Scientific Journal of Impact Factor(SJIF): 3.134
e-ISSN(O): 2348-4470
p-ISSN(P): 2348-6406

International Journal of Advance Engineering and Research Development

Volume 2, Issue 5, May -2015

MODELING OF LAB-SCALE ACTIVATED SLUDGE REACTOR USING ARTIFICIAL NEURAL NEWORKS

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Abstract : *Artificial Intelligence (AI) models are being used for the simulation and control of biological processes in wastewater treatment plant (WWTP). These models can be described as computational methodologies which reflect the behavior of non-linear relationships between cause and effects irrespective to the process. In this study, artificial neural network (ANN) models were used as an AI method for simulation and prediction of effluent parameters in Activated sludge process (ASP). The effluent COD as a model output was predicted by taking time varying input parameters such as pH, TDSinf, BODinf, CODinf of daily data from the measured parameters of ASP. The model was developed by using artificial neural network for multistep- ahead prediction with non-linear auto regressive with external inputs (NARX) tool in MATLAB/Simulink(R2012a). The script was written in the MATLAB with training, validation and testing as the stages of prediction. From the analysis of the results obtained by this model, it was found that the value of regression coefficients for the best fit model was 0.8095 with hidden layer size-8 and trainlm as training function.*

Key words: *Artificial Intelligence (AI), Artificial Neural networks (ANN), Activated sludge process (ASP), non-linear auto regressive with external inputs (NARX), wastewater treatment plant (WWTP).*

I. INTRODUCTION

In recent years Artificial neural network (ANN) modeling studies related to non-linear biological process have become a popular tool to simulate the complicated kinetics of the treatment plant. Due to complexity in nonlinear process in treatment methods, it is impossible to obtain the reliable estimation of unknown dynamical parameters by mathematical emodels [5], for example, biomass concentration in activated sludge process. Improper control of biological processes in ASP causes the serious damaging effects on the water quality of the receiving water body and public health. So the best tool to control and maintain the operation with efficient output standards is modeling and simulation of plant performance by using previous data obtained from the experimental results.

1.1 Activated sludge models

The activated sludge process, which is an aerobic suspended-growth treatment system, was developed in England by Ardern and Lockett (1914) and was so named because it involved the production of an activated mass of microorganisms capable of stabilizing a waste aerobically. Many versions of the original process are in use today, but fundamentally they are all similar [9]. Biological wastewater treatment with the ASP is typically explained in the flow diagram as shown in Figure 2.1. As in the figure the mechanism shows that it is very difficult to understand the operation and its control, so in order to analyze and diagnose these non-linear processes, the modeling of ASP is very much essential to overcome these issues.

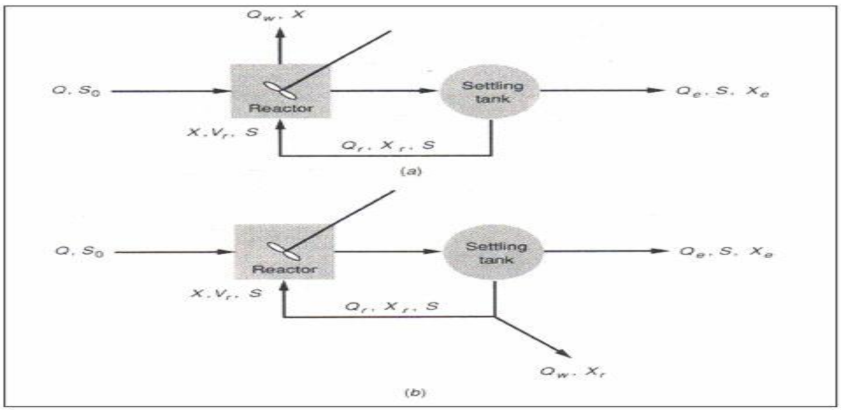

Figure 1 Schematic presentation of completely-mixed reactor with biomass recycle and wasting: (a) from the reactor and (b) from the recycle line (Q: flow rate, S: substrate concentration, X: biomass concentration; subscripts r: return, w: waste, 0: influent, e: effluent e.g. Qr: return flow rate) [9].

