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A NOVEL APPLICATION OF CHAOTIC PROPERTIES IN WATER TREATMENT PLANT

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ABSTRACT

This paper aims at presenting a new optimization proposal to enhance the flocculation process in Water Treatment (WT) plant using a better flash mixing, located at KELAVERAPALLY, in Krishnagiri district, Tamil Nadu, India. Further, Sludge removal is done efficiently which decreases the water wastage as well as improvement in output water quality. Though WT plants are already equipped with systematic and sequential physicochemical processes, still they need to be optimized to obtain a better treated drinking water to maintain the quality standards as prescribed by World Health Organization. Chaotic behavior in chemical systems has been used to optimize the performance of WT plant. Measurement systems implemented in WT plant yield several chaotic based measurement parameters which are used to control the system operations to maintain the target water quality. This intelligible data extraction through the proposed measurement systems in a short span of time improves the plant performance without adding any costly systems except few changes in the existing plant setup. Chaotic behavior is ensured through Lyapunov Exponents and Kolmogorov-Sinai Entropies. Both, water quality improvement and water wastage reduction is achieved simultaneously in the proposed work when a dosage prediction is done using Feed Forward Neural Networks. The treatment plant investigated has a maximum capacity of 14 MLD (Million litres per day) using two parallel streams with 7 MLD each.

Indexing terms/Keywords

Lyapunov Exponents (LE), Kolmogorov-Sinai Entropy (KSE), Chaotic systems, Water treatment.

1. INTRODUCTION

The usage of water especially for drinking purpose is increasing day by day as the population is climbing. Unlike animals, civilized human beings always consume treated water supplied by the government authorities which has been followed over several decades in practice. The potable water supplied by municipal authorities should be absolutely free from any toxic metals and other microorganisms which are the root cause of various known and unknown illness to consumers [1].

Though origin and the major source of drinking water is through rain, it could not be used directly without storing it, as consumption is an eternal process. Hence, surface water stored in reservoirs is considered to be the major source of water supply for drinking, irrigation and industrial purposes. Due to stringent safety regulations imposed on treatment processes to ensure good quality water is supplied to consumers, it is mandatory to treat such water with optimized functionality of the plant [2,3]. Such water treatment processes are sequential batch or continuous, depending on the quantity need to be supplied on per day basis. In earlier decades, contaminants were nominal in ppm (Parts Per Million). But the present modern life is wholly modified by countless industries based on the domains of textile, leather, dyeing, printing etc., all being a major water polluting agents [4]. The water to the treatment plant under research is mainly sourced from Kelaverapally reservoir situated at nearby Hosur town, Tamil Nadu, India, whose GPS locations are given by 12.775242N, 77.874364E. The reservoir has been constructed across the Ponniar River. The river originates from Chennakesava hills and moves towards south east through the districts of Dharmapuri, Krishnagiri, Vellore and Cuddalore for a distance of around 420 kms and get emptied into Bay of Bengal. This work is envisioned to deal the normal raw water inputs from reservoirs and not bounded to sewage water or industrial waste water. But evidences are there to prove that contaminations are added in this water reservoir by various official and unofficial polluting agents. Hence, optimizations are performed in a localized problem of water treatment based on the influents from Kelaverapally reservoir. The conventional plant operation has been briefed as sequence of operations given in Figure 1.

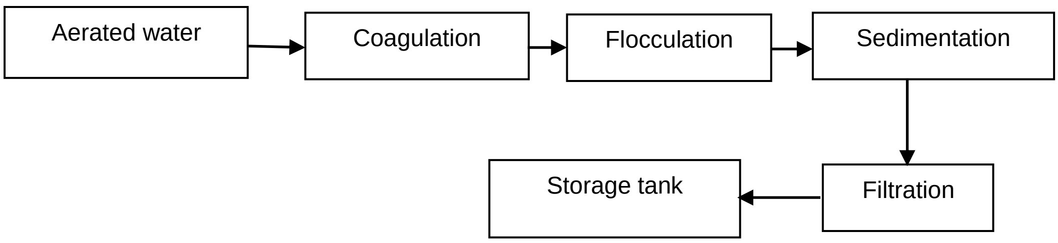

Fig 1: Conventional flow of water treatment process in Keleverapally treatment plant

1.1 Cascade aerator

The water from the reservoir is transported to an off take well situated at 700 m from the treatment plant via metal pipe lines. A water storage capacity of 27.7MLD equipped with 170HP capacity motor to pump 18000 liters per minute. While pumping the raw water to cascade aerator, pre chlorination of 15PPM is done and 250 PPM Alum is mixed in stilling chamber. Due to aeration, bad odor of water is removed to the better extent. The water is spilled out in the upward direction against gravity through the metal pipes facing upwards and ending with plenty of tiny holes. As the spilled water reacts with atmospheric air, ammonia gas is removed to the possible extent.

1.2 Flash mixer

The raw water further flows through a flash mixer operated by a 5HP motor, 1430 RPM inside a space of 2m diameter and 4m depth. However operational volume of flash mixer accounts only 1.5m diameter and 3m depth. The coagulants (Alum) are thoroughly mixed with the influent through this method of rapid mixing.

1.3 Clariflocculator

Though two Clariflocculators are available, one is kept idle due to cost constraints. Entry of coagulated water is through the bottom of the flocculator of diameter 10.5m and 3.5m depth and the clarifier of diameter 15.5m and 3.5m. Maximum detention time of Clariflocculator is 1½ Hours. Desludging is done at the rate of at least once in average of 30 minutes intervals. Nevertheless, it depends on the influent quality. After the water is transported to holding tank by 50HP motor at the rate of 6500 LPM (Litres Per Minute), is mixed with liquid carbon dioxide to expel ammonia and bad scent.

1.4 Rapid Sand Filter

While maintaining the flow rate of 44 litres/sec the water is passed through 8 sand filter beds with a surface area of $33m^2$ each. Overall filtration rate is $8.80m^3/m^2/Hr$. As a final stage, post chlorination of 5-8 PPM dose is added to the filtered water. Above mentioned dosage decisions are based on the jar test conducted in the plant.

Though the plant has a full capacity of 14MLD when operated for 24 hours. Based on official reasons, at present the plant is operated only for 12 hours. Though two parallel flow lines are available, only one line operated and hence at present a maximum 3.5 MLD is supplied to the end users. Overall idea behind this research is to increase the quantity of water treated without compromising the water quality and reduce the water wastage through optimized sludge removal timings.

