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Cascade aeration: a promising post treatment of effluent from UASB reactor

Rinku Walia[1], Pradeep Kumar[2], Amit Handa[3] and Indu Mehrotra[4]

[1,3]IKGPTU, Jalandhar, India
[2,4]Department of Civil Engg., I.I.T. Roorkee, Roorkee 247 667, India

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ABSTRACT

Effluents from (i) bench scale 56 L upflow anaerobic sludge blanket (UASB) reactor and (ii) four UASB based sewage treatment plants (STPs) of capacities ranging from 27 to 70 ML/d stored in containers were pumped to flow over inclined plane at a rate of 200 mL/min**.** The objective of the project is to evaluate the performance of inclined plane and to find correlation between oxidation reduction potential (ORP), dissolved oxygen (DO), chemical oxygen demand (COD) and biochemical oxygen demand (BOD). The DO after fall was dependent on initial COD whereas increase in ORP was dependent on DO increase after fall. The cascade was designed for increase in DO to 4-5 mg/L. However in N-34 and G-70 DO increase was 0.5-2 mg/L. The increase in DO has been shown to be dependent on wastewater characteristics. Oxygen transfer efficiency was found to be independent of DO influent. But it showed positive correlation with DO after fall. E20 of 50% was attained when DO after fall was 5.7 mg/L (63 % of DOs). Overall reduction of COD ranged between 20-40 %. The decay rate of COD and “ ORP ranged between 0.1-0.2 h^{-1} and 0.6-1.2 h^{-1} respectively. The empirical equation of SW2 predicted the temporal variation of fraction of COD in four STPs.

***Key words**: Inclined plane, Anaerobic treatment, Chemical oxygen demand, Wastewater, Oxidation reduction potential*

Introduction

In the developing countries there has been shift from treating sewage by the conventional aerobic processes to anaerobic processes Advantages of high rate anaerobic systems such as up-flow anaerobic sludge blanket reactor (UASB) are low cost, simple in operation, biogas recovery, low energy consumption, and low production of sludge (van Haandel and Lettinga, 1994).

A vast variety of post treatment options such as activated sludge process, Trickling filter, down hanging flow system and natural treatment processes have been explored. Polishing ponds are gaining importance in developing countries at several STPs in India, Colombia and Brazil as post-treatment option because of their simplicity in design and operation (von Sperling and Mascarenhas, 2005; M von Sperling *et al.*, 2001; Chernicharo, 2006; Khan *et al.*, 2011a). In India generally post treatment in the form of non algal pond known as polishing ponds (PPs) is provided. However the detention of effluent for 1 day in polishing ponds is not compatible with discharge standards (Khan *et al.*, 2011b). Aeration is process by which the area of contact between water and air is increased. Aeration of liquid is achieved by diffuser, surface aeration and gravity aerators. Diffusers aeration is influenced by clogging problem while the surface aerator cost is more because of power consumption. While considering

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***Corresponding author's email:** indumfce@iitr.ernet.in[1]Corresponding author's email: waliarinks@gmail.com
[1,3]Assistant Professor, [2, 4] Professor

the power factor and clogging problem it was decided to go for the third stage where DO can be enhanced with simple fall. Cascade or rough surface provides a turbulent liquid-air interface for aeration. Various researchers (Barret *et al.*, 1960; Avery and Novak 1978; Nakasone, 1987 and Gulliver *et al.*, 1990) have developed model equations for oxygen transfer at stepped cascades. The objective of the present study is (a) to evaluate the performance of inclined plane and the kinetics of change in COD, DO & ORP and their correlation (b) to compare observed values with predicted values and (c) to assess the interrelation of ORP, COD & DO in semi-continuous inclined plane aeration.

Experimental Design and Analytical Methods

A cascade type aeration device was fabricated using pebbles for providing rough surface. DO after fall has been shown to be a function of the height of the cascade (Baylar and Bagatur, 2000). The cascade was designed to increase the DO by 4-5 (~ 50% DOs) mg/L. The cascade height was determined by equation developed by Barret (1960)

$$H = \frac{R-1}{0.361ab(1+0.046T)} \quad .. (1)$$

$$R = \text{Deficit ratio} = \frac{DOs - DOo}{DOs - DO} \quad .. (1.1)$$

DOs = 9.46 mg/L at temp=18°C

DOo= Dissolved oxygen concentration of the influent to be aerated H” 0, mg/L

DO = Dissolved-oxygen level after fall or post-aeration, DO ~ 4-5 mg/L

a = constant related to water quality parameter equal to 0.8 for sewage effluents

b = coefficient equal to1 for weir with free fall

T = Water temperature in °C and

H= Height through which water falls in metre.

