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ANALYSIS OF HYDRAULIC PERFORMANCE OF A FACULTATIVE WASTE STABILISATION POND TREATING BREWERY EFFLUENT USING TRACER STUDY - THE CASE OF META ABO BREWERY WASTE STABILISATION PONDS, SEBETA, ETHIOPIA

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ABSTRACT

The hydraulic performance of secondary facultative pond, in a full-scale waste stabilization pond (WSP) system, located in a tropical climate region, Sebeta, Ethiopia, (8° 54.68' N; 38° 55.72' E) was investigated using a stimulus-response tracer technique during the coldest and driest months of the year (December, 2011 – February, 2012) in order to avoid the impact of thermal stratification and to minimize the influence of rainfall on the variability of wastewater flow rate. The tracer, Rhodamine WT dye, was mixed with pond water and injected at the inlet channel of the pond to ensure complete mixing and simulate the actual flow. A lightweight handheld Aquafluor® Fluorometer with a minimum detection limit of 0.40 ppb was used to measure the effluent fluorescent dye concentration at the outlet the pond at sampling frequency of two hours when the tracer dye is expected to pass through the sampling point and every four hours during those times when the tracer is not expected to go through the point. The outlet dye concentration versus time obtained was used to estimate the mean hydraulic retention time, hydraulic performance, dispersion number, zones of stagnation (dead spaces) and the extent of short-circuiting inside the pond. Analysis of result obtained from tracer study indicates that the pond showed poor hydraulic efficiency with λ equal to 0.47, suffering from severe short circuiting as indicated by much shorter average detention time (7.57days) than nominal retention time (16.1 days), large dead zones as indicated by long tail of RTD curve.

INTRODUCTION

Waste stabilization ponds (WSPs) are one of the most ancient wastewater treatment methods known to humans. They have been used as a natural process to treat wastewater for over

3,000 years. WSPs are shallow man made basins constructed through excavation and compaction of earth to create reservoirs enclosed by earth embankments in which organic matter is processed entirely by natural processes. This wastewater treatment method generally requires less energy than other treatment systems and has lower operation and maintenance costs (Hamzeh and Ponce, 2007).

WSPs are used to treat a variety of wastewaters, ranging from domestic wastewater to complex industrial effluents as well as combination of both provided that the wastewater is able to be treated biologically and they function under a wide range of climatic conditions, from tropical to arctic (Shilton and Harrison, 2003). WSPs are the most popular wastewater treatment method in developing countries where sufficient land is normally available and where the temperature is the most favorable for their operation (Madera et al., 2002).

The hydraulic performance of WSP can be analyzed by studying water flow patterns or hydraulic residence time distributions (RTDs) obtained through tracer study. In such study an impulse of an inert substance is introduced at the inlet and subsequently measured at the outlet. After introducing a tracer slug at the inlet of the WSP, the outlet is monitored for tracer concentration and a residence time distribution function (RTD) can be obtained. Thus analysis of hydraulic performance requires the use of hydraulic indices, extracted from RTDs to describe and quantify the hydraulic efficiency (Wahl et al., 2010).

Two basic hydraulic factors influence the treatment performance of a WSP, namely the hydraulic loading rate (HLR) and hydraulic retention time (HRT). The nominal (theoretical) HRT, t_n is defined as the design volume divided by the design flow rate. However, the real HRT, called mean HRT, t_m can be determined from tracer studies. It is the average time that a tracer particle spends in the water system which is described as the centroid of the RTD (Persson, 2005).

Another fundamental expression is the variance, σ^2, which is a measure of the spread of the RTD. A plug flow condition will induce a RTD with a variance equaling 0 (i.e., no dispersion other than the advection).

In WSP, the quality of treated effluent is critically affected by the hydraulic performance. Particularly hydraulic efficiency has been identified as a fundamental factor controlling the performance of WSP (Agunwamba 2006). According to Persson, Somes and Wong (1999) the hydraulic efficiency of WSP can be thought of as a measure of how effective the pond is at maintaining plug flow.

