes the Q_1 for the following time step. The same process is repeated until the last measurement. Three different sites in rural Bangladesh were selected for the purpose of detailed monitoring of performances of mentioned "family filter." In each site/region, groundwater is the prime source of potable water. Table 1 shows the qualities of groundwater

Table 1
Influent water quality and derived values of C_f and R_f

Site	As (μg/l)	Fe (mg/l)	NH_4-N (mg/l)	C_f	R_f
Site 1	425	3.94	0.65	0.23	1.3
Site 2	280	20.5	5.15	0.27	1.35
Site 3	544	15	4.25	0.26	1.34

in each site. Locally collected groundwater was filtered through the filter unit and flowrates within the measuring period of several weeks were measured. Totally, 27 filter units (nine in each site) were installed in 27 houses. However, due to negligence of household members, some filters were not used properly. As such, data from improperly used units were not considered for the current analysis. Finally, six filters from "Site 1," five filters from "Site 2" and eight filters from "Site 3" were selected for the purposes of flowrates monitoring and modelling. Based on collected data from 19 filter units, the best values of C_f and R_f were evaluated through trial and error with the aim of achieving minimum error between the measured and calculated values. To evaluate the difference between the measured and predicted values, following "root mean square error (RMSE)" criteria are used.

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n} \left(X_{\mathrm{obs,i}} - X_{\mathrm{model,i}}\right)^2}{n}} \quad (3)$$

where X_{obs} is measured values and X_{model} is modelled values at timestep i and n is the total number of data/observations.

3. Results

Figs. 2–4 show the comparisons of measured and predicted values for sites 1–3, respectively. As all the

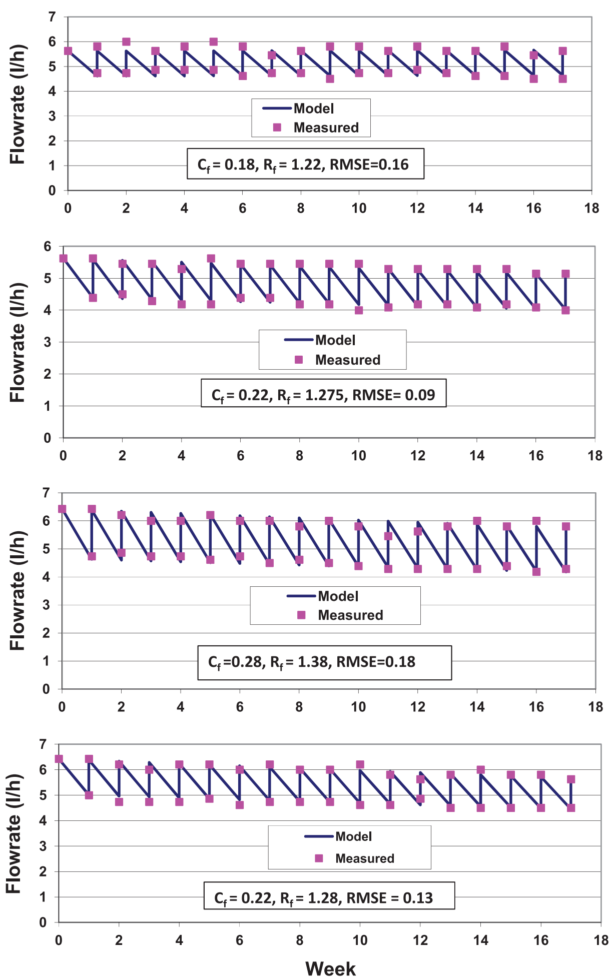

Fig. 2. Comparisons of model results with measured data for "Site 1."

