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Statistical Model for Tube Settler Clarifier at Different Operational Conditions

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ABSTRACT

The present study aimed to find a relationship between turbidity removal percent in tube settler clarifier and independent variables (tube inclination, alum dosage, and surface loading rate) by constructing a statistical model and categorizing these explanatory variables according to their impact on turbidity removal percentage. A pilot scale of tube settlers was designed and fabricated to conduct the experiments. It consisted of a coagulation and flocculation basin, pre-tube settler chamber, and tube settler. Alum was used to coagulate the Tigris river raw water at different dosages. After flocculation, water is transferred to the pre-tube settler chamber and flows through the tube settler. It consists of four tubes of square section, 4 centimeters in diameter, with the flexibility of changing tube length and inclination angle to obtain different levels of surface loading rate. More than 120 experiments were conducted, and the results were analyzed statistically. A regression model was found with a coefficient of determination of 0.802 between turbidity removal percentage as a dependent variable and each tube inclination, alum dosage, and surface loading rate as independent variables. The model is considered good as the model's relationship between actual and predicted values has a slope of one and a constant near zero. Surface loading rate has the highest effect on turbidity removal percentage with 4.44 times that of inclination angle and 2.5 times for the optimum alum dosage model. The study concluded that the linear model is suitable to represent the performance of tube settlers at optimum alum dosage.

INTRODUCTION

Removing suspended particles by sedimentation is one of the most widely used in water clarification. It is a physical process used after coagulation and flocculation. The conventional sedimentation in water treatment plants includes rectangular or circular tanks with a depth of 4.6 to 4.9 meters or greater and a detention time of more than 2 hours (Randtke & Horsley 2012, Davis 2010). Hazen recognized in the previous century that the removal of settleable particles was independent of detention time and basin depth. At the same time, it was a function of the surface overflow rate (Shammas & Wang 2015).

Numerous sedimentation techniques have been developed to decrease detention time and increase water production. Of these techniques is tube settlers, an application of high-rate sedimentation theory (Gurjar et al. 2017). It depends on reducing the distance traveled by particles until they are deposited. Tube settler consists of small tubes with a square or circular, or hexagonal cross-section of 5 cm and a length of 60-120 cm (Davis 2010). The tubes may be adjusted at an angle of 45 to 60 degrees with the horizon to increase the effective settling area and to achieve self-cleaning of sludge from the tubes (Balwan et al. 2016).

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Additionally, tube settler has the advantage of occupying a small space to create it. It can be fabricated and worked indoors, which may decrease the problems caused by algal growth, clogging related to blowing debris accumulation, and odor control (Qasim 2017). In addition, tube settlers and plate settlers can be used to upgrade conventional sedimentation basins (Shammas & Wang 2015). In Ethiopia, Ballcha (2015) found that applying tube settlers can provide better performance than conventional sedimentation by 35.3% and increase water production by 34.5%. Furthermore, many studies found that tube settler clarifiers were more efficient in removing turbidity than other sedimentation systems (Fouad et al. 2016, Wang et al. 2020).

The present water treatment plants in Mosul city/Iraq, use conventional deep sedimentation tanks to remove suspended solids. With the population increase and the town's expansion, there is a need to increase water production and improve the performance of sedimentation tanks. The research aimed to investigate the performance of inclined tube settlers by constructing a statistical model and analyzing the independent variables' effect and weight on the removal efficiency and with respect to others.