Most widely used family of models for ASP consists of ASM1, ASM2, ASM3 and ASM2d. This family of activated sludge models developed by the International Water Association (IWA) and those termed as Deterministic models [2], which are most frequently used models as we studied in literature review so which are considered in this study. The Activated Sludge Model No. 1 (ASM1) [6], can be considered as the reference model, it was taken as a initial step in the general acceptance of WWTP models in research and industry. ASM1 was firstly developed for municipal activated sludge systems in WWTPs to analyze the removal of organic carbon compounds and *N*, with simultaneous consumption of oxygen and nitrate. The model furthermore aims at yielding a good description of the sludge production. Chemical oxygen demand (COD) was selected as the measure of concentration of the organic substrate present in wastewater. In the model, the wide variety of organic carbon compounds and nitrogenous compounds are subdivided into a limited number of fractions based on biodegradability and solubility considerations [2].

1.2 Artificial Neural Networks

An *artificial neural network* is an information-processing system that has certain performance characteristics in common with biological neural networks. ANNs have been developed as generalizations of mathematical models of human cognition or neural biology, based on the assumptions that:
1. Information processing occurs at many simple elements called ***neurons***.
2. Signals are passed between neurons over ***connection*** links.
3. Each connection link has an associated ***weight***, which, in a typical neural net, multiplies the signal transmitted.
4. Each neuron applies an ***activation function*** (usually nonlinear) to its net input (sum of weighted input signals) to determine its output signal.

ANNs provide a means of computation inspired by the structure and operation of the brain and central nervous system. They operate as a parallel computer, which consists of a number of processing elements (PEs) that are interconnected. In feed-forward networks, the PEs are arranged in layers: an input layer, one or more hidden layers, and an output layer (Figure 2). The input from each PE in the previous layer (a_i) is multiplied by a connection weight (W_{ji}). These connection weights are adjustable and may be likened to the coefficients in statistical models. At each PE, the weighted input signals are summed and a threshold value (b_j,) is added. This combined input (u_j) is then passed through a non-linear transfer function ($f(x_j)$) to produce the output of the PE (O_j). The output of one PE provides the input to the PEs in the next layer. This process is summarized in the following equation (1.1) & (1.2) and presented in the figure 2.

$$u_j = \sum_1^n (w_{ij} * a_i) + b_j \quad (1.1)$$
$$O_j = f(x_j) \quad (1.2)$$

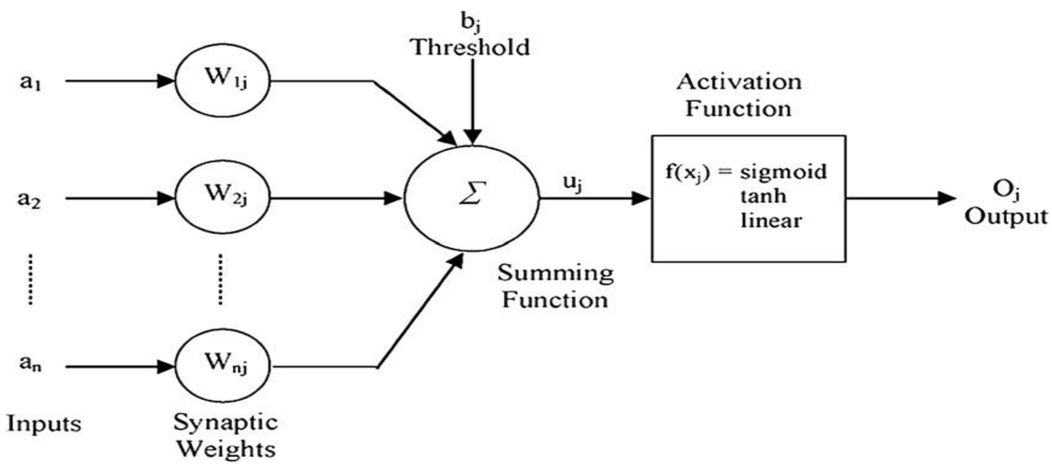

Figure 2. General View of ANN structure [MATLAB/Simulink (2012) user guide]