MATERIALS AND METHODS

Description of the study area

The study was conducted from December, 2011 – February, 2012 in Meta Abo Brewery, Sebeta Ethiopia. Meta Abo Brewery is one of the currently existing eight breweries in Ethiopian brewing industry. It is located in the town of Sebeta, 27 kilometers from the capital, Addis Ababa to the South West, in Oromia region. Geographically, the company is located at an average altitude of 2182 meters above sea level to the south of mount Mogle and at the coordinates of 8° 54.68' North latitude and 38° 55.72' East longitude.

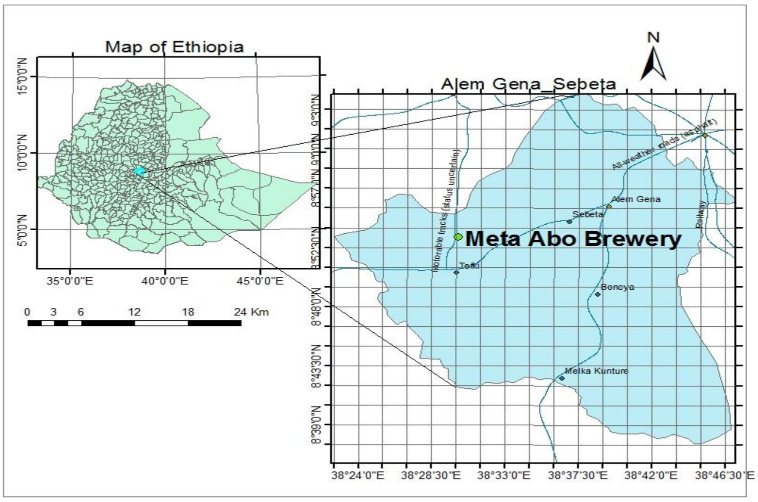

Figure 1. Map of the study area and location of Meta Abo Brewery
(Map source: ENMA, 2012)

The coordinates of the study area were fixed using Global Positioning System Unit (GPSMAP76, Garmin OLATHE®, KS, USA 2009). The map of the study area was developed using ArcGIS 9.1 software.

The study area is characterized by biannual rainy seasons: summer rainy season which occurs between mid June and mid September is responsible for 70% of the annual average rainfall and spring rainy season which covers the period from February to April. The remaining months of the year are generally characterized by having little or no rainfall. The maximum and minimum annual temperature varies from 9 ^{0}C to 30 ^{0}C (ENMA, 2012).

Figure 2. Partial view of facultative pond at Meta Abo Brewery wastewater treatment system

Meta Abo Brewery is the only brewery industry in the country which gets water from a big reserve of soft spring water (locally known as Holy Water of St. Abo). The spring water meets the international brew standard to be used without any form of treatment.

Experimental plan and Methodology

The hydraulic behavior of wastewater stabilization ponds owned by Meta Abo brewery Private Company was investigated using a stimulus-response tracer technique. The study focused on the facultative pond where a full tracer experiment has been performed. A tracer study was conducted during the coldest and driest months of the year to avoid the impact of thermal stratification and minimize the influence of rainfall on the variability of inflow wastewater. The tracer, Rhodamine WT, which is considered non biodegradable and non absorptive in solids was mixed with pond water and added as a pulse in the channel upstream at the inlet of the pond to ensure complete mixing and to simulate the actual flow. The tracer was selected to determine the hydraulic patterns and hydraulic retention time of the pond due its low detection limits, zero natural background and easy operation (Yanez, 1992).

The fluorescence concentration in pond effluent was measured using an Aquafluor® Fluorometer, a lightweight handheld instrument for fluorescence and turbidity measurements in-situ. The measuring device has a minimum detection limit of 0.40 ppb (part per billion).

Water samples were collected using an ISCO Automatic Sampler 6700s. This sampler is programmable with the capacity of holding 24 bottles. Since the reading obtained from a fluorometer is sensitive to temperature all the analysis were made under a controlled temperature in the laboratory by ensuring that the samples are given time to equalize to this temperature. Thus the samples were analyzed at the same temperature using a thermal bath. The influence of natural fluorescence of algal biomass was controlled by measuring the background fluorescence concentration during several hours before the start of the study along with the sampling of other physicho-chemical parameters (Valero and Mara, 2009).