Height of the cascade from Eq.1 worked out to be 1.5 metre. A 1.5 metre long channel of cast iron having 10 cm width was used as cascade aerator. The surface of the channel was made rough by pebbles (0.25-0.75cm).

In batch aeration effluents from four STPs (S-38, G-70, G-56 & N-34) and bench scale reactor stored in containers were pumped to flow over inclined plane at a rate of 200 mL/min. Source of these STP's are given in Table 1. A bench-scale 56 L UASB reactor, housed in a temperature-controlled chamber maintained at 30 ± 2° C, was fed with synthetic wastewater to procure effluent continuously under controlled conditions. The reactor was charged with the sludge from 38 ML/d STP at Saharanpur (S-38). During first 30 days, the reactor was fed with soluble wastewater consisting of sucrose only. Later the reactor was fed with the complex synthetic wastewater (SW) consisting of 40% cellulose, and 60% sucrose and peptone. Composition of the buffer and trace elements added in the feed were as per (Prashant, 2003). Hydraulic retention time (HRT) was reduced stepwise from 12 hour to 6 hour. Samples were drawn for analysis after reactor attained pseudo steady-state (PSS).

Aerated sample after fall were stored for 2h in a 40x30x12.5 cm container. Samples were analyzed for ORP, pH, COD, BOD and NH_3 before and after fall as per Standard Method (APHA, 1995). Also, samples from the storage tank were drawn at regular intervals and analyzed for all the parameters. ORP was measured by Toshicon ORP meter. The electrode was standardized daily by Zobell's solution and the reading was converted to standard hydrogen electrode. DO was analyzed with Aqualytic OX 24 DO meter.

Aeration: Batch Process

Cascade or rough surface provides a turbulent liquid-air interface for aeration. The effluent samples

Table 1. Sources, sample description and feed composition

Sample	UASB	Total COD (CODt) (mg/L)
SW1	224 L/d + (Sucrose)	475 – 550
SW2	224 L/d + (Cellulose, Sucrose and peptone)	525 – 600
S-38	38 ML/d Saharanpur*	202 – 428
N-34	34 ML/d Noida*	330 – 490
N-27	27 ML/d Noida*	278 – 484
G-70	70 ML/d Ghaziabad*	384 – 525

+56 L bench scale UASB reactor at HRT of 6 h

*Location: Between 28° 38¢ N 77° 12¢ E and 29° 58¢ N 77 ° 23¢ E.

were allowed to flow over a rough inclined surface and samples were monitored for ORP, DO and COD. Observations recorded as initial, immediately after fall (AF) and at different time intervals during storage are shown through Fig. 1-4.

Performance of the Cascade: The change in ORP, COD and DO after fall from inclined plane are presented in Table 1. Effluents from N-34 and G-70 have higher COD (~170-200 mg/L) as compared to S-38, G-56 and SW (~90-120 mg/L). The cascade was designed for increase in DO of 4-5 mg/L. However in N-34 and G-70 DO increase was 0.5-2 mg/L indicating that the DO increase is also dependent on wastewater characteristics. Khalifa et al. (2006) also concluded that increase in DO level in wastewater appears to be less than in clean water upon falling from the same height. Kahil and Seif (2014) also observed that organic matter influenced DO after fall. The change in DO during fall appears to depend on initial COD as well as nature of COD. Presence of surfactants may also adversely affect oxygen uptake (Baylar and Bagatur, 2000). The DO of the G-56, S-38 and SW increased to 4-6 mg/L whereas the DO of other two effluents increased to 0.5-2.7 mg/L. The increase in ORP seemed to depend on DO after fall. The correlation is given in Fig. **1.** The increase in ORP ranged from 105 to120 mV for an increase in DO varying from 0.5-2 mg/L for N-34 and G-70 where as for other effluents the increase was in the range of 217-250 mV. The physical process described by this correlation is as follows. Reducing ORP (-ve value) ranging from -84 to -146 mV increased to 92.5 mV before a measurable change in DO is noticeable. Thereafter, an increase of 24 mV brought about an increase of 1mg/L in DO. Immediate oxygen demand (IOD) is initially satisfied up to an ORP of 92 mV. The half cell ORP, however, is not so sensitive to change in DO i.e DO reduction from 9 to 4.5 mg/L changes ORP by 4-5 mV. The performance of cascade aerator thus depends on the performance of UASB reactor. The oxygen uptake leading to increased DO would be facilitated in the effluent of low COD from UASB reactor.