MATERIALS AND METHODS

A pilot scale system was designed and fabricated at the Al-Ayssar water treatment plant in Mosul city, Iraq. Transparent plastic and glass were used in the construction of the model. It consisted of a coagulation-flocculation basin, fixed head basin, pre-tube settler chamber, and tube settlers (Fig. 1). Coagulation-flocculation unit has a volume of 40 L, equipped with a variable speed mechanical mixer (vertical shaft and blades) for fast and slow stirring. It was fed with raw water from the Tigris river by a pump connected with the inlet of the water treatment plant. Raw water turbidity ranged from 20 to 29 NTU. The coagulant dosage was added to raw water manually in this basin and mixed by the mechanical mixer. Coagulation was conducted after alum addition, followed by flocculation at velocity gradients of 1000 sec^{-1} and 80 sec^{-1}, respectively. After that, the flocculated water flows to the fixed head basin until it is filled to the specified level. Subsequently, the flocculated water flows to the "pre-tube settler chamber" (inlet) equipped with a baffle to prevent the turbulence of flocs. The flow was controlled at 1 L per minute. This unit is connected from the top by four squared tubes of 4 cm in length. These tubes have variable lengths

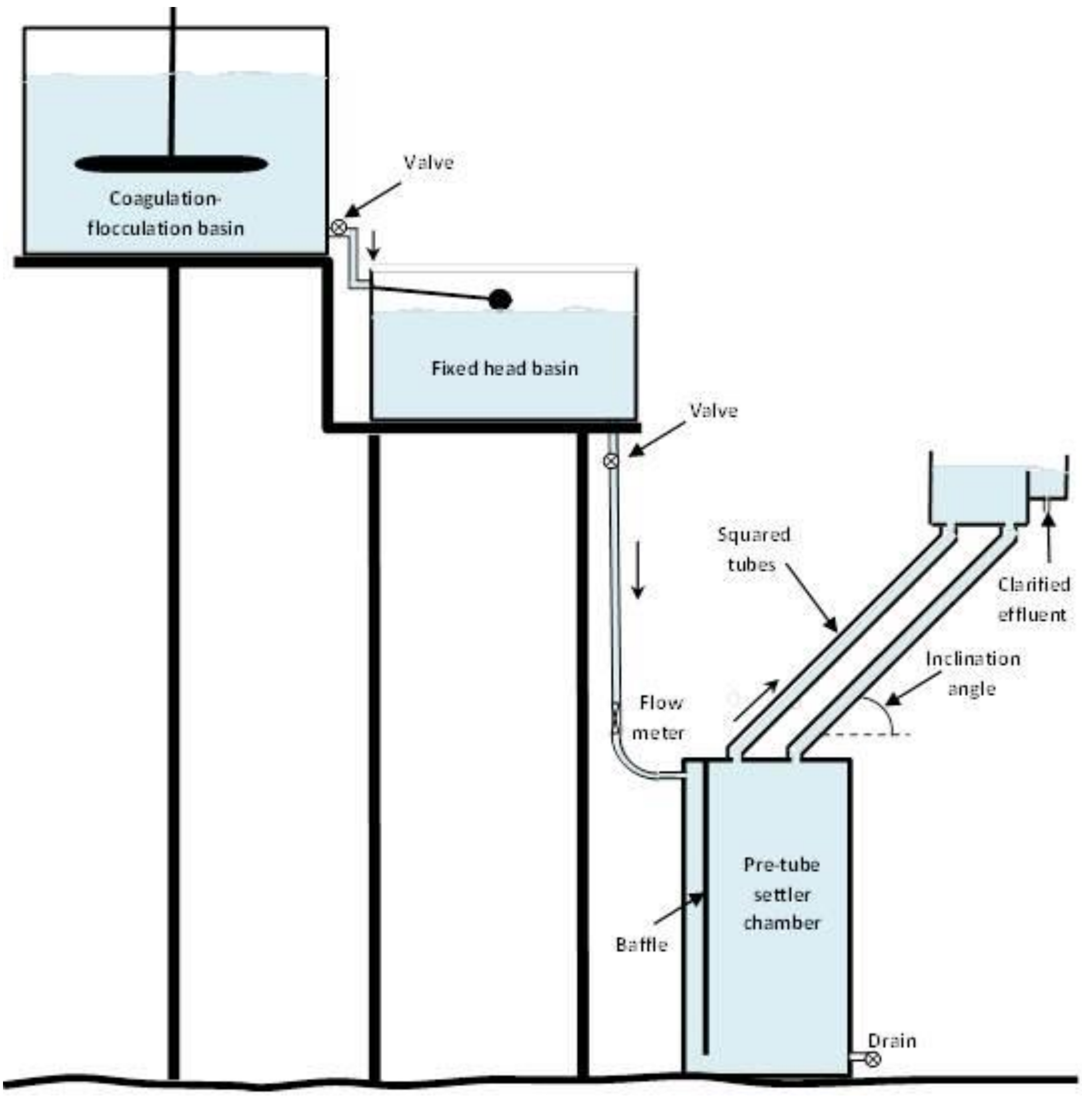

Fig. 1: Schematic diagram of the pilot scale of tube settler apparatus.

(40, 60, 80, 100, and 120 cm) and inclination angles (30, 40, 50, 60, and 70 degrees). As these units are lower than the fixed head basin, the flocculated water rises in the tubes and flows upward till it reaches the top and flows to the outlet unit. Influent and effluent samples were collected and tested for turbidity to find the system's efficiency.

Depending on the tubes lengths and inclination angles, the surface loading rate (SLR) was calculated according to equations (1) and (2) (Brandt et al. 2017):

$$SLR = C * K * \frac{V_o}{L_r} \quad ...(1)$$