The paper has been organized as, section 2 elaborates the existing researches on various water treatment methods and various algorithms used to optimize the plant operation. Section 3 presents a detailed back ground of various metrics through which plant operation is optimized along with experimental set up description. Over all benefits obtained out of proposed method has been submitted in section 4. Conclusive comments have been presented in section 5.

2. LITERATURE SURVEY

Water treatment methodologies have been existing over a century. Treatment plants have progressed all its way through various elevation procedures year by year by the sincere efforts made by various distinguished researchers. Researches have been focused towards

- Maintaining the quality alone.
- Quality of treated water along with effluent quality.
- Treatment process focused only towards a specific contaminant.
- Processes involving reduced maintenance cost.
- Plants with less initial investment.
- Plants with less running cost of chemical agents.
- Treatment procedures based on the usage of water.

Earlier research works related to water treatment could be broadly classified based on, Types of treatment procedures, Modeling and optimization methods

A normal WT plant is almost similar to a Waste Water Treatment (WWT) plant, except certain additional processes included in WWT process. Hence optimizations are commonly needed to WT or WWT. Integrated Controlled Random Search (ICRS) algorithm has been applied by Casares & Rodriguez [5] to evaluate the WWT plant model. The major problem faced by optimization techniques is the non-linear nature of constraints and some process variables. Also, convergence is delayed because of number of constraints. Hence an optimal search algorithm has been used to minimize the construction cost in WWT plant consisting a trickling filter, an activated sludge aeration vessel and a secondary clarifier. The cost estimations in various algorithms have been compared with ICRS as shown in Table 1.

Table 1. Cost comparison of various optimizations

Algorithm	COST(US$)
Generalized reduced gradient	243,841
simplex pattern search	215,095
modified random search	166,490
Integrated controlled random search	156,636

Literature [1] presents a novel concept of utilizing Artificial Neural Network (ANN) and Adaptive Network based Fuzzy Inference System (ANFIS) to optimize the Poly Aluminium Chloride (PAC) dosage used in the coagulation stage. These models are used to predict the dosage when the influent water does not hold any information on its quality. Moreover, the dosage would become fully automatic process to ensure the quality of the treated water under the prescribed norms. Root Mean Square Error (RMSE) is used to analyze the performance of the dosage prediction algorithm between the actual and predicted values obtained in both methods.

Unlike other process controls, WT plant controls need multiple optimizations as it involves several sequential processes specifically applicable to a target water quality parameter as given by Issa et al [6]. Dynamic programming model approach has been suggested to reach a global optimum in order to meet the rigorous norms to ensure the water quality. Tongneng & Peijun [7], did water quality prediction with the available data on dissolved oxygen. Wavelet transforms and support vector machines have been employed for one step and two step prediction of the dissolved oxygen. The performance of prediction has been compared against BPNN (Back Propagation Neural Network) and SVM (Support Vector Machines) has been suggested to be a better prediction method. A comparison presented in Table 2 clearly supports their view.

Table 2. Prediction errors between SVM and BPNN

Error	SVM prediction	BPNN prediction
RMSE	0.191	0.874

The authors of [8], proposed a method to determine the abnormality in the municipal waste water treatment. As raw water quality is totally worse than the normal raw water, treatment process dynamics should be varied instantly. This needs a better knowledge on input parameters. Hence a classification model using support vector machines was proposed using grid search algorithm and particle swarm optimization methods. Following Table 3 shows the validation accuracy obtained in their classification model.

Table 3. Validation accuracy of SVM

Model	Cross validation accuracy
Standard-SVM	94.4724%
Grid search-SVM	97.4847%
PSO-SVM	97.4874%

In majority of the earlier works, serious attempts had been made to fulfill the inflexible regulations recommended by the water board authorities. Since the type of coagulation method, plant structure and treatment processes are finalized during the plant installation, only optimization is possible for instantaneous load parameter variations in influent. Since the quality of output water could not be compromised, optimizations have focused much towards cost reduction while stabilizing the quality. However, detention time reductions have not been attended vigorously. Any optimization attempts with an abrupt change in the plant structure or with any added number of processes would not be appreciable and probably would attract huge amount of investment. Hence, utilizing the knowledge of chemical and mechanical dynamics in specific operations would help to improve the plant efficiency without any huge additional investment. Hence, improving the Velocity gradient in flash mixer and hence a better mixing efficiency would lead to good results. This idea would enhance a fast settling of contaminants and reduce the turbidity. Due to this proposal, it is expected to supply an additional quantity of treated water and reduce atleast 2 MLD of waste water while preserving the quality metrics.

3. MATERIALS AND METHODS

The specific objectives are to improve the mixing efficiency in rapid flash mixer, hence a proper blend of raw water and chemical coagulant would improve the neutralization of negatively charged impurities in water. So, the target is to maintain the uniformity in the concentration of the coagulants through a higher turbulence in mixing tanks. In addition, the stability in sludge settling process and any of its deviation is determined using the instantaneous optical conductivity analysis done with an experimental setup. Using the data acquired from the experimental setup, LE, KSE density and KSE generality values are evaluated. Except FFT analysis, all other metrics are related to chaotic behavioral analysis. Both theoretical and experimental values are compared to show the effectiveness of our proposal. As a final stage, optimal dosage detection is calculated using FFNN. The major reason to work on clarifier instead of flocculator has a significant reason. Normally, in flocculator, larger particles settle down quickly due to its higher mass and due to gravity. However, smaller particles escape from this process and needs much more attention. To say it clear, sludge formation and accumulation is quicker in flocculator, whereas it is more time consuming process in clarifier because of smaller sized particles.

3.1 Stability Metrics

The foremost metrics aimed in this research work are, FFT analysis of instantaneous optical conductivity values in clarifier, LE, KSE density and KSE generality. Though chaotic behavior has been suggested in all earlier works, evaluation of critical metrics, such as Lyapunov exponents, Kolmogorov – Sinai entropy density and Kolmogorov-Sinai density generality were not analyzed. These parameters ensures the system is in chaotic region. Before evaluating the above parameters, a glance of mathematical background has been presented below.

