

# Predicting of Effluent Turbidity from Deep Bed Sand Filters Used in Water Treatment

Hani Mahanna, Moharram Fouad, Kamal Radwan, Hoda Elgamal

**Abstract** Filtration is a solid liquid separation in which water passes through a porous medium to remove suspended or colloidal impurities. Deep bed filter is one of the most important types of filtration process in which solids are removed within the granular medium. Further, it is commonly used in either conventional water treatment plants or direct filtration plants. Various characteristics have been adopted for filtration process monitoring but usually, turbidity is used for this purpose. Turbidity removal is influenced by different parameters. It was needed to predict turbidity removal as a function of these parameters. In this study, experimental pilot plant was constructed to study turbidity removal efficiency and develop a simple predictive model for effluent turbidity by deep sand filter. Sand was used as a filtration media under different filtration rates ranged from 4 m/hr to 8 m/hr. Down flow was applied to the filter through sand media with size 0.7-1.0 mm, while sand depth was 140 cm. Aluminum sulfate (alum) was used as coagulant in different doses ranged from 20 to 40 mg/lit. The used synthetic turbid water was prepared in different turbidities varying from 10 to 30 NTU. Turbidity removal was investigated as functions of sand depth, filtration rate, influent turbidity, run time and alum dose. A mathematical model was obtained for predicting of effluent turbidity from deep bed sand filter with various operating conditions ( filter depth, filtration rate, alum dose, run time, and initial turbidity). The proposed model yield highly accurate results with correlation coefficient ( $R^2$ ) of 0.88. The proposed model showed that the most significant parameters on predicted effluent turbidity are the sand media depth and filtration rate. Also, the simple proposed model can be easily and effectively used as a decision supporting tool for prediction of filtration quality.

**Index Terms**— Deep bed filter, effluent turbidity, filtration rate, influent turbidity, run time, media depth, alum dose.

## 1 INTRODUCTION

Conventional water treatment processes usually consist of coagulation, flocculation, sedimentation and filtration for the removal of suspended solids in water [1]. Recent development of water treatment technologies is to use direct filtration process to make energy efficient with the purpose of reduce the capital and operating cost [2], [3]. Filtration process is a main process in either conventional or direct filtration plants. Through this process water passes through porous medium such as sand to remove suspension particles in water [4], [5]. Different types of filters could be used in drinking water treatment, and they may be listed in different classifications as following:

First classification is according to type of used granular medium. Granular bed filters utilize a substantial depth of sand or another media on the other hand, precoat filters contain a thin layer of very fine medium such as diatomaceous earth. Secondly, there is a classification according to hydraulic arrangement provided to pass water through the medium. In gravity filters, the water flow through the medium by gravity, but in pressure filter, the water is flowing under pressure. Filters may be also classified according to rate of filtration such

as rapid sand filter (100-200  $m^3/m^2/d$ ), slow sand filter (3-5  $m^3/m^2/d$ ), roughing filter (15-20  $m^3/m^2/d$ ), and pressure filter (170-480  $m^3/m^2/d$ ). Finally, there is a classification according to particles removal. If solids are removed within the granular medium, it is called deep bed filter (depth filtration). In cake filtration, solids are removed on the entering face of the granular medium [1], [6].

Deep bed filter is one of the most important type of filters used in water treatment. In this type, the particles are removed from its carrying fluid through a packed bed of granular media by different mechanisms, such as transport, interception, aggregation, sedimentation and diffusion [7],[8]. Deep bed sand filter has great effect on turbidity removal from water but the removal efficiency is strongly influenced by the influent turbidity, filter depth filtration rate, and alum dose [9], [10], [11].

In the beginning of deep filtration run the effluent turbidity is relatively high. It take some minutes to be allowable and this time is called ripening period. This period has been studied in many researches[12], [13] So, the time has an effect on effluent turbidity especially at the beginning of run length.

various studies were done to evaluate the turbidity removal efficiency by deep filters. From these studies, the factors affecting the turbidity removal could be presented in the following paragraph.

The removal of turbidity generally depend on the type of water source [14].In addition, the turbidity removal efficiency is strongly influenced by suspension particles diameter[15]. The percent of turbidity removal will be increased by Using of Polymer with Alum for Coagulation [2]. Filter depth, media size, filtration rate, run time, temperature, and alum dose play

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important role in turbidity removal[3], [11], [16 ].