SLR = surface loading rate

C = constant = $8.64 * 10^2$

$$K = S_c * \frac{L_r}{Sin\theta + L_r\, Cos\theta} \quad ...(2)$$

S_c = shape factor (for square $S_c = 11/8$)

V_o = flow velocity in the tube

L_r = relative length = L/d

L = length of the tube, d = diameter of the tube

θ = tube inclination angle

Statistical Analysis

The results were analyzed statistically using SPSS 26. Simple regression (linear model) was used to find the relationship between turbidity removal percentage and SLR, while a quadratic model was used for the relationship with alum. Multiple linear regression was used to find a model between turbidity removal percentage as the dependent variable and each tube's inclination angle, alum dosage, and SLR as independent variables. Another model was found for turbidity removal percentage at optimum alum dosage as the dependent variable versus tube inclination angle and SLR as independent variables using multiple linear regression. The models were evaluated using the Coefficient of determination (R^2). In addition, correlate predicted versus observed values and compare slope and intercept against a 1:1 line (Pineiro et al. 2008). The significance of the model was found according to F-test. In addition, a t-test was used for the significance of the independent variable. The weight of each variable in the model was found according to standardized coefficients or β-weight.

RESULTS AND DISCUSSION

The effect of tube inclination on the efficiency of the tube settler is explained in Fig. 2. As the tube inclination angle increased, the turbidity removal percentage also increased to 60 degrees, and the trend reversed. As tube inclination grew, the self-cleaning efficiency of settled solids became more efficient. In addition, increasing the inclination angle gives the sliding settled flocs a chance to collide with the rising particles in the tube to form larger settleable ones