II. MATERIALS AND METHODS

2.2 ANN model for hypothetical WWTP

ANN model was developed by using MATLAB/Simulink software which includes various neural network tools, which are most suitable to apply in modeling field. In ANN modeling, it is not always advantageous to continue training until MSE reaches a minimum. Hecht-Nielsen (1987) suggests using two distinct sets of data during training that the first set (training set) is used for computing the error gradient and updating the network weights and biases. The error on the second set (validation set) is monitored during the training process. The training and validation errors will normally decrease during the initial phase of training. However, when the network begins to overfit the data, the error on the validation set will typically begin to rise. At that condition, the training must be stopped in order to avoid generalization or memorizing of the training data patterns [8]. In preparation of the input and output data for training of the ANNs, Single sludge simulation process (SSSP) was used. SSSP can simulate the biological transformations occurring in ASP including simultaneous carbon oxidation, nitrification and denitrification. Process rate expressions employed by the model were derived by a task group formed by the International Association of Water Pollution Research and Control. These rate expressions were incorporated into the total of 12 material balances for the heterotrophic and autotrophic biomass, soluble substrate, nitrate nitrogen, and other constituents that the task group considered significant in the process analysis of WWTPs. Solutions to the material balances are obtained through numerical techniques [4].The ANN model developed for a hypothetical WWTP was constructed by considering the various default data taken from Ankara treatment plant measured daily at a interval of 30min. The parameters taken from the plant were Flow rate(Q), particulates(Xi), and autotrophic biomass(Xs), these were representing the number of hidden neurons and input variables for SSSP. The output layer had 3 neurons each representing output variables of SSSP , these were MLVSS, Xhet and Ss. network fitting tool is selected because which is best suitable tool to select data, create and train the neural network and evaluate its performance using mean square error and regression analysis. A two layer feed-forward network with sigmoid hidden neurons and linear output neurons (fitnet), can fit multidimensional input-output problems, given sufficient data and enough neurons in its hidden layer. Network was trained with different 13 training functions and the hidden layer size was varied from 2-10. The script generated develops the models in 3 stages. First the given set of data was divided into three parts for training, validation and testing about 70% for training, 15% for validation and remaining 15% for testing. Network structure has been determined by selecting number of input variables, hidden layer size and transfer function. Network is training by giving inputs and output values, which gives the results in terms of Mean squared Error (MSE) and Regression analysis (R). Totally 113 models were trained with different training function and varying number of hidden neurons. The best fit models were selected which shows highest regression value.

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2.2. ANN model for a Lab-scale activated sludge reactor

Activated sludge reactor was set up for a lab-scale measurement of time variable parameters in the municipal wastewater in the laboratory. Due to imperfect knowledge of process in the reactor the operation and reaction kinetics cannot be predict easily, So in order to overcome this problem modeling of non-linear process in the reaction is very much essential. In this section the ANN model was developed by using various tools inbuilt in the MATLAB/Simulink. Daily data of various influent parameters were measured and considered for a model, the parameters like pH, Chemical oxygen demand(COD_{inf}), Biological oxygen demand (BOD_{inf}), Total dissolved solids (TDS_{inf}) were taken as inputs to predict the parameter effluent Chemical oxygen demand (COD_{eff}).3 months Daily measured data was considered for an ANN model. Here, a MATLAB script was written by using non-linear auto regressive tool, which is a very suitable tool for time series variable prediction models. The script was run with different combinations of inputs to predict the COD_{eff} and the results obtained from the model were analyzed in terms of regression coefficients (R) and Mean square error (MSE) values. From the obtained results the best fit model was determined and discussed in the next section of this paper. This model is so chosen that, especially suits in situations where the following assumptions get failed 1) for many applications insufficient data are available for calibration of the model. 2) Due to high complexity in describing the non-linear process etc. therefore, Black-box models which entirely identified based on input-output data without reflecting physical, biological or chemical process knowledge in the model structure can be applied by using artificial intelligence technique. i.e. Artificial neural network. ANNs are normally effective to capture the nonlinear relationships that exist between variables in complex systems, and can also be applied in situations where in sufficient knowledge is available to construct a white-box model for the system [2]. So in order to come over the problems Black-box models are combined with ANN to predict the variables by giving Multivariable input data to the script written in the MATLAB using autoregressive and non autoregressive time series tools. This method is totally based on the input-output pattern given in the script; the results obtained for different training functions are in the form of predicted CODeff that were compared with the target values, and regression analysis was studied in order to analyze the model results. Before developing a model the data set has been prepared to remove the noise and exclude the empty cell of the data set. Initially the data set contains 4 months daily measurements, but was having some omitted values in the data set so those blank values are excluded and summing up to 112 days data. After preparation of data for the model development preprocessing was carried out to assign all the variables equal in the weights in weight updating process, especially when using a non-linear transfer function. The preprocessing was done by converting the input and output data into the range [0 1] or [-1 +1].
Normalization: For [0 1] range

$$X_i = \frac{x_i - x_{min}}{x_{max} - x_{min}} \tag{2.1}$$

For [-1 +1] range

$$X_i = 2 * \frac{x_i - x_{min}}{x_{max} - x_{min}} - 1 \tag{2.2}$$

The data was normalized by using appropriate equations as given above in order to maintain the equal weights to all the variables.This is very much essential where transfer functions like tansig-tansig, tansig-logsig were used in processing layers of the structure.