The turbidity removal efficiency could be expressed in different models. M. Fouad, et.al. [11] showed the turbidity removal efficiency equation and it was expressed in equation (1).

$$E (\%) = Kt [ 0.998 X^{0.02} ] * [\tanh (1.25d)^{3.0} ] * [ 0.93 + 0.07 r_t/r_o ] * [1 - \tanh (0.001 d_p^{2.2})]*[1 - 0.5*\tanh (0.8 - 0.02 A )^2] * 100 \quad (1)$$

on the other hand, the effluent turbidity will be as the following:

$$C_e = C_o - Kt C [ 0.998 X^{0.02} ]*\tanh (1.25d)^{3.0} ]*[ 0.93 + 0.07 r_t/r_o]* [1 - \tanh (0.001 d_p^{2.2})]*[1 - 0.5*\tanh (0.8 - 0.02A )^2] \quad (2)$$

where:

$C_e$  = Effluent turbidity (NTU)

$C_o$  =Influent turbidity (NTU)

$X$  = filtration rate ( $m^3/m^2/hr$ )

$d$  = the filter depth (m)

$r_t$  = run time (hr)

$r_o$  = run length (hr)

$d_p$  = particles diameter (mm)

$A$  = Alum dose (mg/lit)

$Kt$  = a correction factor depending on the temperature

Another study [11] showed that the effluent turbidity could be gotten according to the sand media depth from equations (3) and (4).

For depth  $\geq 100$  cm;

$$C_e = - 0.04213*r_t + 0.030146*C_o + 0.113052*x - 2.5321*d + 2.193 \quad (3)$$

For depth  $< 100$  cm;

$$C_e = 0.028472*r_t + 0.090571*C_o + 0.292799*x - 8.02822*d + 6.070 \quad (4)$$

The main objective of this research is to analyze the factors affecting the turbidity removal from deep bed sand filters and to develop a simple predictive model for predicting effluent turbidity at any time and at any depth through deep bed sand filters operation . This model is expected to help in the design of water and wastewater treatment units as well as it can be easily used as a decision supporting tool for prediction of filtration quality.

## 2 MATERIALS AND METHODS

A pilot filter system used in this study was conducted in faculty of engineering, Mansoura university, Egypt. It consists of the following main parts: feeding tanks, feeding pump, constant head tank, filtration column, and backwash pumps. The schematic diagram of the pilot filtration plant is shown in Figure 1.

Feeding tanks consist of two groups one for feeding raw water to constant head tank and another group used for backwashing. The filtration column has square cross section with inlet dimensions 20 cm \* 20 cm and its height equals 2.5 m. It was partially filled with sand media taken from a full scale water treatment plant. The down flow filter was fed with raw water. The raw water was prepared by dispersing

fine clay , passing from sieve No.200 having a size 0.074 mm in tap water. The sand media depth was 140 cm supported with 25 cm gravel layer.