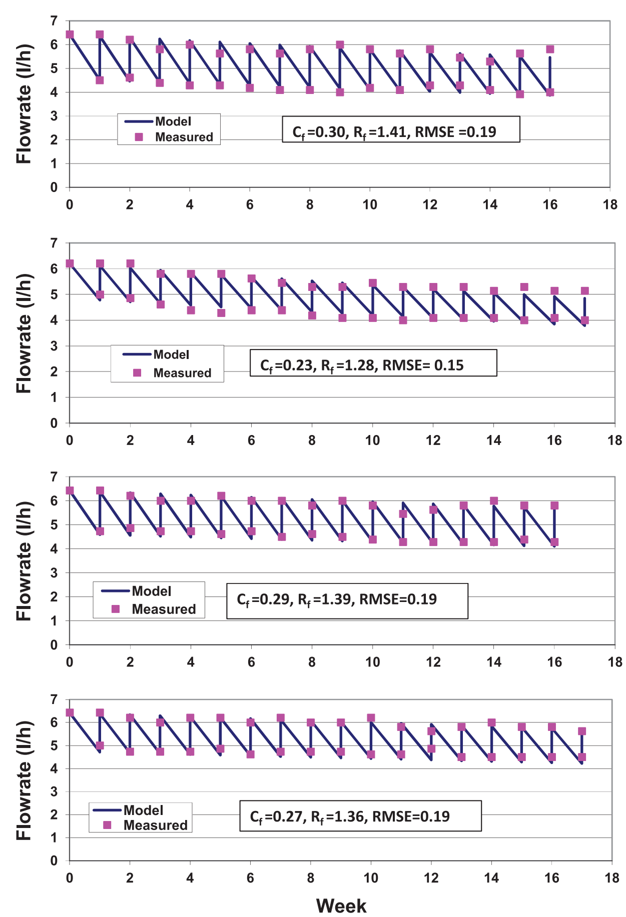

Fig. 3. Comparisons of model results with measured data for "Site 2."

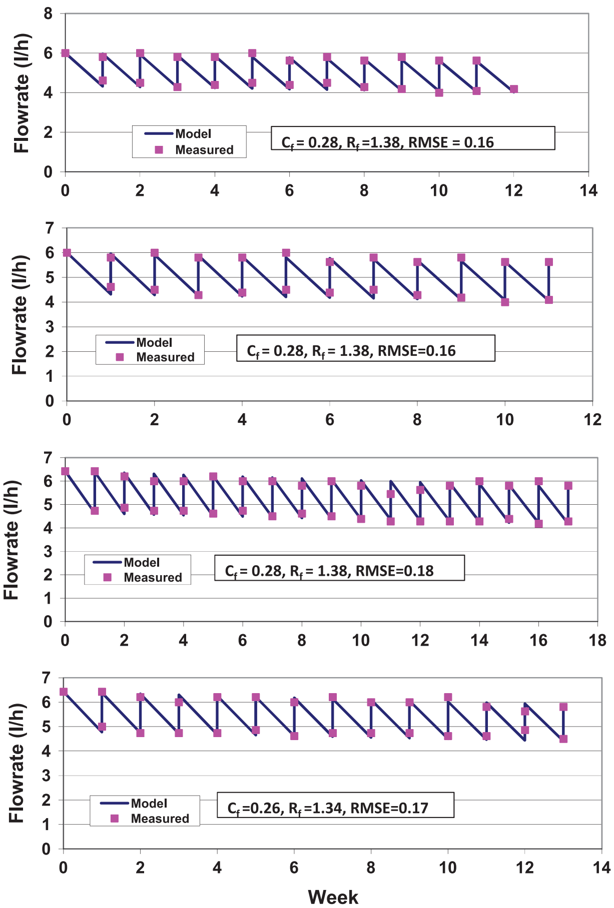

Fig. 4. Comparisons of model results with measured data for "Site 3."

comparisons look similar, in each figure, comparisons from four filters are presented. Corresponding RMSE value for each filter unit is also shown in the figure. For each family filter, a set of C_f and R_f values was derived, which provide best fit of the measured data. Eventually, C_f and R_f values for a particular site were

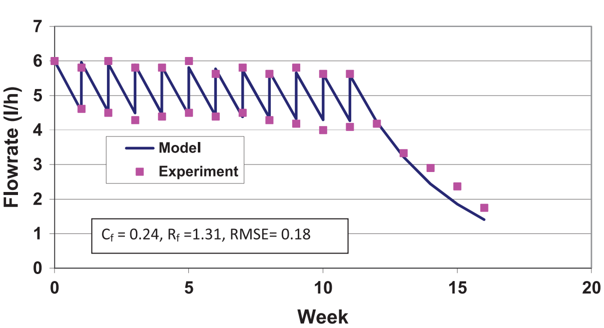

Fig. 5. Comparison of model results with measurements for a filter not cleaned after week 11.

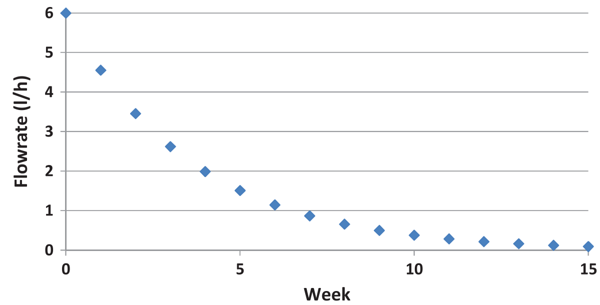

Fig. 6. Continuous decline of flow capacity for a filter without cleaning with C_f = 0.24.