Sampling frequency was every two hours when the tracer dye is expected to pass through the sampling point and every four hours during those times when the tracer is not expected to go through the sampling point. A sampling point was set up at the outlet of the facultative pond. The instant of the addition of tracer was taken as time zero ($t = 0$) and the concentration of tracer (Rhodamine WT) in the effluent was monitored continuously at the outlet of the pond at equal time intervals until approximately all the tracer passed the outlet point using handheld Aquafluor® Fluorometer. Each sample was about 20mL and sampling was run about 21 days long during the coldest and driest months of the year. Enough dye was placed into the inlet zone of the pond so that the water there had a concentration of 700 mg active dye/L. The quantity of tracer required for the tracer study was chosen based the cost, lowest concentrations that can accurately be measured at the outlet in the effluent and availability in the market. By assuming that the tracer added to the pond becomes fully mixed, the amount of tracer need to be added to the pond volume was calculated to ensure the effluent concentration would be well within the range that can be accurately measured by the analytical instrument.

According to the manufacturer, the instrument Fluorometer needs to be set for an excitation wavelength of 540 nm and an emission wavelength of 585nm. Wastewater without tracer dye was used as the blank sample that the spectrophotometer compares the samples to the change in absorbance to the concentration in those samples that had tracer dye in them.

Based on Beer's Law which states that if absorbance values are below 1.00 a better linear relationship exists between absorbance and concentration so that decision was made that 540 nm was the best wavelength because at 540nm the more samples with absorbances below 1.00 were found so that a better calibration relationship could be obtained at this wavelength. Thus all samples and calibration sets have been analyzed at this wavelength. This has given significant linear relationships between the concentration of the dye in the samples and the absorbance. Initially the calibrations were made at the beginning of the experiment but when replicating the experiment it was found that it is better to calibrate each time the samples retrieved from the ISCO6700s samplers. In order to increase the significance of the linear relationship between absorbance and concentration, the calibrations were divided into sets of dilutions of one tenth, tenth, hundredth and thousandth.

Determining initial dye concentrations required

In order to accurately measure with the flourometer the initial dye concentration was calculated. Based on the calibrations made it was known that at 700mg active dye/L, the absorbances were approximately constant (3.0 almost every time). So 700 mg active dye/L was decided to be the most acceptable dye concentration for the trace study. Thus it required about 3L of dye to bring the inlet target dye concentration.

Due to change in the characteristics of wastewater it is very important to keep the calibration update. Every time samples were retrieved from the sampler, another liter of wastewater was taken as a blank sample for calibration and quality control. A 20ml sample was picked up from each sampler set and 3ml were taken to be spiked with enough dye to bring a 3ml volume without any dye in it to a 5mg active dye/L. Following each sample analysis, the spiked sample's absorbance was compared to the appropriate absorbance. If there is difference of more than 5% between the two, calibrations was done again with the fresh wastewater blank and the samples analyzed once again.

RESUTS AND DISCUSSION

Hydraulic Retention Time analysis

The trapezoidal rule was used to estimate the mean hydraulic retention time, which is the centroid under the effluent tracer concentration versus time curve. According to this rule the sum of the product of effluent tracer concentration and time, divided by the sum of the effluent tracer concentrations should estimate the average hydraulic retention time, $\bar{\mu}$. The data obtained from the experimental run at the outlet of dye concentration is presented in table 1a through table 1b. This table is used to compile the graph indicated in figure 3. The resulting time distribution functions were used to estimate the mean hydraulic residence time (HRT), hydraulic efficiency, hydraulic performance, dispersion number, zones of stagnation (dead spaces) and the extent of short-circuiting inside the ponds.