FFT analysis

FFTis a public domain algorithm, through its computing revolution, considered to be one of the indispensable algorithms in digital signal processing. Fourier transform is an approved method to detect the harmonic content in power signals, such as voltage and current. The presence of harmonics reduces the power quality of an electrical system. Hence FFT analysis, plays a vital role in detecting the spectrum contents in any time domain signal. By performing Fast Fourier transform, the time domain signals are transformed to frequency domain. As given by Rockmore [9], any time series could be decomposed into the summation of its sinusoidal components is the basic idea behind the FFT. The optical conductivity time series is analyzed with its harmonic content. Whenever a least Total Harmonic Distrotion (THD) is noticed, that is considered to be the possible stability of the system.

FFT algorithms have been approached in different ways at various complexities. The term DFT and FFT refers to the same output, except that FFT is faster as the name reveals. By decomposing the time series into various frequency components, DFT is obtained [10]. Applications of DFT are enormous and unavoidable in the modern world of control system. But it is impractical to apply it for any online applications because of its less speed. Hence, FFT is preferred to obtain the results quickly. The total number of arithmetic operations required to compute DFT is $\Theta(N^2)$, while an FFT needs $\Theta(N \log N)$ operations. Since logarithm is involved, the difference in number of operations and speed will be very high where larger time series is taken and it is proportional to $N / \log N$.

Generally, FFT depends on the factorization of N, but there are FFTs with $\Theta(N \log N)$ complexity for all N, even for prime N. Many FFT algorithms only depend on the fact that $e^{-2\pi i/N}$is an N^{th} primitive root of unity, and thus can be applied to analogous transforms over any finite field, such as number-theoretic transforms. DFT and inverse DFT differs only by a negative sign and a factor *1/N,* the computation complexity in transforming between the time and frequency domain is same Let $x_0, \ldots, x_{N-1}$ be complex numbers. The DFT is defined by the formula given in Eq. 1

$$X_k = \sum_{n=0}^{N-1} x_n e^{\frac{-i2\pi kn}{N}} \qquad (1)$$

Where $k=0,1,2\ldots.N-1$.

This needs $\Theta(N^2)$ operations and totally N outputs X_k, and each N requires a sum of N terms. An FFT is a method to compute the same results in $\Theta(N \log N)$ operations [11].

Lyapunov Exponents

Lyapunov exponents are very useful in analyzing the dynamical systems. The sensitivity of divergence or convergence of trajectories in phase space with respect to the initial conditions are measured through Lyapunov exponents. A system with at least one positive exponent is considered to be in chaotic region.

LE is a measure of how diverse the lattices are, for each time iteration and it is given by Eq. 2

$$\lambda(i) = \lim_{n \to \infty} \frac{\log|\sigma(i)|}{n} \qquad (2)$$

Where n is the number of iterations which tends to infinitiy and λ(*i*) is the Lyapunov Exponent. λ(*i*) are calculated from the eigenvalue $\sigma(i)$ of R_n as given in [12].

R_n is calculated using Eq. 3 from the initial values of the lattices by constructing the Jacobian matrix J_n as given in [13] is calculated in each iteration. Then we define

$$R_n = \prod_{k=1}^{n} J_k \qquad (3)$$

After calculating the LE values, those lattices have positive values are understood to be in chaotic region. In this work, lattice values are nothing but the time series values obtained by Chua's circuit related to flash mixer drive and time series obtained from optical conductivity data from clarifier. The sum of Lyapunov exponents reveals the damping nature of a system and any changes in damping could be monitored with Lyapunov exponents. Calculation of Lyapunov exponents is done in many methods, the one given in Eq. 2 is related to discrete time system. Few other approaches to calculate LE, when a continuous time series are reported below. Computing the Lyapunov exponents and Instantaneous Lyapunov exponents utilized phase space and tangent space approach in [14]. In the algorithm developed by Sano & Sawana [15], Short Term Averaged Lyapunov exponents(SLEs) are introduced. This is needed when the experimental data (timeseries) gives an inaccurate ILEs from a time series due to computational errors. A similar concept to the SLEs, the LLE (Local Lyapunov Exponents) was proposed by Abarbanel et al [16]

It is convinient to model a dynamical continuous time system by ordinary differential Equation which is of the form given in Eq. 4 and 5

$$\frac{dx}{dt} = f(x_1, x_2, x_3 \dots \dots x_n) \qquad (4)$$

$$= \left[\frac{dx_1}{dt}, \frac{dx_2}{dt}, \dots \dots \frac{dx_n}{dt}\right]^T \qquad (5)$$

Where $x=[x_1,x_2, ..x_n]^T$

The above Eq. 5 gives a set of trajectories in phase space. The i_{th} Lyapunov Exponent is calculated as given in Eq. (6)

$$\lambda_i = \lim_{t\to\infty} \frac{1}{t} ln \frac{P_i(t)}{P_i(0)} \qquad (6)$$

Where, the Eigen values are ordered from largest to smallest. Since the integration time is infinite, it is practically not possible for infinite time series. Hence, LE calculation based on finite number of iterations is useful as given in Eq. 7

$$\lambda_i = \frac{1}{t} ln \frac{P_i(t)}{P_i(0)} \qquad (7)$$

Optical Conductivity time series is analyzed to obtain its Lyapunov Exponents and it gives a better idea on how the nearby orbits diverge due to initial conditions.

Kolmogorov-Sinai Entropy Density

The spatiotemporal chaotic system of the proposed system can be considered as L dimensions dynamics, the Kolmogorov–Sinai entropy of the L dimensions dynamics is the sum of positive Lyapunov exponents. Without loss of generality, the Kolmogorov–Sinai entropy density is employed here to eliminate the effect of number of lattices, which is presented in Eq. 8 as follows

$$h = \frac{\sum_{i=1}^{L} \lambda^+(i)}{L} \qquad (8)$$

Where, *h* is the KSE density and the numerator is the sum of positive values of Lyapunov exponents [17].

Kolmogorov–Sinai Entropy Generality

The Kolmogorov–Sinai entropy density indicates whether the spatiotemporal chaotic system is in chaos. However,Kolmogorov–Sinai entropy density cannot present chaotic majority of L lattices since Kolmogorov–Sinai entropy densityis positive. Here, we employed Kolmogorov–Sinai entropy universality *hu* as given in Eq. 9

$$hu = \frac{L'}{L} \qquad (9)$$

Where, *hu* is the KSE generality and L′ is the number of positive Lyapunov exponents in spatiotemporal chaotic system of the proposed system [17]. The Kolmogorov–Sinai entropy universality is the percentage of lattices in chaos, which evaluates the space complexity in *L* dimensions of dynamics [18].