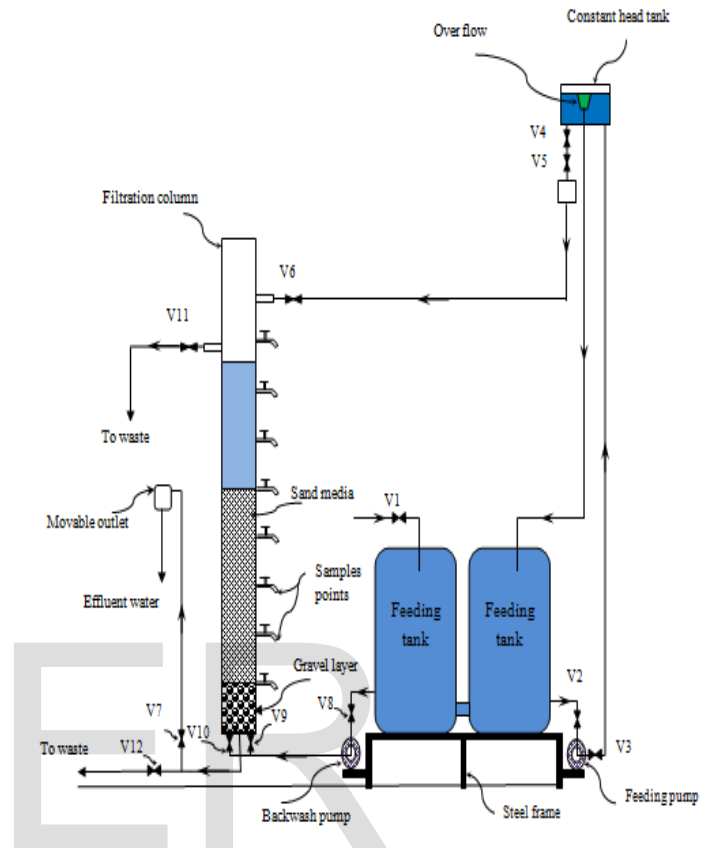


Fig. 1. Schematic diagram of the experimental pilot plant

The effective size of sand media was 0.8 mm with uniformity coefficient of 1.2. Piezometers were located at upper and lower end of media to measure the head loss. The average influent turbidities in this study were 10, 20, and 30 NTU which are suitable for Egyptian conditions. The used filtration rate were 4, 5, 6, and 8 m/hr. Aluminum sulfate (alum) is used as a coagulant with doses varying from 20 to 40 mg/lit.

The operation of the pilot plant was controlled by 12 valves. These valves facilitate different modes of filter operation. The down flow filtration mode was running as follow,

- 1- Preparing the synthetic turbid water in the feeding tanks (open valve V1).
- 2- Valves V2, V3, V4, V6 and V7 were fully opened.
- 3- The filtration rate was controlled by valve V5.
- 4- Other valves were closed.

The end of filtration run was considered when effluent turbidity started to increase (turbidity breakthrough) or when head loss reaches the maximum value (assumed 1.0 m) or the run length exceeds one day . Once either of this condition was reached, the filter run was terminated and the filter needs to backwash mode to remove the accumulated solids inside its bed.

The media backwashing mode was running as follow,  
 1- Preparing the Backwash water in the second group of feeding tanks

2- V8 was fully opened.

3- The water was pumped to the filtration column with the required rate by Backwash pumps.

4- The valves V9 and V10 were used to create a certain velocity through the media. The velocity of the water expands media in the flow direction.

5- V11 was opened to waste the backwash water.

6- Other valves were closed.

The design of the pilot plant allowed the monitoring and measuring the water quality through different depths of media length by sampling points at 20 cm intervals. In the present study turbidity measurement was used as water quality measure. Turbidity is a characteristic related to the concentration of suspended solid particles in water and has been adopted as an easy measure of overall water quality [17]. Turbidimeter model (Orbeco TB300-IR) was used to measure the turbidity level.

### 3 RESULTS AND DISCUSSION

#### 3.1 Turbidity Removal Results

In this study, the effluent turbidity was measured each 5 minutes during the first 30 minutes at different filtration rates and different alum doses in different cases of influent turbidity. Then it was measured every hour during filtration run length. The effluent turbidity during the first 30 min of run length was plotted as shown in Figure 2. Effluent turbidity was plotted versus time at different depths as shown in Figure 3.

Figures 2 and 3 are examples of results for special cases and the other results were not shown in this paper.

It was noticed that the effluent turbidity was significantly influenced by media depth, filtration rates, alum dose, influent turbidity, and run time.

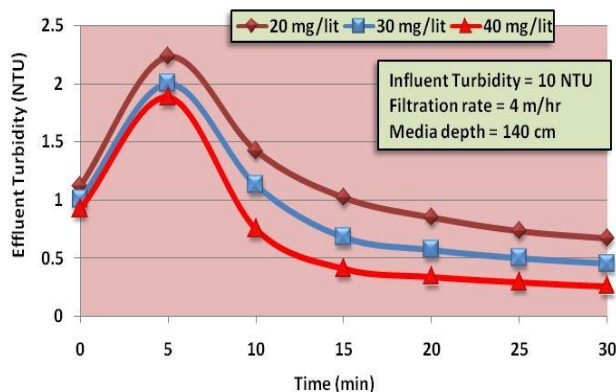


Fig. 2. The effluent turbidity during the first 30 min of run length (C<sub>o</sub> = 10 NTU, v = 4 m/hr)