III.RESULTS AND DISCUSSIONS

In this section, two models were developed for an activated sludge process by using artificial neural network. One of the models was a hypothetical ASP model developed by using the principle of SSSP, the other model was for an actual treatment plant i.e. black-box model using MATLAB/Simulink (R2012a version). In first case the hypothetical plant data as default data was used to simulate the SSSP, with different training function by varying number of hidden neurons from 2-10, the results obtained from the model were in terms of regression coefficient(R) values. Totally 113 models were developed for hypothetical plant and best models were listed in table.2 based on the R values which having regression value more than 0.9.

Table 2. Combinations of variables used in individual runs of the script

Data allocation	Training function	No of hidden neurons	R_{MLVSS}	R_{S_S}	R_{Xhet}	R_{avg}
70% training 15% validation 15% testing	trainbr	4	0.9769	0.9616	0.9535	0.964
	trainbr	5	0.9763	0.9557	0.9533	0.961767
	trainbr	8	0.9768	0.9645	0.9517	0.964333
	trainbfg	10	0.9709	0.9608	0.9422	0.957967
	traincgb	6	0.972	0.9577	0.9315	0.953733
	traincgf	10	0.9743	0.9619	0.9318	0.956
	traincgp	6	0.9731	0.9588	0.9335	0.955133
	traincgp	9	0.9755	0.9626	0.9377	0.9586
	traingda	9	0.9701	0.9597	0.9298	0.9532
	trainlm	6	0.9743	0.963	0.9488	0.962033
	trainlm	7	0.9751	0.9608	0.9486	0.9615
	trainlm	8	0.977	0.9644	0.9526	0.964667

From above results the average values of R for all models were listed, the best fit model for these hypothetical SSSP process was selected based on the average R values. All the R_{avg} are above 0.9, in that for trainlm training function with hidden layer size 8 was found to be 0.9647 and the results are plotted as shown in the figure so this model is considered as the best fit model for hypothetical plant .