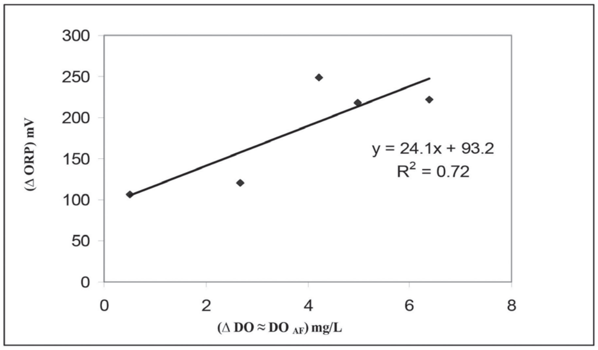

Fig. 1. Cascade Aeration: change in ORP with change in DO

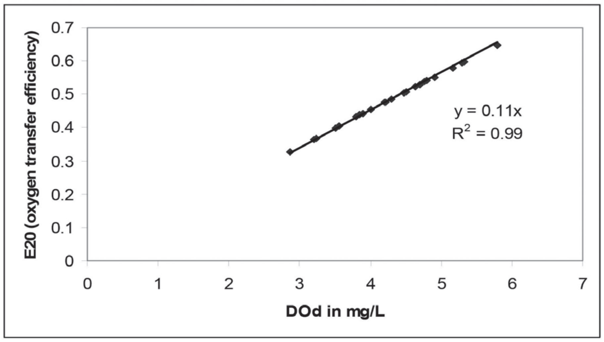

Fig. 2. Variation of oxygen transfer efficiency with DO after fall

The oxygen transfer efficiency for SW2 has been modeled by using Eq. 2a. The oxygen transfer efficiency (aeration efficiency), E, is defined as (Gameson, 1957):

$$E = \frac{DOd - DOu}{DOs - DOu} = 1 - \frac{1}{r} \quad \text{.. (2a)}$$

Where

u and d = subscripts indicating upstream and downstream locations, respectively

r = oxygen deficit ratio [(DOs-DOu) / (DOs – DOd)].

The DOu (before fall) is nearly zero for all the ef-

Table 1. Performance of cascade

	ORPi	ΔORP	ΔORP/ORPi	CODi	ΔCOD	ΔCOD/CODi	$\Delta DO \approx DO_{AF}$
N-34	-146.0	107.0	-0.7	171.0	14.4	0.15	0.5
G-56	-84.0	218.0	-2.59	107.0	7.44	0.07	4.97
G-70	-100.0	121.0	-1.2	197	12.8	0.06	2.68
S-38	-93.3	222.0	-2.3	87	14.4	0.16	6.39
SW2	-137.0	249.0	-1.8	117.0	23.3	0.19	4.22

fluents. Therefore 2(a) can be rewritten as 2(b)

$$E = \frac{DOd}{DOs} \quad ..\ (2b)$$

i.e E depends on DO after fall i.e slope of the line gives 1/DOs. To provide a uniform basis for comparison of measurement results, the aeration efficiency is often normalized to a 20 °C standard. Gulliver *et al.* (1990) proposed the Eq. 3 to describe the influence of temperature

$$1\text{-}E20 = (1 - E)^{1/f} \quad (3)$$ where

E is the transfer efficiency at actual water temperature (T);

E20 the transfer efficiency at 20 °C and

f, the exponent is a function of temperature and is described by

$$f = 1.0 + 2.1 \times 10^{-2}\,(T\text{-}20) + 8.26 \times 10^{-5}\,(T\text{-}20)^2 \quad ..(4)$$

The data from aeration of SW has been analyzed to evaluate oxygen absorption at 20°C (E20). Oxygen transfer efficiency shows a positive correlation with DO after fall (Fig. 2). From empirical relation E20 was found to be 50% when DO after fall is 5.7 mg/L. This is in accordance with the design parameters considered. The line of the slope is 0.11 which is exactly equal to 1/Cs (1/9.02). Baylar and Bagatur (2000) investigated the aeration performance of different shaped weirs over a range of flow between 1 and 4 L/s with drop heights from 0.15-0.9 m. They found an increase in aeration efficiency with increase in drop height in all cases. The predictive equations that have been developed by various researchers for oxygen transfer at hydraulic structures generally use physical parameters of the structure or flow conditions, i.e., drop height, depth of tailwater, discharge, Frouds number etc. The pilot scale studies are required for generating these.