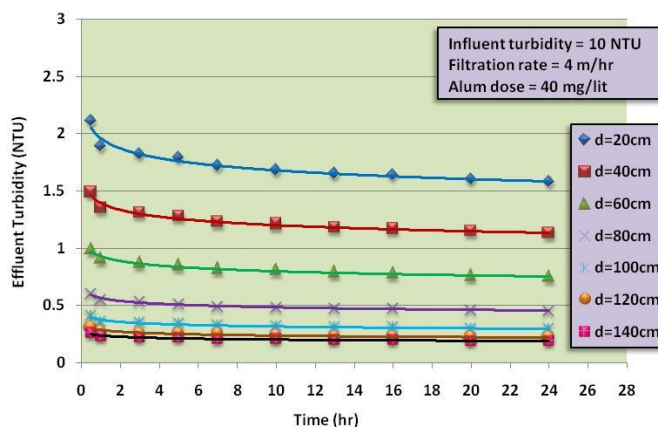


Fig. 3. Effluent turbidity verses time at different depths (C<sub>o</sub> = 10 NTU, V = 4 m/hr, S = 40 mg/lit)

#### 3.2 Model Development

The data from all runs was combined in one database and used to develop an predictive model for effluent turbidity through deep bed sand filters. Regression analysis using the least square method was used for model development. Many trials were conducted in order to develop an simple accurate prediction model for effluent turbidity based on the measured experimental data. The final trial was performed by taking into account five parameters ( media depth (L), filtration rate (V), run time (T), influent turbidity (C<sub>o</sub>), and alum dose (S)) to get high accuracy. The final form of this model is shown in Equation (5)

$$C_e = 36.2 * L^{-0.07} + 2.37 * \ln V + 0.57 * T^{-0.37} - 33.8 * C_o^{-0.04} + 49.2 * S^{-1.28} \quad (5)$$

Where:

C<sub>e</sub> = predicted effluent turbidity (NTU)

L = media depth (cm)

V = filtration rate (m/hr)

T = run time (hr)

C<sub>o</sub> = influent turbidity (NTU)

S = alum dose (mg/lit)

For example: Consider the following characteristics:

Influent turbidity = 15 NTU,

Rate of filtration = 5 m/hr,

Media depth = 120 cm,

Alum dose = 30 mg/lit, and

Run time = 10 hrs

The expected effluent turbidity = 0.26 NTU (from equation (5))

From the above Equation (5), it was noticed that all parameters have power function except filtration rate has logarithmic function and this is in order to give high accuracy and low bias. Effluent turbidity model yielded a high coefficient of determination (R<sup>2</sup> of 0.88), and low percent of Se/Sy (0.348). Figure 4 shows the relationship between the predicted and measured effluent turbidity through sand bed filter along with the goodness of fit statistics.

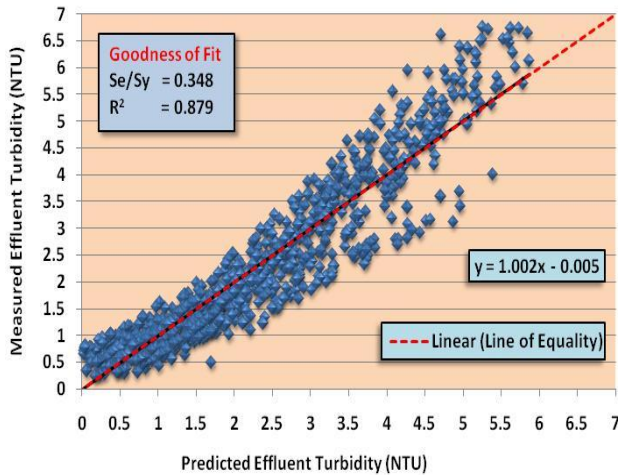


Fig. 4. Measured versus Predicted Effluent Turbidity

### 3.3 Model Precision and Bias

Figure 4 and the goodness of fit statistics of the model show very low scatter and highly accurate predictions. Bias is defined as the systemic difference between observed and predicted values. The bias in the model predictions was evaluated statistically. A linear regression on the measured and predicted effluent turbidity was performed and the following hypothesis tests at a significance level of 5 percent ( $\alpha = 0.05$ ) were done.

**Hypothesis 1:** Determines whether the linear regression model developed using measured and predicted effluent turbidity has an intercept of zero by testing the following null and alternative hypotheses:

$H_0$ : Model intercept = 0; and

$H_A$ : Model intercept  $\neq$  0.

A rejection of the null hypothesis ( $p\text{-value} < 0.05$ ) would indicate the linear model had an intercept significantly different from zero at the 5 percent level of significance. This means biased model predictions.