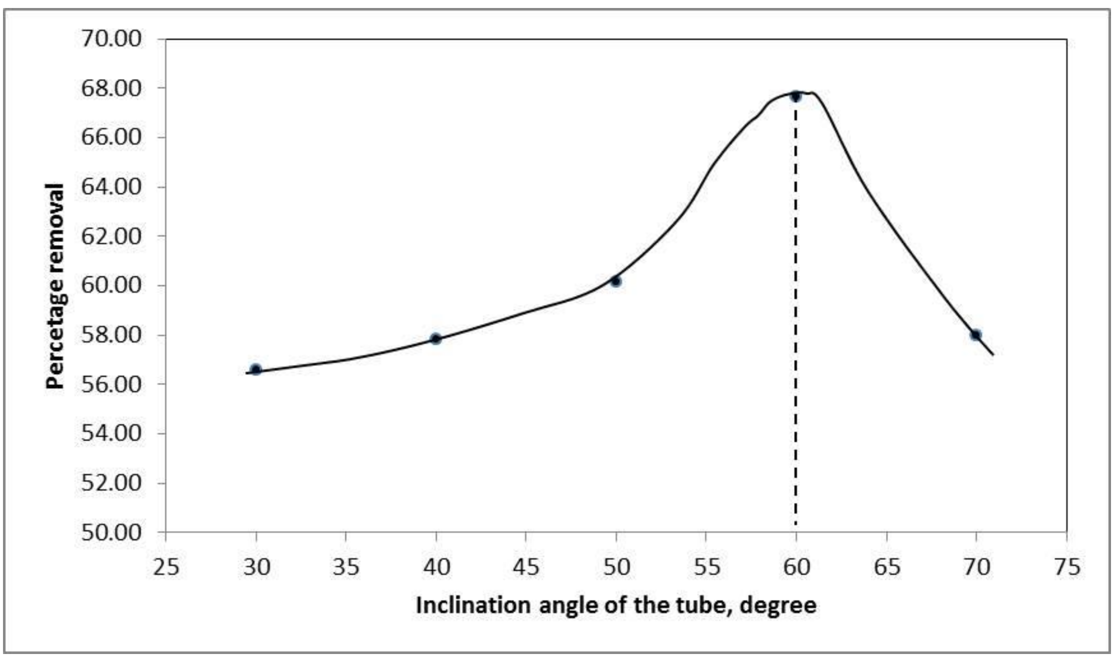

Fig. 2: Effect of the inclination angle of the tube settler on effluent turbidity.

(Al-Dulaimi & Racoviteanu 2019). Furthermore, increasing the inclination angle will decrease SLR, which in turn will improve the efficiency of the clarifier, as stated by Faraji et al. (2013). More increase in inclination angle over 60 degrees leads the tube settler to lose its characteristics as a shallow depth settler.

An inverse relationship was observed for the surface loading rate (SLR) relationship with turbidity removal percentage (Fig. 3). As SLR increases, the velocity of flow increases, which decreases the chance of particles settling and lowering turbidity removal percentage. These results coincided with the results of Al-Dulaimi & Racoviteanu

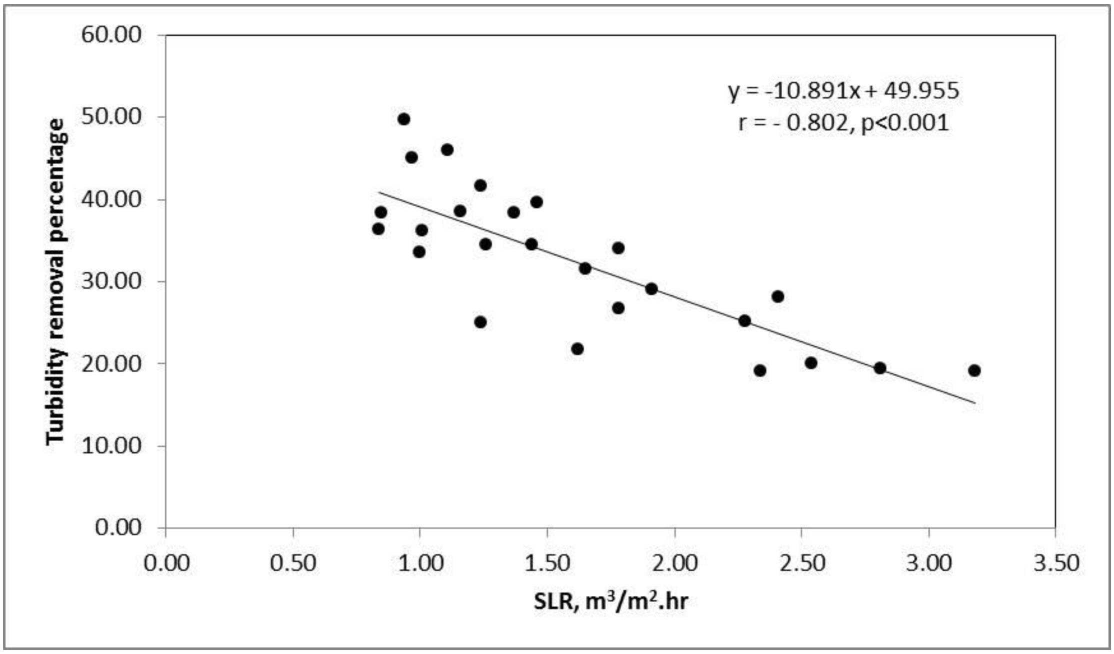

Fig. 3: Relationship between surface loading rate and turbidity removal percentage in tube settler.