Temporal Variation of ORP, DO and COD: The temporal variation of ORP of effluents S-38, G-70, G-56, N-34 and SW2 are presented in Fig**. 3**. The increased ORP after fall subsequently reduced on storage. ORP of the effluent ranged from -84 to -145 mV. After fall from inclined plane ORP increased to 112, 129 mV and 133 mV for SW2, S-38 and G-56 respectively where as for N-34 and G-70 it remained in the anaerobic zone, i.e. -39 and 20 mV. During storage the temporal trend in ORP of G-56, S-38 and SW2 is nearly the same and is different from that of N-34 and G-70.

DO profile presented as histograms is shown in Fig. 4. DO of the effluent increased significantly (except N-34) within a short period of contact (<1 min) with rough inclined surface. An increase in DO of this level would normally occur over several kilometers in a river. DO increase after fall ranged from 4.2-6 mg/L in case of S-38, SW2 and G-56 where as for N-34 and G-70 it was 0.5 and 2.7 mg/L. During cascade aeration the oxygen transferred to N-34 and G-70 was low. Variation in change in ORP is due to difference in oxygen uptake by the effluent during aeration rather than COD reduction (Fig. 1 and Table 1).

During storage DO decreased gradually as it was utilized for the oxidation of residuals. After 120 minutes of detention the DO of N-34 & G-70 decreased to ~ 0.1 mg/L. However, DO present in G-56 and S-38 effluents were 2 and 5 mg/L respectively. Both ORP and DO decreased during storage. The decrease in ORP of S-38 was less as compared to other effluents. This may be due to the difference in decrease in COD as well as COD of the effluents. COD of S-38 is found to be minimum of all the samples at every stage. Unlike ORP and DO, COD decreased at all stages, i.e. ORP and DO increased after fall and then decreased whereas COD continued to decrease. However, the fraction of COD (COD/COD initial) of different effluents showed a

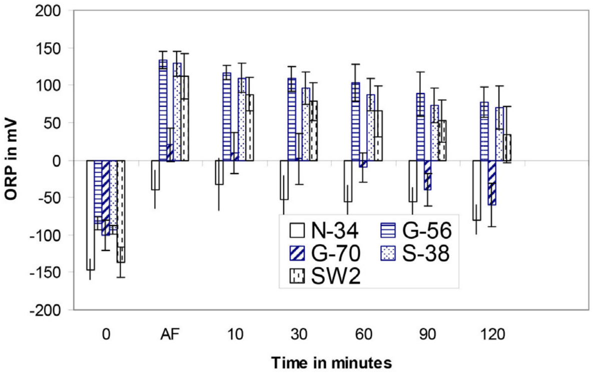

Fig. 3. Inclined Plane Aeration: Temporal Variation of ORP

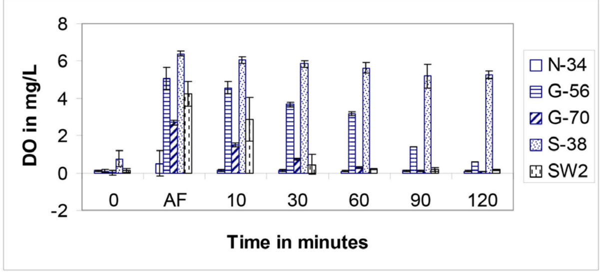

Fig. 4. Inclined Plane Aeration: Temporal Variation of DO

narrow range of temporal variation (Fig. 5.0). Overall COD reduction, i.e. during fall and storage ranged from 20-40%. The COD reduction of G-70 & N-34 was 20-25% where as COD of the other samples reduced by 35-40%.