**Hypothesis 2:** Determines whether the linear regression model developed using measured and predicted effluent turbidity has a slope of unity by testing the following null and alternative hypotheses:

$H_0$ : Model slope = 1.0; and

$H_A$ : Model slope  $\neq$  1.0.

A rejection of the null hypothesis ( $p\text{-value} < 0.05$ ) would involve that the linear model has a slope significantly different from 1.0 at the 5 percent level of significance and thus the model systemically yields biased predictions.

**Hypothesis 3:** A paired t-test was done to determine whether the measured and predicted effluent turbidity had the same average.

$H_0$ : Mean measured effluent turbidity = Mean predicted effluent turbidity; and

$H_A$ : Mean measured effluent turbidity  $\neq$  Mean predicted effluent turbidity.

A rejection of any of the three null hypotheses ( $p\text{-value} < 0.05$ ) would imply that predicted effluent turbidity model results are biased predictions. If the model passed all three hypotheses

tests successfully, the model predictions are not biased. The results of the conducted hypotheses tests are summarized in Table 1.

TABLE 1  
STATISTICAL COMPARISON OF MEASURED AND PREDICTED EFFLUENT TURBIDITY

Hypotheses	(1) $H_0$ : Intercept = 0	(2) $H_0$ : slope=1.0	(3) $H_0$ : Mean Measured= MeanPredicted
Freedom degree	1	1	998
Coefficients	- 0.005	1.002	-
Standard Error	0.0307	0.0118	-
t Stat	- 0.1838	0.2158	-
P-value	0.854	0.829	0.999
Lower 95%	0.0659	0.9794	-
Upper 95%	0.0547	1.0256	-

### 3.4 Sencitivity Analysis

The predicted model was used to test the sensitivity of predicted effluent turbidity to each parameter. The results of the sensitivity analysis are shown in Figures 5 to 9.

