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EFFECT OF CONTROL PARAMETERS OF BIOLOGICAL WASTEWATER TREATMENT SYSTEMS ON BIODEGRADABLE DISSOLVED ORGANIC CARBON IN EFFLUENTS

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ค่าบีโอดีเป็นพารามิเตอร์ที่ใช้ในการบ่งบอกลักษณะและประสิทธิภาพของระบบบำบัดน้ำเสียในปัจจุบันอย่างแพร่หลาย อย่างไรก็ดีในการวิเคราะห์น้ำเสียที่มีสารอินทรีย์ต่ำมักขาดความถูกต้องและแม่นยำ งานวิจัยนี้ได้ศึกษาผลของปัจจัยควบคุมที่มีต่อค่าบีดีโอซีในน้ำเสียจากระบบแอคติเวดเตดสลัดจ์ระบบโปรยกรองและระบบจานหมุนชีวภาพ และวิเคราะห์พารามิเตอร์อื่นๆ ได้แก่ ค่าบีโอดี ค่าซีโอดี ค่าทีโอซี มวลชีวภาพ ความสามารถในการดูดกลืนคลื่นที่ความยาวแสงยูวี เพื่อเปรียบเทียบประสิทธิภาพและความแม่นยำในการวัดค่าบีดีโอซีอีกด้วย จากผลการศึกษาจากแบบจำลองของระบบแอคติเวดเตดสลัดจ์พบว่า ค่าบีดีโอซีที่ได้จากระบบบำบัดที่มีเวลากักตะกอนต่ำ มีค่าสูงกว่าที่พบในน้ำที่บำบัดที่มีเวลากักตะกอนสูง นอกจากนี้ยังพบว่าประสิทธิภาพในการบำบัดโดยวิเคราะห์จากค่าบีดีโอซีมีความสัมพันธ์กับเวลากักตะกอนอย่างเห็นได้ชัด ซึ่งอาจสามารถใช้ความสัมพันธ์นี้มาทำนายและใช้ในการออกแบบระบบแอคติเวดเตดสลัดจ์ได้ในอนาคต ค่าบีดีโอซีของน้ำที่ผ่านการบำบัดจากระบบโปรยกรองค่อนข้างสูงเมื่อเทียบกับน้ำที่ได้จากการบำบัดของระบบแอคติเวดเตดสลัดจ์ ชี้ให้เห็นว่าประสิทธิภาพในการบำบัดน้ำเสียของระบบแอคติเวดเตดสลัดจ์สูงกว่าระบบโปรยกรอง ค่าบีดีโอซีในน้ำซึ่งได้จากการบำบัดผ่านระบบโปรยกรองแปรผกผันกับภาระชลศาสตร์ในน้ำเสียจากระบบบำบัด และพบว่าระบบสามารถบำบัดสารอินทรีย์ที่ย่อยสลายได้ถึงสองเท่าโดยเพิ่มภาระทางชลศาสตร์ของระบบจาก 0.5 เป็น 3 $ม^3/ม^2$ วัน ในการศึกษาระบบจานหมุนชีวภาพพบว่า ค่าบีดีโอซีมีแนวโน้มเพิ่มขึ้นตามภาระทางชลศาสตร์และเป็นที่น่าสังเกตว่าค่าบีดีโอซีมีความสัมพันธ์กับค่าดีโอซีและบีโอดี อย่างไรก็ตาม ควรเพิ่มจำนวนของข้อมูลเพื่อให้ได้ผลที่ชัดเจนยิ่งขึ้น จากผลของการศึกษาของทุกระบบพบว่าค่าบีดีโอซีมีความแม่นยำในการวิเคราะห์เหนือกว่าค่าบีโอดีอย่างมีนัยสำคัญ

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PISCHA WANARATNA: EFFECT OF CONTROL PARAMETERS OF BIOLOGICAL WASTEWATER TREATMENT SYSTEMS ON BIODEGRADABLE DISSOLVED ORGANIC CARBON IN EFFLUENTS. THESIS ADVISOR: ASST.PROF. EAKALAK KHAN, Ph.D., THESIS CO-ADVISOR: ASST.PROF.SUTHA KHAODHIAR, Ph.D., 94 pp. ISBN 974-17-0915-3.