The reduced level of COD reduction (%) of G-56 and N-34 may be due to low availability of oxygen (DO) and/or nature of organics. The low DO or oxygen absorption is probably due to nature of wastewater or presence of surfactants. "Surface active agents in particular appear to modify the process by reducing surface tension, forming diffusion –inhibiting films at the air-water interface and affecting the hydrodynamic characteristics of the flow (Baylar and Bagatur, 2000)".

In another approach empirical equations have been developed using data obtained for SW. The values for the effluents from field plants have been predicted from these and compared with the observed values. The temporal variation in COD and DO have been described by logarithmic decrease (Eq. 5.1-5.2) where as in case of ORP, the change in ORP (ΔORP) has been modeled (Eq.5.3).

$$\ln \frac{COD}{COD_i} = -k_c t \qquad .. (5.1)$$

$$\ln \frac{DO}{DO_{AF}} = -k_a t \qquad .. (5.2)$$

$$\Delta ORP\text{-}_{AF} = \Delta ORPi\ e^{\,kot} \qquad .. (5.3)$$

where

CODi is the initial concentration of COD (mg/L)

ORP_{AF} and DO_{AF} are the concentration after fall (mV and mg/L)

k_c, k_a and ko are the rate constants of COD, DO and ΔORP respectively in hr^{-1}

The empirical correlations according to Eq. 5.30 describing kinetics of increase in ORP (ΔORP) are given in Table 2.0. ΔORPi is the initial decrease (i.e 10 min AF). The initial change in ORP as well as well as exponential constants given in the Table (2) broadly fall in two categories. The ko for G-56, S-38 and SW is ~ 0.01/min (0.6/h). For G-70 and N-34 the ko is ~ 0.02/min (1.2/h). The initial decrease in ORP after 10 min for S-38, G-56 and SW is between 17-23 mV, whereas for the other samples it is 4-10 mV. The kinetics of the process i.e. DO uptake and COD reduction during fall and subsequent reduction in DO and COD during storage appear to be sensitive to the nature of contaminants as well as strength of the wastewater.

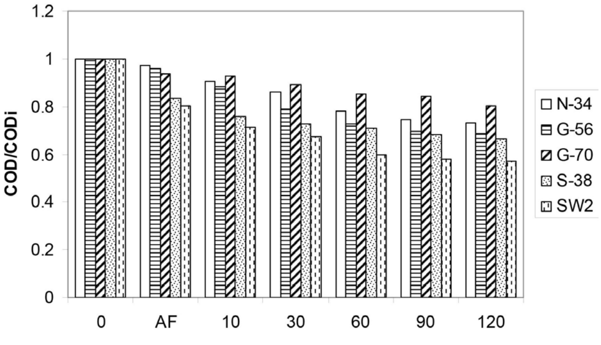

Fig. 5. Inclined Plane Aeration: Temporal Variation of Fraction of COD

Table 3 gives the value of constants ko, k_a and k_c. The rate constant for COD reduction (k_c) of G-70 and N-34 is nearly the same. The numerical values of these are less than that of SW, which in turn is less than the k_c of G-56 and SW2. The residuals in N-34 and G-70 after UASB treatment are more resistant to air oxidation than those present in other effluents. The nature of organics present probably influenced the oxygen uptake and increase in ORP during fall through the cascade. The exponential decrease in DO during storage has not been modeled for samples having DO less than 2 mg/L. The DO after fall of N-34 was 0.5 mg/L and DO of G-70 and SW2 reduced to 0.5-0.7 mg/L after 30 min. of storage. The probability of error is high in measuring such low values of DO. The k_a values of S-38 and G-56 are in accordance with the corresponding k_c values.

Table 3. Rate Constants for ORP, COD and DO

Sample	ko hr^{-1}	k_a hr^{-1}	k_c hr^{-1}
S-38	0.6 (0.88)	0.096 (0.91)	0.14 (0.8)
G-56	0.6 (0.98)	0.48 (0.89)	0.23 (0.85)
G-70	1.2 (0.98)	*	0.09 (0.88)
N-34	1.2 (0.75)	*	0.15 (0.78)
SW2	0.6 (0.98)	*	0.22(0.80)