LE, KSE density and KSE generality are the metrics useful in two ways in this research. 1. Improved Stability in mixing process. By applying chaotic voltages, the mechanical movement of mixing plane is in chaotic region and hence the chemical process followed by mixing is also in chaotic behavior. This method of better diffusion helps in the reduction of dosage(optional) as well as the time of flash mixing. 2. Stability in sludge formation process, where the time series captured from optical conductivity measurement system is analyzed for chaotic behavior. The performance of the system is evaluated with above mentioned metrics.

3.2 Flash Mixer Operations

It is very common to use Alum, Ferrous Sulphate, Ferric Chloride, Ferric Sulphate as coagulants in treatment plants. The chemical reaction has been presented for Alum based treatment, as this is used as the primary coagulant in the research plant.

$$Al_2(SO_4)_3 + 3\ Ca(HCO_3)_2 \text{ ----------->} 2\ Al(OH)_3 + 3CaSO_4 + 6\ CO_2 \quad (10)$$

Eq. 10 reveals that the positive ions released by the Alum destabilizes the impurities which are already negatively charged. Hence a charge neutralization expels the negatively charged impurities from the water molecule. Consequent flocculation process is discussed in following sub sections.

There exists no rigorous mathematical models to validate a coagulation process. Studying the dynamics of the coagulation and flocculation process is very difficult and hard to model it. Destabilization of colloidal particles and agglomeration takes place in coagulation and flocculation respectively. This is highly dependent on the turbulent fluid dynamics [19].

As a fundamental understanding, mixing is done to convert any heterogeneous system into homogeneous system with respect to any physical or chemical property or both. Such mechanical force based mixing, ensures de-agglomeration. Such mixing processes induce a laminar flow or a turbulent flow inside the mixing tank depending on the power supplied from external power source. A turbulent flow is induced in the flash mixer tank, by using impellers when rotated at higher RPM (Revolutions per minute). While the Alum is mixed with clean water and mixed with raw water, the physical and chemical properties of the mixture is not distributed uniformly for example, the concentration of the alum in the mixture. When the mixture is disturbed by inducing a flow, the dissolved alum is spatially distributed over the full volume of the raw water. In case, if they are not properly distributed and blended, this would result in serious issues such as, high amount of residual alum in treated water and reduces the overall efficiency of the flocculation process. Hence, it is necessary to increase the detention time, to enhance the quality of output water. While increasing the detention time, by reducing the flow rate, results in reduced quantity of treated water. Hence, it is brilliant to vary other parameter involved, called as Velocity Gradient (G).

Hence, the overall idea is to modify the G value obtained in the conventional flash mixer, with a new model of chaotic based flash mixer. It is needed to prove that the G value is increased effectively through the proposed mixing model. Edzwald [20], has emphasized that G value as a disadvantage because, G value needed is proportional to the volume of the raw water treated. They try to achieve the required uniformly distributed concentration with a hydraulic based flash mixing, instead of mechanical based. Also, they claimed that the power needed to improve G is a proportional to G.

Even though a better model was proposed with hydraulic mixing, authors of this paper intended to implement an improvement in the existing impeller based mixer, as the major concern is to improve the performance of Kelaverapally treatment plant existing already with huge initial investment. An additional multiplication factor of 2, reveals that external additional power from the normal direction could impact on G values. Through this hypothesis, it is to prove that, the coagulants and raw water are mixed thoroughly. Hence, the plane of impeller is moved up and down, that means the axis of shaft is moved up and down where already horizontal mixing is in chaotic motion. Hence, over all G is approximately doubled and hence the coagulation is very effective.

Due to this approximate doubling of velocity gradient, the mixing process is very efficient and it has been simulated using COMSOL software using finite element analysis. The chaotic behavior too, is maintained due to the horizontal movement of impellers driven by a chaotic voltage. COMSOL Multi physics is an optimal tool, to simulate mechanical, electrical and chemical systems based on finite element analysis.The model tree in the software helps the users to access, the geometry, boundary conditions and visualizations through animations etc. COMSOL has provisions to interface it with MATLAB, CAD and ECAD software. The product is capable of building and simulating cross-disciplinary products is the highlight of COMSOL. It is very user friendly and simple to simulate as the parameters used for simulation of the flash mixer is given in Figure 2. The mixer tank was agitated using an impeller with four blades and four number of baffles on the inner side of the mixer tanks. The simulation was done to the actual dimensions of the flash mixer as it exists in the Kelaverapally plant. While building the model, the turbulence created in the fluid (water) is shown in the form of vectors in white colored arrow marks as given in Figure 3.