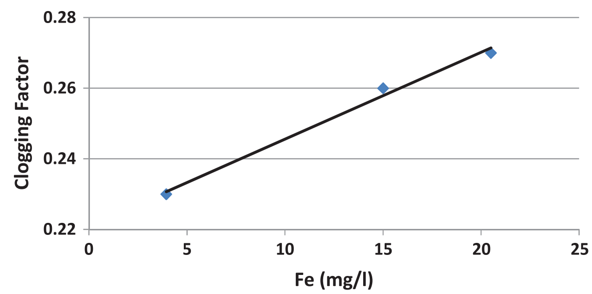

Fig. 7. Relationship of clogging factor with influent iron concentration.

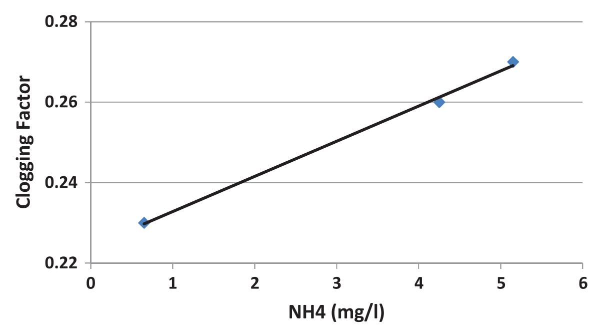

Fig. 8. Relationship of clogging factor with influent ammonium concentration.

averaged for further analysis. Table 1 shows the derived and averaged values of C_f and R_f as well as respective influent water qualities in three different sites.

In one house within "Site 1," the filter was not cleaned/backwashed for consecutive 5 weeks after several weeks' of operation. As such flowrate was continuously decreasing to a very low value, Fig. 5 shows the comparison of model results with the measured values for this particular filter. It is found that with the selected clogging factor model can still predict the accumulated clogging of filter for several weeks with a very good accuracy. As such, this sort of model can be used to predict effective functioning period of such filters under continuous operations without backwashing. Fig. 6 shows the continuous decline of efficiency of such filter in regard to flow capacity having a clogging factor same as for the case of Fig. 5, with an initial flow capacity of 6 l/h. It is found that within 15 weeks of continuous operation without cleaning, flow capacity of such filter will become close to zero.

In order to assess relationship between clogging factor and influent water quality, derived clogging factors were plotted with respect to influent water qualities. Figs. 7 and 8 show the relationships of clogging factor with influent iron (Fe) and ammonium (NH_4) concentrations, respectively. It is clear that the clogging factor is linearly related to both iron and ammonium concentrations, i.e. the higher the amount of any of these in the influent water, the higher the clogging will be. The reason behind this is that bacterial and/or algal growths are enhanced by higher concentrations of iron and ammonium, and higher growths of bacteria and/or algae cause bio-clogging. Hasselbarth and Ludemann [16] reported that higher concentration of iron enhances certain bacterial growth, especially "iron bacteria." It is well established that ammonium concentration increases algal growth. Also, Nyerges et al. [17] reported that ammonium content in the water enhances growth of certain bacteria (e.g. Methylocystis).

4. Conclusion

A simple, linear clogging and backwashing efficiency model was developed incorporating two factors, clogging and recovery. With proper selection of model factors/parameters, model can simulate field measurements of flows through filter media after clogging and after backwashing. Model factors were evaluated for nineteen test units/filters in three different sites. RMSE values for all the predictions were less than 0.20, meaning model can predict flow behaviour through such filter media with good accuracy. Derived factors were used for subsequent analysis to assess behaviours of these factors with different influent water quality parameters. It is found that clogging factor is linearly related with the concentrations of both the iron and ammonium in the influent water. It is concluded that higher iron and ammonium concentrations in the inflow water cause higher growths of certain bacteria and algae, which causes bio-clogging of the filter media. However, as the linear relationships were established with only three sets of data, it is recommended that further studies with more data sets are required to ascertain such relationships. Also, it is to be noted that the derived factors are valid only for the particular type of filter media used for the data collection. However, such type of simple model can be developed and calibrated for any filtration process to predict flow behaviour of the process. This type of model is very useful for the filter users, as many of them forget to regularly clean/backwash the filter media. Even with regular cleaning, after a long period of operation, efficiency of any such filter is expected to become very low as with every cycle of clogging and cleaning overall efficiency of the filter deteriorates slightly. With continuous deteriorations of such slight efficiency, over a long period, the efficiency is expected to go down significantly. This type of model can give an indication on how long a particular filter media will be effective with and without regular cleaning.

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