Table 1a. Tracer concentrations at the outlet of the facultative pond studied

Sample #	Conc. (mg/L)	Time (Hrs.)	Sample #	Conc. (mg/L)	Time (Hrs.)	Sample #	Conc. (mg/L)	Time (Hrs.)
1	0	0	**28**	6.40	108	**55**	2.8	202
2	0	4	**29**	4.60	112	**56**	1.90	204
3	0	8	**30**	7.10	116	**57**	0.40	206
4	0	12	**31**	6.50	120	**58**	0.20	208
5	0	16	**32**	6.30	124	**59**	0.30	210
6	0	20	**33**	3.20	128	**60**	6.20	212
7	0	24	**34**	2.40	132	**61**	3.10	214
8	0	28	**35**	4.80	136	**62**	0.90	216
9	0	32	**36**	4.50	140	**63**	3.20	218
10	0	36	**37**	2.40	144	**64**	4.70	220
11	0	40	**38**	2.10	148	**65**	4.20	222
12	0	44	**39**	3.70	152	**66**	4.0	224
13	0	48	**40**	2.70	156	**67**	4.60	226
14	0	52	**41**	3.70	160	**68**	4.60	228
15	0	56	**42**	4.10	164	**69**	4.60	230
16	0	60	**43**	5.50	168	**70**	5.10	232
17	0	64	**44**	6.30	172	**71**	4.90	234
18	0	68	**45**	8.50	176	**72**	6.90	236
19	0	72	**46**	5.90	180	**73**	2.90	238
20	0	76	**47**	6.60	184	**74**	0.30	240
21	0	80	**48**	1.90	188	**75**	4.9	244
22	0	84	**49**	2.70	190	**76**	0.50	249
23	0	88	**50**	1.80	192	**77**	0.50	253
24	10.4	92	**51**	1.70	194	**78**	0.40	257
25	8.90	96	**52**	3.60	196	**79**	0.30	261
26	4.30	100	**53**	3.50	198	**80**	0.40	265
27	3.4	104	**54**	3.30	200	**81**	0.90	269

According to Wong and Somes (1995) hydraulic efficiency is described as how well the incoming wastewater distributes within the pond. Although it is unrealistic assumption all design models currently in use assume uniform flow conditions and unrestricted opportunities for contact between the incoming wastewater and the organisms responsible for the biodegradation of pollutants (Reed, Crites and Middlebrooks, 1995). According to the Water Pollution Control Federation (WPCF, 1990) optimal flow is a flow with uniform velocity profile in which the water molecules move parallel, with no water movement sidewise. Therefore, the WPCF (1990) recommends that waste stabilization ponds ought to have a plug flow, since such a flow is characterized as having a uniform velocity profile. However, flows with a uniform velocity profile exist only in ponds with a large length-to-width ratio.

Table 1b: Tracer concentrations at the outlet of the facultative pond (continued)

Sample #	Conc. (mg/L)	Time (Hrs.)	Sample #	Conc. (mg/L)	Time (Hrs.)	Sample #	Conc. (mg/L)	Time (Hrs.)
82	3.30	273	**102**	0.20	353	**122**	0.30	433
83	0.70	277	**103**	0.40	357	**123**	0.30	437
84	0.50	281	**104**	0.20	361	**124**	0.20	441
85	0.80	285	**105**	0.30	365	**125**	0.90	445
86	0.80	289	**106**	0.20	369	**126**	0.10	449
87	0.20	293	**107**	0.20	373	**127**	0.20	453
88	0.50	297	**108**	0.50	377	**128**	0.60	457
89	0.40	301	**109**	0.50	381	**129**	0.20	461
90	0.60	305	**110**	0.50	385	**130**	0	465
91	0.60	309	**111**	0.70	389	**131**	0	469
92	0.60	313	**112**	1.10	393	**132**	0	473
93	0.60	317	**113**	0.20	397	**133**	0	477
94	0.60	321	**114**	0.60	401	**134**	0	481
95	0.60	325	**115**	0.10	405	**135**	0	485
96	0.40	329	**116**	0.80	409	**136**	0	489
97	0.10	333	**117**	0.40	413	**137**	0	493
98	0.30	337	**118**	0.60	417	**138**	0	497
99	0.20	341	**119**	0.70	421	**139**	0	501
100	0.10	345	**120**	0.10	425	**140**	0	505
101	0	349	**121**	0.20	429	**141**	0	509

Generally, the pond water does not move homogeneously, but rather in eddies and with re-circulation. Therefore, in practice, local velocity profiles or velocity vectors give limited information for the evaluation of the hydraulic performance compared to tracer experiments.