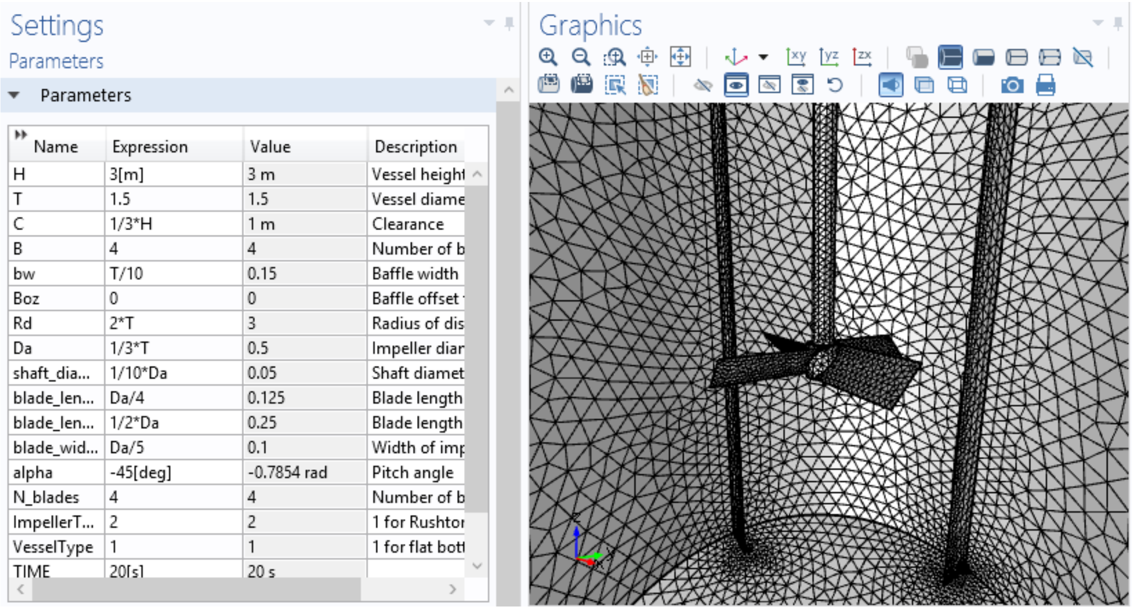

Fig 2: Parameters and graphics of flash mixer in COMSOL platform

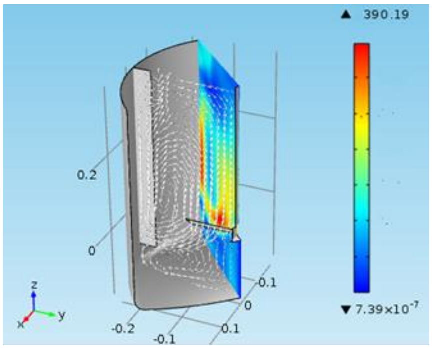

Fig 3: Velocity vectors of flash mixer in COMSOL

A three dimensional view with a scale pointing the lowest and highest velocity gradient is shown. Impeller speed was set to 1430 rpm along with an additional stress in vertical direction. While conducting simulations, finest size of mesh could consume more memory and largest size of mesh could lead to compromise in accuracy. Hence, it worthwhile to set the mesh size to be nominal instead of too small and too large. Velocity gradient G was obtained as 390.2 s^{-1}

Chaotic based motor activation

Chaotic systems are basically, pseudo random systems, where the system behavior is predictable at certain conditions. The systems would appear to be random, but not random, rather predictable. Chaos occurs in many natural systems, such as weather variations, chemical reactions and liquid crystal convection and even in some biological networks. Coupled map lattices is a dynamic system, where the system behavior is based on the neighborhood lattices which could produce a spatio-temporal chaos [21]. Chaotic behavior of any system can be evaluated with a coupled map lattice based model which are well applicable for low dimensional systems as well as high-dimensional systems.

In [22], it has been emphasized that, the Chua's circuit is able to produce chaotic behavior based on the rigorous proof. Hence, it is a good idea to use Chua's circuit to drive the motor used in mixing process. The chemical mixing process, is in chaotic behavior while the energizing system is chaotic. Further, positive suggestions offered by Alvarez-Hernandez [23]. supports our idea of mixing raw water with coagulants through flash mixer on chaotic basis. Introducing chaotic based mixing process has been inspired by Zhong Zhang & Guanrong Chen [24]. Results shows that mixing time is reduced. But the major drawback in their work, is supposed to be, the developed turbulence in their research. Since turbulence is related to the velocity gradient G, it has to be increased for better turbulence. A mathematical model to improve the value of G has been analyzed and it could be achieved by adding a vertical mixing process by the way of moving the blades setup vertically up and down. The works presented in [24] actually achieve a chaotic mixing, by energizing the DC motor with a chaotic voltage waveform. The averaged DC current supplied to motor produced chaotic oscillation in the speed and hence the chaotic mixing. But this method could not produce a higher value of G. Chaotic state could be achieved by using better constructional and controlling methods. Hence, it is proposed to use an additional mixing towards vertical direction without using additional impellers, but moving the impeller up and down. In addition to the chaotic based RPM variation in impellers, the impellers are moved up and down, which increases G. The Chua's circuit as suggested in [22] with sufficient modifications in Chua's non-linear diode has been used to generate chaotic voltage. This voltage waveform is used to energize the driving motor to produce both shear stress and additional stress in normal direction through a conventional drive. It was already discussed that a normal stress in a liquid is applicable to solids but not for liquids. Hence an attempt made to produce the normal stress from an external source would further increase the shear stress. This is how we gain an additional velocity gradient G. With the values suggested by Kennedy [25], a circuit has been developed and simulated. However, Chua's Circuit plays a role only in horizontal mixing and not in vertical mixing.

Role of Detention time

The detention time(T_d) shown in Eq. 11 is given by

$$T_d = \frac{V}{Q} \quad -(11)$$

Where T_d, is the detention time in seconds, V is the volume of the liquid in m^3, and Q is the flow rate in m^3/s.

The velocity gradient in conventional system is obtained as given in Eq. 12 is followed

$$G = \sqrt{\frac{P}{\mu V}} \quad (12)$$

G= 238.26 s^{-1}, is obtained when,

Input power delivered by 5HP motor = 5 x746 W = 3730 watts,

Viscosity=0.0186 kg/ms (when Alum is added with raw water), radius = 0.75m , Height excluding the clearance is 2m and

Volume of the tank $V = \pi r^2 h = \pi x 0.75^2 x2$
$= 3.5325\ m^3$.

When repeated the calculations for twice the input mechanical power of 7460 watts as per our proposal, yields a G of 336.95 s^{-1} . This is against the simulated value of 390.2 s^{-1} as obtained in Figure 3. This difference is due to the pyhsical damage of baffeles in the actual flash mixer in the Kelaverapally plant. While considering the baffle area of 0.27 m^3, the volume of the mixing tank is revised to V=3.2625 m^3. Hence revised G is obtained as 350.62 s^{-1} , which is fairly similar to the simulation results. The difference is neglected due to different operating temperatures in real environment.