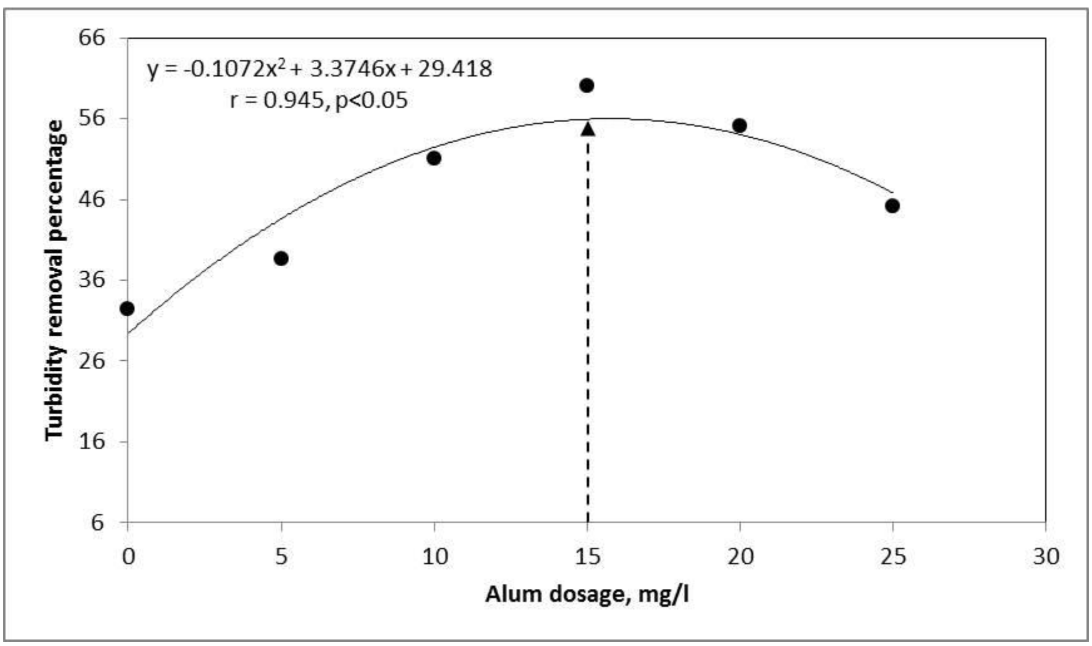

Fig. 4: Relationship between alum dosage and turbidity removal percentage in the tube settler.

Table 1: Regression analysis results for turbidity removal percentage in tube settler versus independent variables.

Variable	Coefficient	SE	β-weight	t-value	p-value
Constant	53.69	2.395			
Inclination angle (degree)	0.142	0.039	0.142	3.64	<0.001
Alum dosage [$mg.L^{-1}$]	0.695	0.064	0.419	10.91	<0.001
SLR [$m^3.m^{-2}.hr^{-1}$]	-13.96	0.861	-0.631	16.21	<0.001

$R^2 = 0.564$, $p < 0.001$, dependent variable = turbidity removal percent, SE = Standard error, R^2 = Coefficient of determination.