The wastewater treatment system of Meta Abo Brewery does not have a Parshall flume or other system to measure the flow. Thus the flow rate was measured by the bucket-and-stopwatch method. Many researchers have proven that the bucket-and-stopwatch method gives more accurate results than a secondary measuring device and therefore recommended as a calibration method for secondary devices. Based on this measurement the flow rate for the study period was estimated to be 251m^3/d for facultative pond. Based on the analysis of tracer concentration measured at the outlet of the pond versus time curve was used to analysis the hydraulic performance of the pond as well as to predict treatment efficiencies in conjunction with the first order reaction equation.

Nominal Residence Time

The nominal residence time, t_n, is calculated from V/Q by assuming the pond is making use of the entire volume by uniformly distributing the flow. Traditional estimates of treatment efficiency are based on nominal residence time and ideal plug flow conditions. In reality, dead zones or re-circulating zones reduce the effective volume of the WSP by creating preferential flow paths. This in turn shortens the average residence time as the result of short-circuiting which shifts the centre of the distribution towards the origin and below the theoretical residence time (Wahl et al. 2010).

For a waste stabilization pond, the theoretical hydraulic retention time (THRT) can be obtained using:

$$\theta_t = \frac{V}{Q} \qquad (1)$$

Where V is volume of the pond (m^3), Q is design flow rate (m^3/d) and θ_t is theoretical hydraulic retention time. This means that the approximate volume of the facultative pond is 4044.44m^3 and average flow rate is about 251m^3/d which gives the value of nominal hydraulic retention time of about 16.1 days.

$$\theta_t = \frac{4044.44m^3}{251\mathrm{m}^3/\mathrm{d}} = 16.1\ days$$

Apparent mean hydraulic retention time

Real ponds don't operate at their theoretical hydraulic retention time (THRT). This is due to the fact that compared to the constant value used to calculate the theoretical hydraulic retention time (THRT), the flow rate is constantly changing and the ponds are partly filled with sludge over time. Even if a pond is operating at its theoretical hydraulic retention time (THRT), its hydraulic efficiency is still likely to be suboptimal due to hydraulic dead space and hydraulic short-circuiting (Shilton and Harisson 2003).

A hydraulic detention time distribution is commonly used to represent the time that various fractions of water spend in the pond. A recommended method of characterizing the RTD in a flow system including waste stabilization pond is by using their moments such as the mean and variance. According to Weinstein and Dudukovic (1975) the average mean residence time $\bar{\mu}$ of the wastewater (the apparent mean residence time) is by definition the mean (first moment) of the residence time density function which is given by:

$$\bar{\mu} = \frac{\int_0^\infty t\, C\,(t) dt}{\int_0^\infty C\,(t) dt} \qquad (2)$$

In discrete form

$$\bar{\mu} = \frac{\sum_0^\infty t_i\, C\,(t_i)\ \Delta t_i}{\sum_0^\infty C\,(t_i)\ \Delta t_i}$$

Accordingly from the tracer study conducted on the facultative pond operated by Meta Abo brewery, the mean value or the centroid of distribution is:

$$\bar{\mu} = \frac{141517.4}{778.6} = 181.76\ hours \sim \mathbf{7.57days}$$

The variance (σ^2) rooted from the standard deviation (σ) is a measure of the spread of the RTD and can be defined by:

$$\sigma^2 = \frac{\int_0^\infty (\bar{\mu} - t)^2 \, C(t)dt}{\int_0^\infty C(t)dt} \qquad (3)$$

$$\sigma^2 = \frac{4802159.1}{778.6} = 6167.7\,(hours)^2 \sim 256.9\,(\boldsymbol{days})^2$$