Values in parentheses represent the R^2 value

* Due to very low DO AF or at time t, these have not been modeled

COD-DO-ORP Correlation : All the samples after fall exhibit a narrow range of variation (decrease) in COD and DO with reference to initial COD and DO_{AF} (i.e. COD/CODi & DO/DO_{AF}). Therefore the correlations of these with ORP have been attempted. The fractional decrease i.e DO/DO_{AF} varied linearly with ORP (Fig. 6). The fractional decrease in COD (COD/CODi) presented in Fig. 7 showed two different correlations, one for G-70 and N-34 and the other one for G-56, S-38 and SW2 due to difference in the nature and COD of the samples. Generally ORP increases with decrease in COD, in these cases however, ORP decreases linearly with fractional decrease in COD. A good linear empirical correlation exists between COD/CODi and ORP. A decrease in ~ 66% DO reduces ORP from 125 to zero mV (Fig. 6) and around 60% reduction in COD also reduces ORP to zero. However, the later one does not explain the physical process. The change in ORP appears to be more sensitive to change in DO. Two important observations emerged from this are (i) An ORP of ~ 125 mV after fall corresponds to a DO of 4-5 mg/L and (ii) Change in ORP of ~ 100 & 220 mV corresponds to an initial COD of ~ 200 & 100 mg/L.

DO/DO$_{AF}$

Model Development from Aeration of SW

To have wider scope, empirical equation from the data of the aeration of the effluent from bench scale UASB reactor has been developed. The standard errors for the respective predictions are given in Table 4.0. The standard error (SE) compared measured and predicted values as follows:

$$SE = \sqrt{\frac{\sum (E_m - E_p)^2}{n}}$$

Where Em and Ep are measured and predicted values respectively; and n = number of comparisons. The effluents from STPs having minimum standard error provide the best estimate for empirical equation. Fraction of COD of the effluent from STPs can be modeled by the SW2. One category comprising of S-38 and G-70 can be modeled by SW where as N-34 and G-70 shows variation. Standard error of 0.3 was found for N-34 and G-70 and for other two the S.E was 0.1.

The fraction of COD can be modeled by equation developed for SW. ORP-COD correlation developed for SW however, describes G-56 & S-38, i.e. wastewater of similar nature.

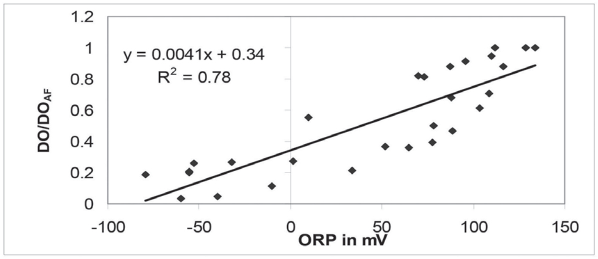

Fig. 6. Inclined Plane Aeration: Variation of DO/DOi with ORP

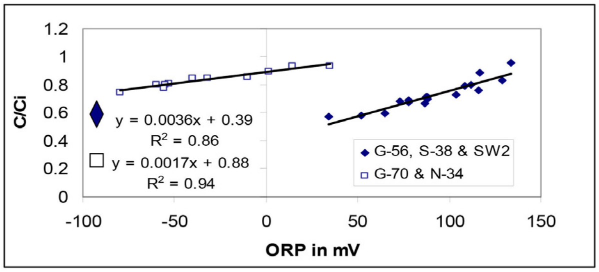

Fig. 7. Inclined Plane Aeration: Variation of COD fraction with ORP

Conclusion

The cascade aeration though promises encouraging results however the stirring during storage is recommended. Further improvements in the efficiency of cascade are expected by stirring during storage and changing the height of cascade. Effluents from N-34 and G-70 have higher COD (~170-200 mg/L) as compared to S-38, G-56 and SW (~90-120 mg/L). The increase in DO of N-34 and G-70 was 0.5-2 mg/L indicating that the DO increase is also dependent on wastewater characteristics. Overall reduction of COD ranged between 20-40 %. The decay rate of COD and " ORP ranged between 0.1-0.2 h^{-1} and 0.6-1.2 h^{-1} respectively. The empirical equation of SW predicted the temporal variation of fraction of COD in four STPs.

Table 4. Standard Error of Predicted equation for Four STPs

Equation	Standard Error			
	S-38	G-56	G-70	N-34
$C/Ci = 0.91\ e^{-0.0033\ xtime}$	0.07	0.05	0.11	0.07
C/Ci = 0.002xORP + 0.57	0.13	0.1	0.3	0.39

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