Since the overall idea is to maintain the GT (Velocity gradient x Detection time) product fairly high, G has been targeted to increase. If T is increased, it would reduce the water handling capacity at the benefit of mixing efficiency. If G is increased it helps in thorough mixing while maintaining the same volume of water without affecting the water handling capacity. The target is not to increase the overall GT product, but to maintain it as same as existing GT. When the detention time is 90 seconds and by using the values obtained in Eq. 12, GT is obtained as follows.

$$GT = 238.26\ s^{-1}.\ 90 = 21443.4$$

In practical cases, GT in the order of 1000 would naturally leads to turbulent flow, and obtained GT proves the flow is sufficiently turbulent. The same value of GT is preserved by doubling the G and halving detention time T_d. Through the empirical relationship, revised G is obtained as 350. 62 s^{-1}. When GT is maintained same, then T_d could be reduced exactly by half. So the revised detention time could be 45 seconds. This never compromise with the quality of the treated water, as GT product is maintained same. Hence the quantity of the treated water is exactly doubled. The average power obtained from the impellers is given by Eq. 13

$$P_{ave} = N_p \rho N^3 D^5 \quad (13)$$

Where,
N_p= power number for a given impeller (0.003929),
p = density of liquid (1000 kg/m^3),
N = rotational speed (1200/60)of impeller per second,
D = impeller diameter (m)

$$N_p = 7460/\ 1000 * 20^3 * 0.75^5$$
$$= 0.003929$$

Reynolds number is given by the ratio of inertial forces to viscous forces as given in Eq. 14 below.

$$R = \frac{DV\rho}{\mu} \quad (14)$$

Where,
D is diameter of the flash mixing tank (2m, excluding clearance),
V is the velocity gradient (350.62 s^{-1}) and
ρ is the density of water(1000kg/m^3),
μ is the viscosity (0.0186 kg/m-s) of the raw water when mixed with alum at the temperature of 20’C.

While substituting all the available values, R= 37701075 is obtained which is a dimensionless quantity. From the obtained Reynolds number, it is very clear that the flow is turbulent. However, the performance could be improved if the velocity gradient is still improved. The above calculations are just to show that sufficient turbulence is available in the flash mixer.

When the detention time is 90 s, then the flow rate equals 0.08722 m^3/s. When the plant is operated for 12 hours, the total volume handled by the plant is given by

$$V = 0.08722 \times 60 \times 60 \times 12 = 3767.904\ m^3 = 3.7679\ \text{MLD}$$

With the revised detention time of 45 s, the total volume treated per 12 hours is given by

$$V=3.7679 \times 2 = 7.5358\ \text{MLD}.$$

For every ½ hour interval the treated water accounts to 0.3139 MLD. It is found that 10% of water is wasted in sludge removal while discharging the sludge. Other wastage of water in back wash in sand filter bed has not been considered, since the focus of work is towards sludge removal process. For every 30 minutes interval, 0.03139 MLD of water is wasted.

3.3 Clariflocculator Operations

After the coagulated water is ejected from flash mixer it reaches the Clariflocculator which consists of concentric wells. Inner cylindrical construction performs flocculation and the outer one performs clarification. Here the sludge discharging time is always critical, as it would be added with treated water if not drained at proper intervals. Hence, it is proposed to optimally find the draining instant of sludge using optical conductivity measurement. The optical conductivity measurement needs an excitation source, two electrodes, and associated circuitry.

The conventional scenario is to measure electrical conductivity of the treated water at end of the treatment process (after the water is pumped out from sand filter bed to the storage sumps). While choosing an option of which time series data to acquire, electrical conductivity data is worthless in clarifier. Because, the treatment process is continual and accumulated sludge consists of majority of organic materials and only 0.01% of dissolved metals in the sludge. Hence electrical conductivity data extraction and placing the test electrodes in appropriate place is very challenging. Moreover, such test setup could introduce a small level of electrical coagulation. An issue in electrical coagulation is, the contaminants move upwards against gravity and gets accumulated on the top layer of clarifier, which may be mixed with treated water. Whereas chemical coagulation methods are based on settling of sludge due to gravity. So, it would be offense to place energized electrodes in clarifier.

Hence optical based system is proposed to measure the sludge content in treated water. Usually in present systems, the sludge removal process is purely manual and the removal interval is once in 30 or 60 minutes. If the raw water quality is very poor, then sludge accumulation would be faster and the interval might be reduced to 10 minutes, provided appropriate dosage levels are maintained. This dynamic variation of raw water quality would never allow the sludge discharging interval to be constant. Hence, there should be an automatic system which alarms the operator to discharge the sludge. Hence sludge discharging is done based on the optical conductivity of the water in clarification Meta stage. The optical signals are generated through Chua’s circuit to produce a chaotic voltage. The same is transmitted via high brightness and high divergence Light emitting diodes. After a distance of 5cm the same is collected via, a light depending resistor. The received optical signals are properly filtered and conditioned to obtain electrical signals out of it.

Optical Conductivity Testing In Clarifier

The light transmitter and receiver setup is placed at a height of 1 feet from the bottom of the clarifier. This minimum clearance of 1 feet is maintained to ensure the measurement system is not immersed fully in sludge. As the lighter particles slowly moves down, they act as obstacles to light and hence the voltage obtained from the measurement setup is varied. The system was constructed with a high power light emitting diode with a wavelength of 800nm and powered by 12w electrical power source. The voltage waveforms were generated based on Gaussian attractor, α= 5.9 and β = -0.5, as these values ensure the chaotic behavior of the system. Light depending resistors were used to collect the light propagated through water.

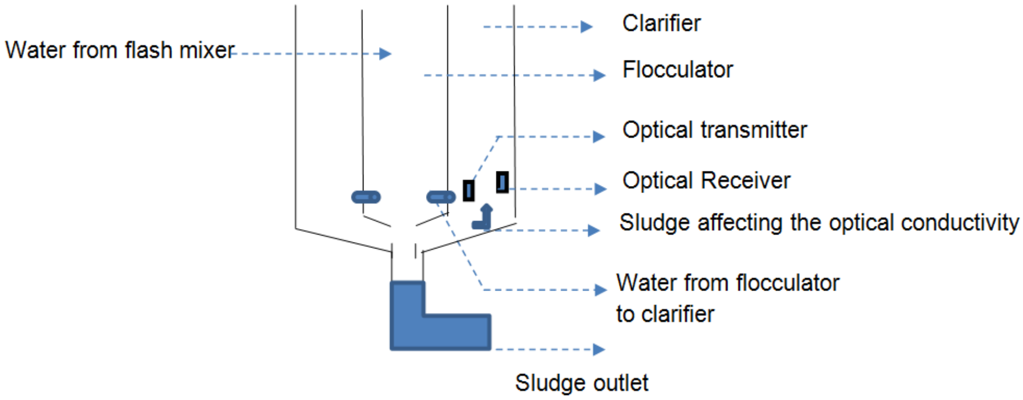

Fig 4: Schematic view of optical conductivity measurement

An array of sensors were used to cover an area of 3x3 inches. The whole setup has been covered with proper insulation and positioned at the bottom of the clarifier, just 0.25 feet higher to bottom most level as shown in Figure 4. As the water is continuously moving at slow speeds, the bottom layer would be highly turbid but still the water is transparent to light and continues to transmit light to LDR array. There could be a question, that why not to use a level sensor to check the accumulation of sludge?. The sludge formed is neither solid nor semi solid, rather it is still a homogenous solution of impurities partially mixed with good water. Hence, stable regions of sludge could not be detected using level sensors. To mention additionally, applying these chaotic metrics would open a new era in water treatment processes.