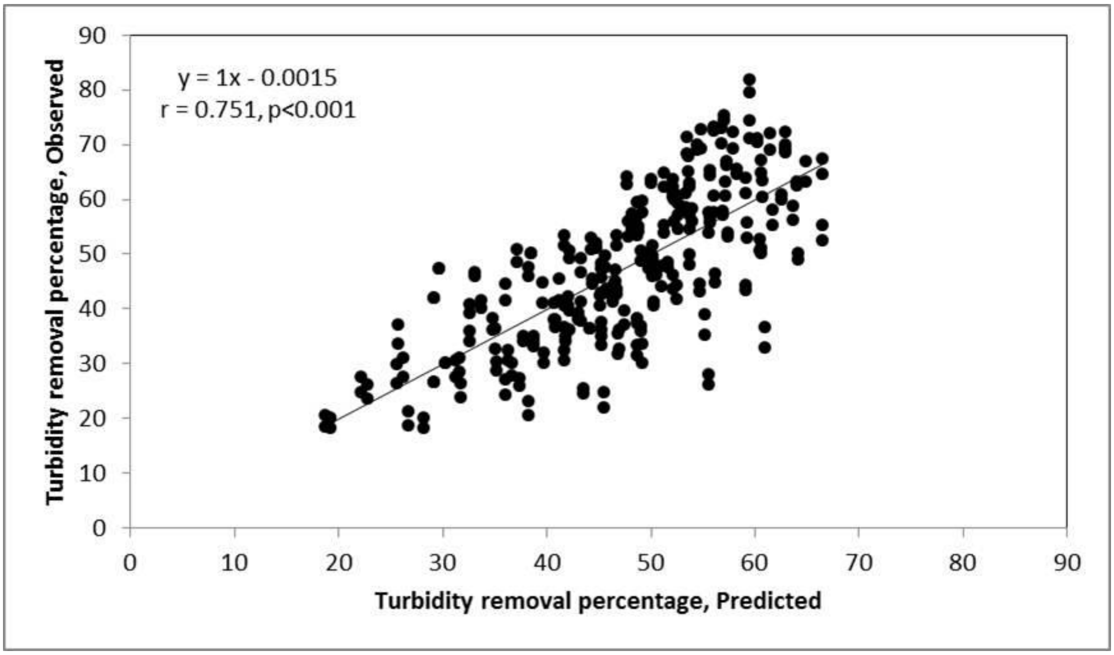

Fig. 5: Observed versus predicted turbidity removal percentage for the statistical mode.

(2018), Lekhak & Amatya (2021), and Oli et al. (2021). Additionally, this relationship was statistically significant ($p < 0.001$) with a correlation coefficient of 0.802. The increase in SLR by one unit exhibits a 10.89% decrease in turbidity removal (Fig. 3).

Alum dosage was correlated significantly with turbidity removal percentage in the tube settler ($p < 0.05$). The quadratic relationship between them was more suitable with a correlation coefficient of 0.945 (Fig. 4). The optimum alum dosage was recorded with 15 $mg.L^{-1}$ for a maximum turbidity removal percentage of 56% as a mean for 20-29 NTU influent. On the other hand, alum over-dozing leads to charge reversal and destabilizing of particles, which will decrease turbidity removal percentage (Saritha et al. 2017).

The linear model results show a significant effect of the studied parameters on turbidity removal percentage at $p < 0.001$ (Table 1). Independent variables were responsible for 56.4% of the variation in turbidity removal percentage. Inclination angle and alum dosage directly correlate with turbidity removal percentage versus inverse relationship for SLR. According to standardized coefficients (β-weight), SLR has the highest effect on turbidity removal percentage variation among the other independent parameters. It has 4.44 (0.631/0.142) times the impact of tube inclination angle, which agrees with the results of Al-Dulaimi and Racovite-anu (2018), while it has only 1.51 times the effect of alum dosage (Table 1). On the other hand, alum dosage has a 2.95-time tube inclination angle effect on turbidity removal percentage variation.

The relationship between observed and predicted turbidity removal percentage values of tube settlers was evaluated as good as it has a slope of 1 (Fig. 5) and a constant near zero (0.0015) (Pineiro et al. 2008).

The statistical model for turbidity removal percentage in the tube settler for optimum alum dosage shows that the inclination angle of the tube settler and SLR were responsible for 81.9% (R^2) of the variation in the dependent variable with significance ($p < 0.001$). The effect of SLR was more

Table 2: Regression analysis results for turbidity removal percentage at optimum alum dosage in tube settler versus independent variables.