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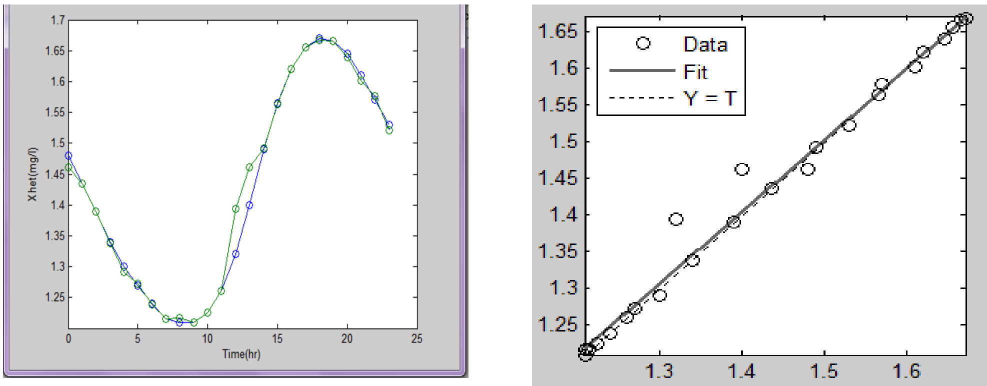
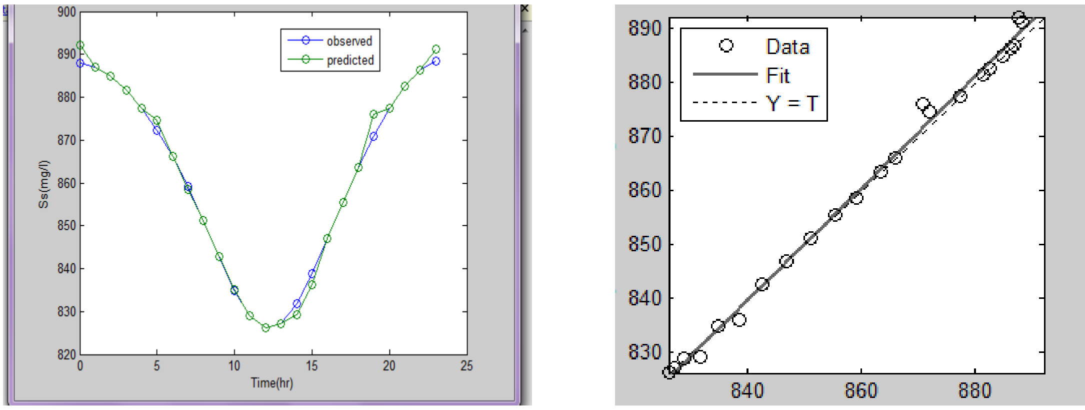
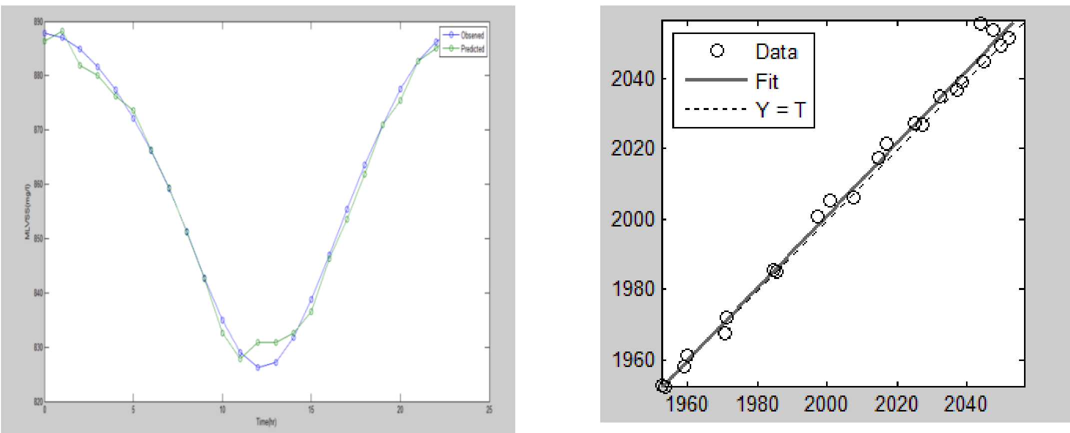


Predicted Xhet



Predicted Ss



Predicted MLVSS

Figure 3.ANN results for best fit model with hidden layer size-8 and trainlm as training function.

In the second model a set of data was used for ANN modeling of Lab-scale Activated sludge reactor. The three months daily data of different parameters were taken as a source of input parameters and the target values. In this modeling process, four of the system variables were used to build an ANN model. The system variables used in this model development are pH, BOD of the influent (BODinf), Total dissolved solids (TDSinf), and COD of the influent (CODinf). These variables, singly or in combinations were used to predict the COD of the effluent of the treated wastewater. Many

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models were developed for these combinations but only those models which are having maximum R value are presented in this study.

3.1. ANN model development

The MATLAB script was used to construct the ANN model automatically by using the data for the STP. The script contains the multi-step-head prediction for given combinations of input variables to predict the COD_{eff} as output variable. Various combinations for this model are given in the table. These combinations were tried in the given order until we get a best fit model for these plant variables by considering correlation coefficient R values.

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Table.3. Combinations of variables used in individual runs of the script

Combination	pH	BOD_{inf}	TDS_{inf}	COD_{inf}	Best R
1	√	√	√	√	0.8095
2	√	√			0.785
3	√		√		0.685
4	√			√	0.625
5		√	√		0.5923
6		√		√	0.7829
7			√	√	0.7920
8	√	√		√	0.569
9		√	√	√	0.645
10	√	√	√		0.8023
11	√		√	√	0.7925

As can be seen in the above table the best fit model to predict the effluent COD data was obtained with the combination 1, having highest correlation coefficient R= 0.80595. The graphical representation of the results is given in the following figure.