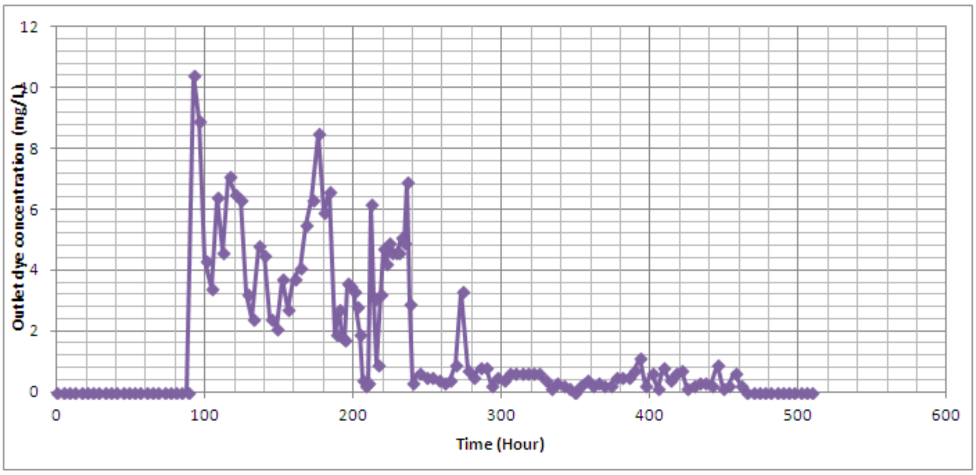

Figure 3. Outlet tracer concentration versus time curve for the tracer study

As can be seen from Figure 3, the tracer concentration versus time curve looks like more a uniform flow than a bell shaped curve. The curve had more than four major distinctive peaks and many smaller ones. The first peak indicates a short circuit that is faster than the others, while the dead zones are indicated by the longer tail of the curve. The curves are similar to what would be expected from a mixed reactor suffering from short-circuiting and stagnation zones. The last peak and the tail of the curve further indicate stagnation zones.

As already calculated from tracer concentration measured at the outlet versus time the mean hydraulic retention time is 7.57 days. More generally it illustrates the importance of sound hydraulic pond design that avoids premature release of the wastewater into ecologically sensitive water bodies.

One method used to quantify the effect of short circuiting on the treatment efficiency is using the index of short-circuiting which is the ratio of the time at which tracer first appears and theoretical residence time. This ratio is 1 for plug flow and approaches zero for increased short-circuiting. However, this index does not differentiate between completely mixed flow and flow that has short-circuited. This is another reason why the mean hydraulic retention time needs to be calculated. Accordingly the time at which dye tracer appears first is 92 hours and the theoretical residence time is 16.1 days. Thus the ratio is 0.24 which indicates the existence of severe short circuiting of wastewater through the pond that misses out on a significant amount of treatment.

Hydraulic efficiency

The hydraulic efficiency of waste stabilization pond was formulated in an attempt to reflect the two basic features in the hydrodynamic performance of detention system. The first is the ability to distribute the inflow evenly across the detention system and second is the amount of mixing or re-circulation, i.e. deviations from plug flow (Persson, Somes and Wong 1999). As both components have a value between 0 and 1, the index is designed to give each an equal weighting on the overall efficiency. This consideration has led to the hydraulic efficiency (λ) becoming one of the most common tools for assessing hydraulic efficiency (Wahl et al. 2010). Despite its common use, the hydraulic efficiency index is not free from to criticism of inaccuracy. This is because tracer responses are often characterized by positively skewed distributions with long tails. Thus, the calculation of means and standard deviations of an RTD can vary significantly depending on the selected end point of the tracer measurement (Persson, Somes and Wong 1999).

According to Persson et al. (1999) the hydraulic efficiency, λ, can be calculated as mean hydraulic retention time divided by the theoretical hydraulic detention time.

$$\lambda = \frac{t_{mean}}{t_n} \qquad (4)$$

$$\lambda = \frac{7.57\text{days}}{16.1\text{days}} = 0.47$$

The closer to 1 λ is, the better the hydraulic efficiency of the waste stabilization pond. Accordingly the hydraulic efficiency obtained indicates that the pond could be on the edge of sliding into poor hydraulic efficiency.

Effective volume and dead volume

According to Persson (2000) λ equal to effective volume ratio, *e*, which is a proportion that is equal to the effective volume divided by the design volume.

$$e = \frac{t_{mean}}{t_n} = \frac{V_{effective}}{V_{total}} = \lambda \qquad (5)$$

Where V_{total} is the total volume of the pond and $V_{effective}$ is the total volume minus the dead volume.

$V_{effective}$ = Total (design) volume x λ

= 4044.44m^3 x 0.47 = **1901m^3**

Thus the effective volume of the pond for this study is approximately 1901m^3, which is less than half of the design volume of about 4044.44m^3. The dead volume is the total volume minus the dead volume. It is volume of water that has no interaction with the water flowing through the pond.