Chaotic behavior of optical conductivity time series

As discussed earlier, in chaotic flash mixing, a chaotic voltage generator using Chua's circuit is used. In order to obtain a Gaussian behavior of the sludge movement, a Gaussian attractor is utilized to generate the optical signal from LED. When the measurement setup is placed and energized with chaotic voltage generated from Gaussian attractor, optical receiver is expected to receive the same waveform, without any change in the shape or any delay. However amplitude depends on the color and turbidity of the water under treatment. In order to eliminate the high frequency currents due to negligible water turbulence, FFT based analysis is done and all high frequencies are filtered out.

When the sludge enters between the light transmitter and light collector, it produces opaque path to the light. Hence, the output at the light receiver circuit would saturate a maximum DC voltage instead of its actual Gaussian chaotic voltage. The number of samples saturated depends on the percentage of sludge entered into the test setup. The following Table 4 shows the number of samples pulled to saturation based on the sludge entry with respect to the area of the measurement panel. It is evident that, chaotic behavior is lost due to the sludge entry between the optical setup.

Table 4. Time samples modification in simulation

Cases	Sludge entry %	No of samples pulled to maximum DC
1	0	0
2	12.5	25
3	25	50
4	50	100
5	100	200

There exists a variation on KSE density and KSE generality with respect to sludge formation and its upward movement towards optical sensor setup. When the sludge formation reaches its saturation, it is witnessed that, h and hu values reaches zero. This means the system is not in chaotic state. As the overall stability is disturbed, it is time to discharge the sludge, is the ultimate decision obtained through the metrics.

From the Figure 5, seen in x axis, after 50 minutes KSE density has reduced less than 0.2 (green trace), but Mean positive LE is still averaged at 0.25(black trace). But, while in physical observation, the sludge started almost closing the light sensors. Hence, it is inferred that the choice is to use KSE density values rather than Lyapunov exponents alone.

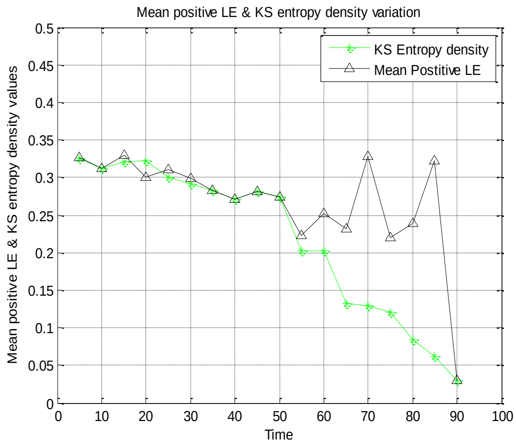

Fig 5: Variation KSE density and LE

Figure 6, 7, and 8 shows the variation of dosage levels when predicted using Feed forward neural network. While observing the samples collected in 12 different time slots, negligible deviations in dosage detections is seen.

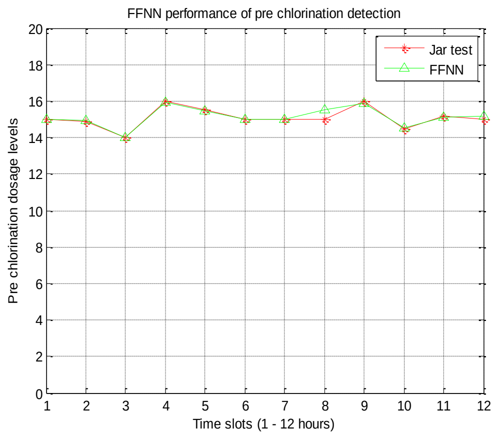

Fig 6: Variation in pre-chlorination dosage

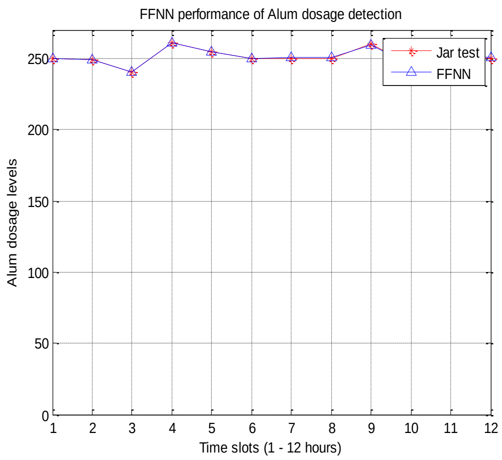

Fig 7: Variation in Alum dosage

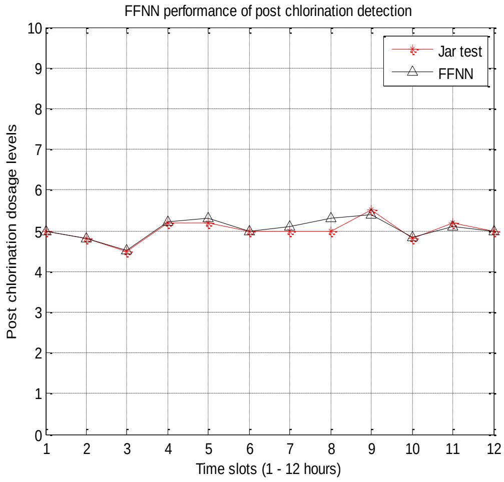

Fig 8: Variation in post chlorination dosage

Our task is to further increase the volume of the water to be treated. This is accomplished by increasing the velocity gradient through additional power supplied in vertical direction. As chaotic behavior is induced in horizontal mixing, the mixing is uniform. This opens a way to reduce the detention time while maintaining the GT product constant. This in turn needs an increased flow rate to pull down the detention time. Hence, total volume handled per 12 hours has been increased. At the same time, Sludge removal timing has been optimized through the metrics of chaotic systems. This limits the wastage of water during every interval of sludge removal. Ultimately, over all dosage needed for the treatment process is predicted using FFNN, which could help the operator to decide on dosage based on the target quality parameters of the treated water.