In the last few years, biodegradable dissolved organic carbon (BDOC) methods have been studied and used for characterizing the quality of secondary treated wastewater from activated sludge (AS) process. However, BDOC removal efficiency through AS process treating actual wastewater has not been investigated. Furthermore, BDOC has never been applied to processes other than AS. In this study, two bench-scale AS and trickling filter (TF) processes and a full-scale rotating biological contactor (RBC) process experiments were conducted using actual primary wastewater to determine the effect of SRT and HLR on BDOC in the effluents. For the bench scale experiments, BDOC removal at different SRTs and HLRs was also determined. Effluent BDOCs were lower at higher SRTs and lower HLRs for the AS and TF processes, respectively. An excellent relationship between BDOC removal and SRT was obtained from the AS experiment. Secondary wastewater effluent from the full-scale RBC contained relatively high BDOC (2.8 and 1.5 times of BDOC in the effluents of AS and TF, respectively) of which 30 to 80% was biodegradable during the BDOC test. BDOC correlated well with dissolved organic carbon (DOC) and soluble biochemical oxygen demand at 5 days ($SBOD_5$). However, a poor relationship was observed between BDOC and ultraviolet absorbance at 254 nm (UV_{254}) of RBC effluent. $SBOD_5$ and BDOC were analyzed simultaneously to compare the precision between the two methods. Results show that the BDOC method is substantially more precise than the $SBOD_5$ method.

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CONTENTS

Pages

ABSTRACT (THAI) ……...…….... iv
ABSTRACT (ENGLISH) ……... v
ACKNOWLEDGEMENT …….. vi
CONTENTS …… vii
LIST OF FIGURES ……. x
LIST OF TABLES …….. xiii
NOMENCLATURE …… xiv

CHAPTER 1 INTRODUCTION

1.1 Background and Motivation …….. 1
1.2 History of BDOC Development …… 3
1.3 Problem Statement …… 4
1.4 Objectives ……. 5

CHAPTER 2 LITERATURE REVIEW

2.1 Overview of Design and Control Parameters for AS, TF, and RBC . 6
2.1.1 SRT and Kinetic Equations for AS …… 6
2.1.2 HLR and Kinetic Equations for TF …… 9
2.1.3 HLR and Kinetic Equations for RBC ……. 13
2.2 Overview of the Classical Measurement of Water Quality …….. 18
2.2.1 Advantages and Limitations of classical measurement of water quality ……... 19
2.3 Biodegradable Dissolved Organic Carbon (BDOC) ……. 19
2.3.1 Definition …… 20
2.3.2 BDOC methods ……. 20
2.3.2.1 Static Methods …… 20
2.3.2.1.1. Biomass-Based method …….. 21
2.3.2.1.2 DOC-Based methods …… 21

CONTENTS (Cont'd)

Pages

2.3.2.2 Dynamic Methods ……... 23
2.3.3 BDOC applications …… 25
2.3.3.1 Indicating Raw Water Quality …… 25
2.3.3.2 Indicating Finished Water Quality …….. 26
2.3.3.3 Designing, Monitoring, and Optimizing Operationing Conditions of Biologically Activated Carbon (BAC) System ……. 28
2.3.3.4 Measuring the Effect of Water Treatment Processes Other Than BAC ……. 28
2.3.3.5 Indicating the Quality of Reclaimed and Secondary Treated Wastewater ……... 31

CHAPTER 3 METHODOLOGY

3.1 Activated Sludge and Trickling Filter Studies …….. 34
3.1.1 Sample collection and preparation ……. 34
3.1.2 Experimental set up and Operation …… 34
3.1.2.1 Activated Sludge ……. 34
3.1.2.1.1 Experimental set-up ……. 34
3.1.2.1.2 Experimental operation……. 35
3.1.2.2 Trickling Filter …… 37
3.1.2.2.1 Experimental set-up …….. 37
3.1.2.2.2 Experimental operation …… 37
3.2 Rotating Biological Contractor (RBC) Studies …… 39
3.2.1 Sample Collection …….. 39
3.3 Analyses …… 40

CHAPTER 4 RESULTS AND DISCUSSION

4.1 Effect of SRT on BDOC and other parameters in Activated Sludge Process Study ……. 42

CONTENTS (Cont'd)