Dead volume = Total (design) volume – effective volume

4044.44m^3 – 1901m^3 = **3143.44m^3**

This gives the approximate dead volume of the pond for this study of 2143.44m^3 which is greater than half of the design volume. This indicates that more than half of the pond volume is occupied by dead volume as a result of settled sludge. Treatment efficiency would thus be substantially improved by correcting these large dead volumes.

Degree of mixing

Degree of mixing represents how large portion of the water that moves quickly or slowly through the pond in relation to the main flow, but also because mixing processes lowers the concentration of soluble pollutants. A large degree of mixing therefore ought to result in poor removal efficiency. In order to avoid the effect of overestimation of efficiency due to extremely high N values, it is preferable to use the mixing factor $(1 - (1/N))$ instead of N. This also puts the mixing factor $(1 - (1/N))$ in an interval between 0 and 1.

$$\lambda = \bar{\mu}_\theta \left(1 - \frac{1}{N}\right) = \bar{\mu}_\theta\left(1 - {\sigma^2}_\theta\right) \qquad (6)$$

Thus mixing factor is given by:

$$\left(1 - \frac{1}{N}\right) = \left(1 - {\sigma^2}_\theta\right) \qquad (7)$$

The dimensionless variance (${\sigma^2}_\theta$) normalized by equation 9 provides information on the amount of mixing present in a pond system.

Table 2a. Computational procedure for calculating the tracer HRT

Sample #	t(hr.)	C(t) (mg/L)	C(t)dt	tC(t)dt	Sample #	t (Hr.)	C(t) (mg/L)	C(t)dt	tC(t)dt
1	0	0	0	0	40	156	2.7	10.8	1684.8
2	4	0	0	0	41	160	3.7	14.8	2368
3	8	0	0	0	42	164	4.1	16.4	2689.6
4	12	0	0	0	43	168	5.5	22	3696
5	16	0	0	0	44	172	6.3	25.2	4334.4
6	20	0	0	0	45	176	8.5	34	5984
7	24	0	0	0	46	180	5.9	23.6	4248
8	28	0	0	0	47	184	6.6	26.4	4857.6
9	32	0	0	0	48	188	1.9	7.6	1428.8
10	36	0	0	0	49	1 9 0	2.7	5.4	1026
11	40	0	0	0	50	192	1.8	3.6	691.2
12	44	0	0	0	51	194	1.7	3.4	659.6
13	48	0	0	0	52	196	3.6	7.2	1411.2
14	52	0	0	0	53	198	3.5	7	1386
15	56	0	0	0	54	200	3.3	6.6	1320
16	60	0	0	0	55	202	2.8	5.6	1131.2
17	64	0	0	0	56	204	1.9	3.8	775.2
18	68	0	0	0	57	206	0.4	0.8	164.8
19	72	0	0	0	58	208	0.2	0.4	83.2
20	76	0	0	0	59	210	0.3	0.6	126
21	80	0	0	0	60	212	6.2	12.4	2628.8
22	84	0	0	0	61	214	3.1	6.2	1326.8
23	88	0	0	0	62	216	0.9	1.8	388.8
24	92	10.4	41.6	3827.2	63	218	3.2	6.4	1395.2
25	96	8.9	35.6	3417.6	64	220	4.7	9.4	2068
26	100	4.3	17.2	1720	65	222	4.2	8.4	1864.8

Table 2a. Computational procedure for calculating the tracer HRT (Contd….)

Sample #	t(hr.)	C(t) (mg/L)	C(t)dt	tC(t)dt	Sample #	t (Hr.)	C(t) (mg/L)	C(t)dt	tC(t)dt
27	104	3.4	13.6	1414.4	66	224	4	8	1792
28	108	6.4	25.6	2764.8	67	226	4.6	9.2	2079.6
29	112	4.6	18.4	2060.8	68	228	4.6	9.2	2097.6
30	116	7.1	28.4	3294.4	69	230	4.6	9.2	2116
31	120	6.5	26	3120	70	232	5.1	10.2	2366.4
32	124	6.3	25.2	3124.8	71	234	4.9	9.8	2293.2
33	128	3.2	12.8	1638.4	72	236	6.9	13.8	3256.8
34	132	2.4	9.6	1267.2	73	238	2.9	5.8	1380.4
35	136	4.8	19.2	2611.2	74	240	0.3	0.6	144
36	140	4.5	18	2520	75	244	4.9	9.8	2198.2
37	144	2.4	9.6	1382.4	76	249	0.5	2	498
38	148	2.1	8.4	1243.2	77	253	0.5	2	506
39	152	3.7	14.8	2249.6	78	257	0.4	1.6	411.2