Variable	Coefficient	SE	β-weight	t-value	p-value
Constant	71.416	2.648			
Inclination angle	0.238	0.046	0.327	5.20	<0.001
SLR	-14.47	1.010	-0.902	14.33	<0.001

$R^2 = 0.819$, $p < 0.001$, dependent variable = percent removal, for optimum alum dose 15 $mg.L^{-1}$. R^2 = Coefficient of determination.

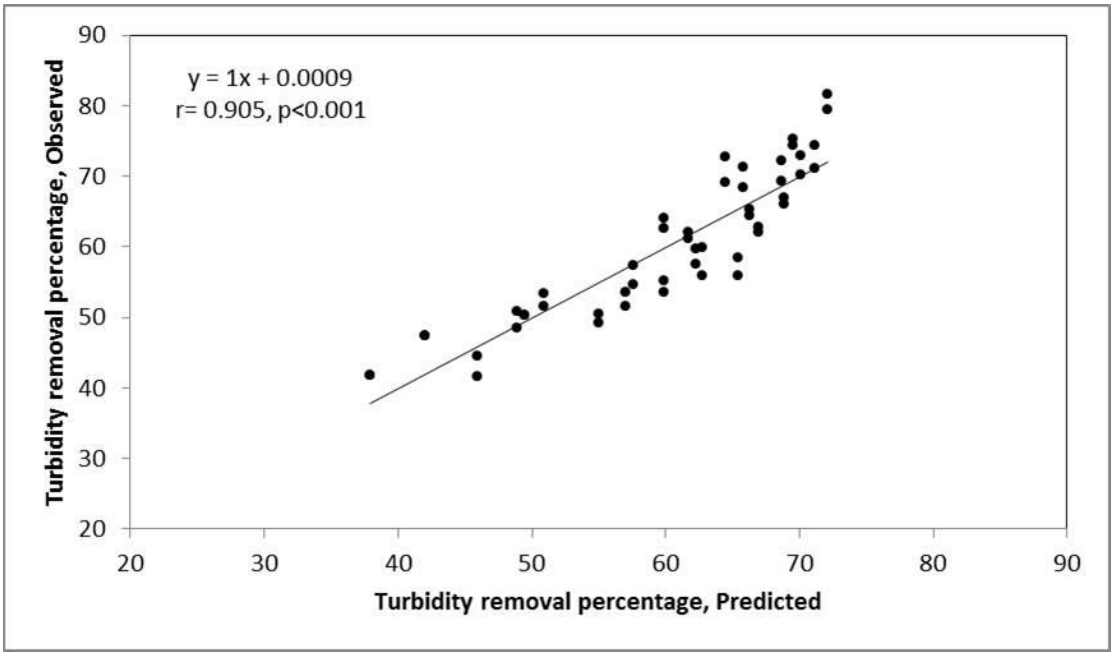

Fig. 6: Observed versus predicted turbidity removal percentage for optimum alum dosage 15 $mg.L^{-1}$.

than 2.5 (0.902/0.327) times that of the inclination angle of the tube (Table 2). This means that the weight of SLR relative to tube inclination angle decreased from 4.44 to 2.5 at optimum alum dosage.

The relationship between observed and predicted turbidity removal percentage at optimum alum dosage of tube settler was evaluated as good also as it has a slope of 1 (Fig. 6) and a constant near zero (0.0009) (Pineiro et al. 2008).

CONCLUSIONS

1. Surface loading rate (SLR) has the highest effect on the efficiency of the tube settler, among other parameters.
2. The tube settler inclination angle of 60 degrees produced the best turbidity removal at optimum alum dosage.
3. The surface loading rate has more than 2.5 times the effect of inclination angle on the response turbidity removal percentage in tube settler.
4. The linear model is suitable to represent the performance of the tube settler at optimum alum dosage.
5. The increase in the length of the sedimentation tube in the tube settler improved the performance of the settler as SLR decreased.

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