4. RESULTS AND DISCUSSION

The sludge formation is earlier during monsoons because of mixed silt and clay in the influent. The same is slow when during the summer seasons. Fixing a KSE threshold of 0.05 as obtained from Figure 5, as a sludge discharging instant improves the system performance. Anyhow, this threshold depends on many gain parameters related to optical circuits. However, this method would alarm the operator to open sludge valve at appropriate intervals.

4.1 Water Wastage And Quantity Of Treated Water

The time integral of water wastage when sludge discharge was performed once in 30 minutes lead to a total wastage of 0.75366 MLD for the whole of 12 hour operation, when 0.03139 MLD water is wasted during every sludge discharge. Due to the sludge monitoring process incorporated in our work, the sludge removal is done only when the LE, KSE density, KSE generality parameters trigger the sludge removal process. The following table shows the time interval based on above mentioned metrics. The sludge removal was alarmed during the time intervals (hr) 0.7, 1.4, 2.2, 2.8, 3.5, 4.22, 5, 5.8, 6.5, 7.3, 8, 8.7, 9.5, 10.2,11 and 12. This alarming was done based on the KSE density values. Hence the time integral gives only 0.50224 MLD. A pie plot shown in Figure 9 reveals the fact pictorially.

The total water supplied W_S is given by

$$W_S=W_T-W_W$$

Where $W_T$is the total water treated and $W_W$is the total water wasted in 12 hours treatment process, while considering wastage of water only in sludge removal process. The values are 3.0143 MLD and tabulated as given below for existing and proposed.Since the wastage in water is reduced, it is gained in the amount of treated water for a detention time Td of 90 s. as shown in Figure 10. However, treated water quantity is doubled by reducing T_d to 45 s.

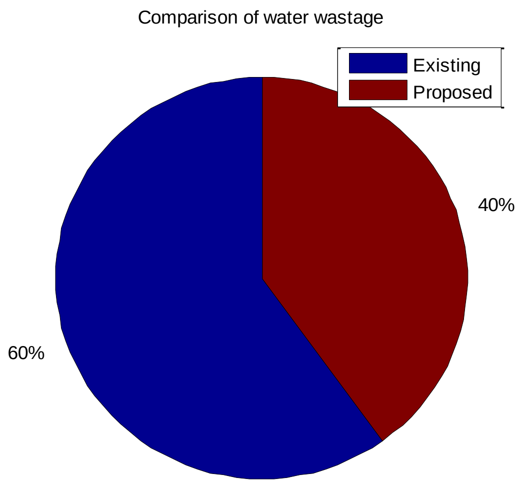

Fig 9: Water wastage

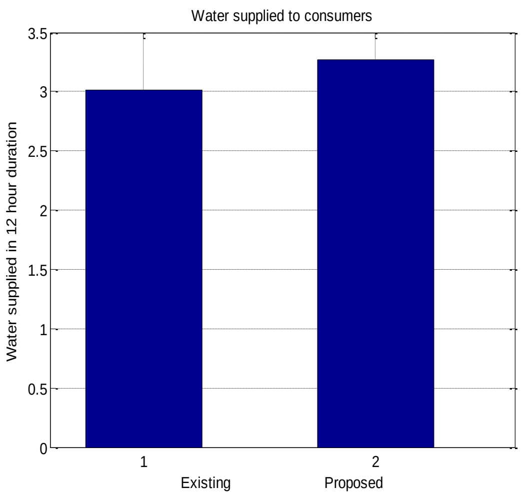

Fig 10: Water supplied

4.2 Dosage Detection and Water Quality Metrics

In dosage detection, the target values such as Pre chlorination, Alum and Post chlorination are the neurons of the output layer. Whereas, influent water quality parameters are the input layer neurons. Hence, FFNN would evaluate the total dosage required to obtain the targeted quality of the water. In order to evaluate the performance of the neural based dosage predictor, Root Mean square error (RMSE) between the dosage detected from FFNN and jar test is calculated as follows.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}[x_i - y_i]^2}{n}}$$

where, n represents the number of elements, x_i refers values predicted in jar test and y_i refers to the values predicted by FFNN. Table 6 shows the obtained water quality parameters of treated water before and after optimization.

. **Table 5. RMSE comparison**

Prediction method	**Existing NN**	**FFNN after Proper sludge discharge**
RMSE (Average of all doses)	0.874	0.5241

Table 6. Water quality parameters

Parameters	Units	Raw water	Treated water	After optimization
Turbidity	NTU	15.1	7.2	6.5
Total dissolved solids	Mg/l	788	772	760
Electrical conductivity	Micro Mhos/cm	1126	1103	1052
Total Hardness	Mg/l	210	160	140
Calcium(Ca)	Mg/l	52	48	43
Free ammonia (as NH_3)	Mg/l	16.52	16.30	14.57
Chloride (Cl)	Mg/l	210	200	190

5. CONCLUSION

In order to meet the strict regulations followed in water treatment process, mixing efficiency in flash mixer and further stability issues on sludge removal has been proposed in this research. Though this research is not focused towards complete modeling of the plant, a conventional method of dosage detection using FFNN has been used, where dosage levels are determined through a user friendly menu. Effective chaotic metrics based mixing and sludge removal has revealed that more volume of raw water is treated, at least 5MLD more per day. But as per the present plant setup, total volume of the treated water has been increased from 3.7679 MLD to 7.5358 MLD. But, this is achieved without compromising any quality parameter as existing in present case. The following recommendations are put forth to be followed in Kelaverapally water treatment plant.

- Water samples to be gathered once in every hour and dosage values to be obtained through our user friendly menu.
- To watch the attainment of stability in Clariflocculator through the computer calculations of chaotic parameters, then to start discharging the sludge, and control the flow rate input to the Clariflocculator.
- The sludge removal process to be done in a disciplined way, based on the alarms triggered by the optical sensor setup mounted at the bottom layer of the clarifier.
- Periodic cleaning of the optical setup is very essential in order to obtain true time series from the optical receiver.

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