Table 2b. Computational procedure for calculating the tracer hydraulic retention time (HRT)

Sample #	t(hr.)	C(t) (mg/L)	C(t)dt	tC(t)dt	Sample #	t (Hr.)	C(t) (mg/L)	C(t)dt	tC(t)dt
79	261	0.3	1.2	313.2	110	385	0.5	2	770
80	265	0.4	1.6	424	111	389	0.7	2.8	1089.2
81	269	0.9	3.6	968.8	112	393	1.1	4.4	1729.2
82	273	3.3	13.2	3603.6	113	397	0.2	0.8	317.6
83	277	0.7	2.8	775.6	114	401	0.6	2.4	962.4
84	281	0.5	2	562	115	405	0.1	0.4	162
85	285	0.8	3.2	912	116	409	0.8	3.2	1308.8
86	289	0.8	3.2	924.8	117	413	0.4	1.6	660.8
87	293	0.2	0.8	234.4	118	417	0.6	2.4	1000.8
88	297	0.5	2	594	119	421	0.7	2.8	1178.8
89	301	0.4	1.6	481.6	120	425	0.1	0.4	170
90	305	0.6	2.4	732	121	429	0.2	0.8	343.2
91	309	0.6	2.4	741.6	122	433	0.3	1.2	519.6
92	313	0.6	2.4	751.2	123	437	0.3	1.2	524.4
93	317	0.6	2.4	760.8	124	441	0.2	0.8	352.8
94	321	0.6	2.4	770.4	125	445	0.9	3.6	1602
95	325	0.6	2.4	780	126	449	0.1	0.4	179.6
96	329	0.4	1.6	526.4	127	453	0.2	0.8	362.4
97	333	0.1	0.4	133.2	128	457	0.6	2.4	1096.8
98	337	0.3	1.2	404.4	129	461	0.2	0.8	368.8
99	341	0.2	0.8	272.8	130	465	0	0	0
100	345	0.1	0.4	138	131	469	0	0	0
101	349	0	0	0	132	473	0	0	0
102	353	0.20	0.8	282.2	133	477	0	0	0
103	357	0.40	1.6	571.2	134	481	0	0	0
104	361	0.20	0.8	288.8	135	485	0	0	0

Table 2b. Computational procedure for calculating the tracer hydraulic retention time (HRT) (Contd.…)

Sample #	t(hr.)	C(t) (mg/L)	C(t)dt	tC(t)dt	Sample #	t (Hr.)	C(t) (mg/L)	C(t)dt	tC(t)dt
105	365	0.30	1.2	438	136	489	0	0	0
106	369	0.20	0.8	295.2	137	493	0	0	0
107	373	0.20	0.8	298.4	138	497	0	0	0
108	377	0.50	2	754	139	501	0	0	0
109	381	0.50	0.8	282.2	140	505	0	0	0
Overall summation (Table 2a and b)								778.6	141517.8

A plug flow condition will induce an RTD with a $\sigma^2{}_\theta$ equaling 0, whereas a completely stirred flow induces a $\sigma^2{}_\theta$ equal to 1.

$$\sigma^2 = \frac{\int_0^\infty (\bar{\mu} - t)^2\, C\,(t)dt}{\int_0^\infty C\,(t)dt} \qquad (8)$$

$$\sigma^2{}_{\theta} = \frac{\sigma^2}{t^2{}_n} \qquad (9)$$

This gives the normalized dimensionless variance of

$$\sigma^2{}_{\theta} = \frac{156.9\ (days)^2}{(16.1\ days)^2} = 0.61$$

Degree of mixing, $\left(1 - \frac{1}{N}\right)$ is 1 -0.61 which gives the value of **0.39**.

Where is N is number of cells in series of tanks.

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