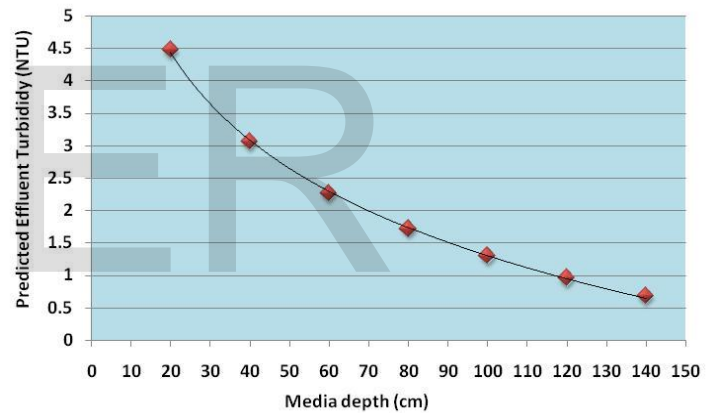


Fig. 5. Media depth versus predicted effluent turbidity

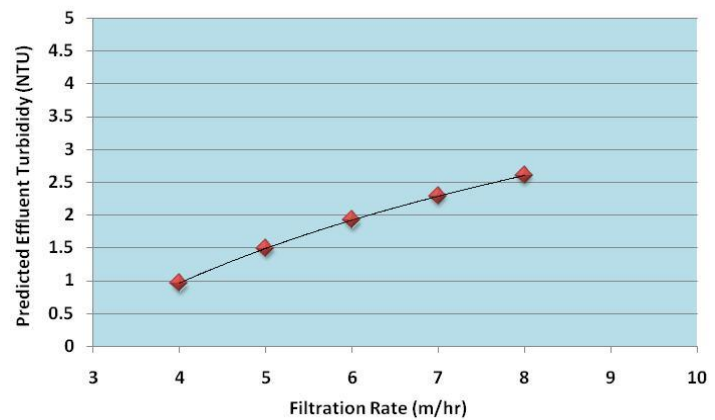


Fig. 6. Filtration rate versus predicted effluent turbidity

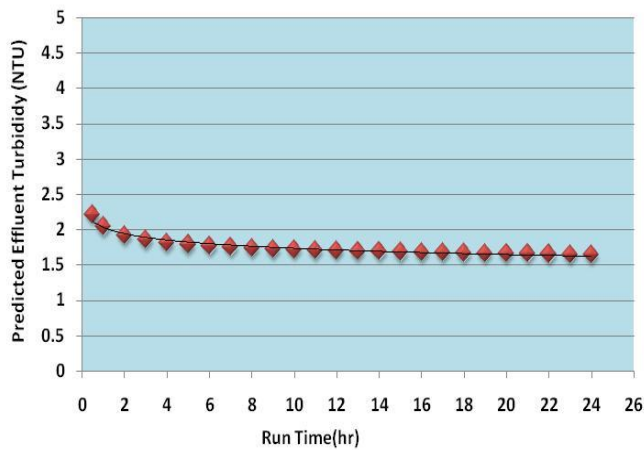


Fig. 7. Run time versus predicted effluent turbidity

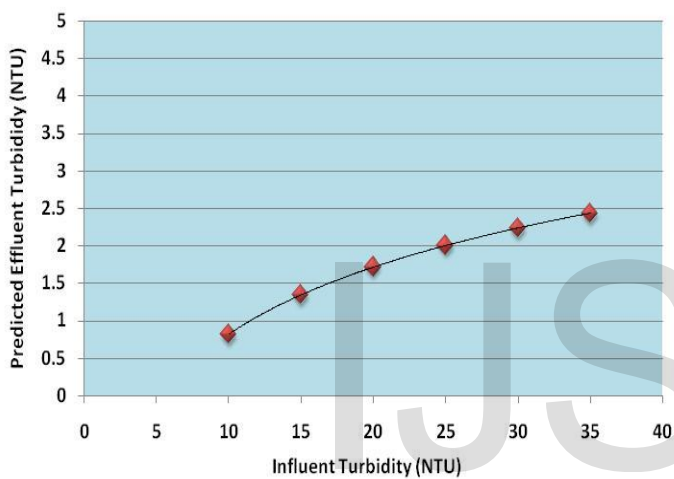


Fig. 8. Influent turbidity versus predicted effluent turbidity

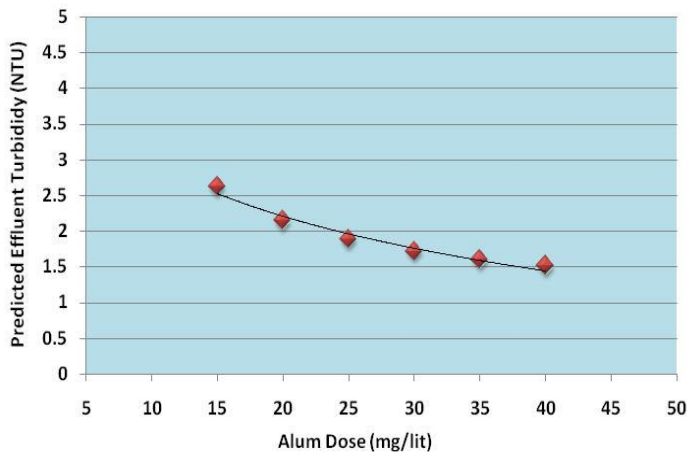


Fig. 9. Alum dose versus predicted effluent turbidity

Figure 5 shows that as media depth increases, the predicted effluent turbidity significantly decreases, but as the filtration rate increases, the predicted effluent turbidity considerably increases as shown in Figure 6. The sensitivity results in Figure 7 show that, the effect of run time on the predicted effluent turbidity is significant at the beginning of filtration run time,

but this effect decreases with time.

Furthermore, as the influent turbidity increases, the predicted effluent turbidity slightly increases, as shown in figure 8. On the other hand, as the alum dose increases, the predicted effluent turbidity slightly decreases, as shown in figure 9.

In addition, the input parameters can be ranked according to its significantly effect on effluent turbidity as the following:

- 1-Media depth
- 2- Filtration rate
- 3- Influent turbidity
- 4-Alum dose
- 5- Run time

### 3.5 Model Restrictions

It is obvious that, the model has been deduced based on regression analysis of experimental data, so the model will be of use in the range at which the data were taken. The suggested conditions for applying the model are,

- Filtration rate < 200 m<sup>3</sup>/m<sup>2</sup>/day
- Turbidity level < 30 NTU
- Alum dose < 40 mg/L
- Sand media depth < 140 cm
- Particle size of media = 0.7-1.0 mm

any limits of parameters out of range must be studied then the model can be modified.