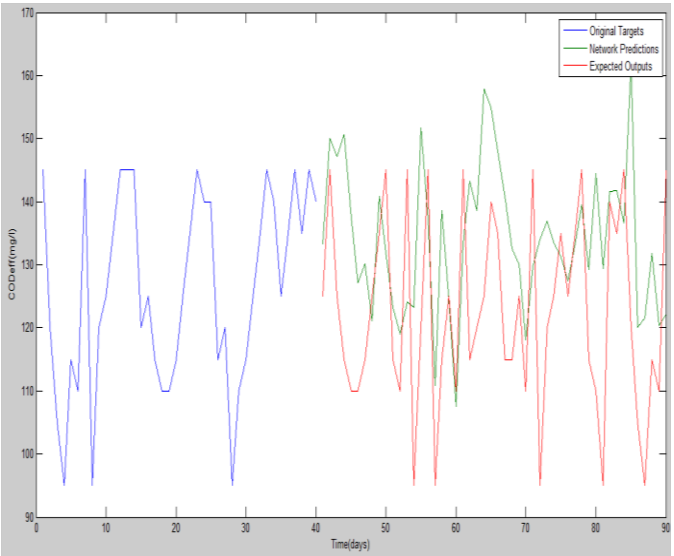

Figure 4. Prediction of effluent COD without providing target values from 41st day to 90th day

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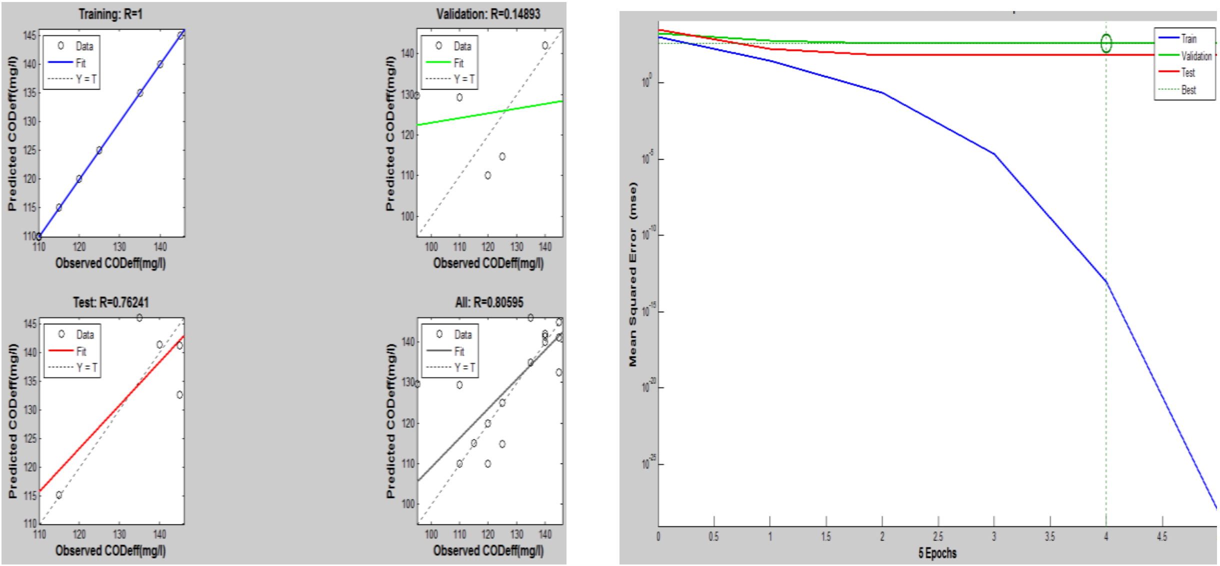

Figure 5 Regression analysis of the ANN model for training,validation and testing and minimum Mean square error at epoch 5.

From the above figures it can be seen that the results obtained were quite good. The best correlation coefficient obtained was 0.80. The best results obtained using this MATLAB script, are given in the above table.

CONCLUSIONS

In the present study, artificial neural network (ANN) models were developed for non-linear operation of an activated sludge process. The models were developed by using MATLAB/Simulink software which includes various neural network tools. First, a model was developed for an hypothetical wastewater treatment plant by generating the data from SSSP. Another model was developed by using the data from the lab-scale experimental activated sludge reactor. The results obtained in terms of R value was 0.964. This indicates the best model with training function 'trainlm' and 8 layered ANN structure. In the second model, the lab-scale experimental data was used to predict the COD_{eff} of the activated sludge reactor with Non-linear Auto Regressive (NARX) tool and the R value obtained was 0.8095. This shows that NARX is the best tool for the prediction of time varying parameters of ASP.

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