## 4 CONCLUSION

The present study was conducted using experimental pilot plant. Effluent turbidity through deep bed sand filter was measured in various runs. Based on the measured data, a simple predictive model for effluent turbidity from deep bed sand filters was developed. This model predicted the effluent turbidity as a function of run time, filtration rate, filter depth, influent turbidity, and alum dose. The model showed excellent prediction accuracy with R<sup>2</sup> of 0.88 and S<sub>e</sub>/S<sub>y</sub> of 0.348. The results of the conducted hypotheses tests showed that the model predictions are not biased. The sensitivity study of the model identified that media sand depth and filtration rate as key factors affecting the predicted effluent turbidity. Other variables could be used in the predictive models such as media properties, temperature, and water characteristics. So, many researches with these variables should be studied.

## REFERENCES

- [1] AWWA, *Water Quality and Treatment*. Fourth Edition, McGraw-Hill, Inc., New York, 1990.
- [2] F. Kathily, "Direct Filtration for Drinking Water, Habbaniyah Lake (Iraq)," *Global Journal of Researches in Engineering:(E)*, vol. 14, no. 2, 2014, Version 1.0.
- [3] M. Fouad, R. Barakat and A.Fadel, "A Simplified Empirical Model For The One-Stage Direct Filtration," *Ninth International Water Technology Conference, IWTC9, Sharm El-Sheikh, Egypt, 2005*.
- [4] T. R. camp, "Theory of water filtration," *J. Sanit. Eng. Div. ASCE*, vol. 90, no. 4, pp.1, 1964.
- [5] W.Q. Betancourt and J.B. Rose, "Drinking water treatment processes for removal of Cryptosporidium and Giardia," *Veterinary Parasitology*,

vol.126, pp.219-234, 2004.

- [6] J.H. Dillingham, J. L. Cleasby, and E.R. Baumann, "prediction of Diatomite filter Cake Resistance," *J. Sanit. Eng. Div. ASCE*, vol. 93, no. 1, pp. 57, 1967.
- [7] V.Gitis, I. Rubinstein, M.Livshits and G. Ziskind, Deep-bed Filtration Model with Multistage Deposition Kinetics, *Chem. Eng. J.*, 163, 2010, 78-85.
- [8] K.Yao, M.T. Habibian, and C.R. O'Melia, "Water and Waste Water Filtration: Concepts and Applications," *Environmental Science & Technology*, vol. 5, no. 11, pp. 1105-1112, 1971.
- [9] V. Jegatheesan and S. Vigneswaran, "Deep Bed Filtration: Mathematical Models and Observations," *Crit. Rev. Environ. Sci. Technol.*, vol. 35, no. 6, pp. 515-569, 2005.
- [10] J. S. Chang and S. Vigneswaran, "Ionic strength in deep bed filtration," *Water Res.*, vol. 24, no. 11, pp. 1425-1430, 1990.
- [11] H. M. Amin and A. A. Mohamed, "Effect Of Some Parameters On Performance Of Direct High-Rate Filtration In Water Treatment," *Journal of Engineering Sciences Assiut University Faculty of Engineering*, vol. 42, no. 3, pp. 609-628, 2014.
- [12] A. Amirtharajah and D.P.Wetstein, "Initial degradation of effluent quality during filtration," *Journal of AWWA*, vol. 72, no. 10, pp. 518-524, 1980.
- [13] J. E. Amburgey, "Optimization of the extended terminal subfluidization wash (ETSW) filter backwashing procedure," *Journal of Water Research*, vol. 39, pp. 314-330, 2005.
- [14] J. K. Mwabi, B. B. Mamba, and M. N. B. Momba, "Removal of escherichia coli and faecal coliforms from surface water and groundwater by household water treatment devices/systems: A sustainable solution for improving water quality in rural communities of the southern african development community region," *Int. J. Environ. Res. Public Health*, vol. 9, no. 1, pp. 139-170, 2012.
- [15] M. Zielina, "Experimental Research Into Depth Filtration," Institute of Water Supply and Environmental Protection, Cracow University of Technology, Poland, Vol. 33, No 2, pp. 249-256, 2007.
- [16] C. R. O'Melia "Particles, Pretreatment, and Performance In Water Filtration," *ASCE*, vol. 111, no. 6, pp. 874-890, 1986.
- [17] M. Zielina, "Measurement of Suspended Particles in Water Filtration," *Fourteenth International Water Technology Conference, IWTC 14*, Cairo, Egypt, 2010.