Pages

4.2 Effect of HLR on BDOC and other parameters in Trickling Filter Process Study …… 51
4.3 Rotating Biological Contactor (RBC) Study ……... 56
4.4 Correlations between BDOC and other parameters in biological wastewater treatment processes …… 64
4.5 Precision of BDOC and $SBOD_5$ methods ……... 70

CHAPTER 5 CONCLUSIONS …….. 72

CHAPTER 6 RECCOMENDATIONS FOR FUTURE STUDIES ……..... 74

REFERENCES …… 75

APPENDICES …… 80

BIOGRAPHY ……..... 94

LIST OF FIGURES

Pages

2.1	Schematic of activated sludge process with recycling and wasting …….	7
2.2	Effluent waste concentration and removal efficiency for the complete-mix and plug-flow reactors with recycle versus SRT …….....	9
2.3	Typical trickling filter process ……	10
2.4	Effect of hydraulic loading rate on the BOD removal efficiency of trickling filter process …….	13
2.5	Typical RBC flow diagram for secondary treatment ……..	15
2.6	RBC process design curve for total BOD removal and total and soluble effluent BOD ……...	16
2.7	Plot of Equation (2.21) ……...	18
2.8	Plot of Equations (2.21) and (2.22) …….	18
3.1	Dimensions of activated sludge bench-scale unit …….	36
3.2	The bench-scale AS unit during normal operation …….	36
3.3	Schematic and dimensions of trickling filter bench-scale unit ……..	38
3.4	The bench-scale TF unit during normal operation …….	38
4.1	Relationship between MLSS and SRT……..……..	44
4.2	Influent and effluent pH versus SRT……	44
4.3	Influent and effluent SCOD versus SRT …….	45
4.4	Relationship between SCOD removal and SRT ……...…..	45
4.5	Influent and effluent $SBOD_5$ versus SRT ……...……	46
4.6	Relationship between $SBOD_5$ removal and SRT……..…	46
4.7	Influent and effluent BDOC versus SRT …….……...	47
4.8	Relationship between BDOC removal and SRT …….	47
4.9	Influent and effluent DOC versus SRT …….…….....	48
4.10	Relationship between DOC removal and SRT ……	48
4.11	Influent and effluent $SBOD_5$/COD versus SRT ……..……	50
4.12	Influent and effluent BDOC/DOC versus SRT ……...	50

LIST OF FIGURES (Cont'd)

Pages

4.13	Influent and effluent pH versus HLR……..	53
4.14	Influent and effluent $SBOD_5$ versus HLR ……..	53
4.15	Influent and effluent BDOC versus HLR ……	54
4.16	Influent and effluent DOC versus HLR ……..	54
4.17	Relationship between $SBOD_5$, DOC, and BDOC and HLR ……...	55
4.18	Influent and effluent BDOC/DOC versus HLR …….	55
4.19	OLR of the RBC plant ……..……..	58
4.20	OLR of the two parallel sections of the RBC plant …….	58
4.21	HLR of the RBC plant ……..……..	59
4.22	HLR of the two parallel sections of the RBC plant ….……...	59
4.23	Secondary effluent pH of the two parallel sections of the RBC plant …	60
4.24	SBOD of primary effluent and secondary effluent from the two parallel sections of the RBC plant ……	60
4.25	$SBOD_5$ of the secondary effluent versus HLR of the two parallel sections of the RBC plant …….	61
4.26	BDOC of the secondary effluent versus HLR of the two parallel sections of the RBC plant ……..…	61
4.27	BDOC of the secondary effluent of the two parallel sections of the RBC plant ……	62
4.28	DOC of the secondary effluent versus HLR of the two parallel sections of the RBC plant ……..…	62
4.29	Secondary effluent BDOC/DOC of the two parallel sections of the RBC plant ……	63
4.30	UV_{254} of the secondary effluent versus HLR of the two parallel sections of the RBC plant …….	63
4.31	Correlation between BDOC and $SBOD_5$ of the effluent of AS, TF, and RBC processes ……	66

LIST OF FIGURES (Cont'd)

Pages

4.32 Correlation between BDOC and DOC of the effluent of AS, TF, and RBC processes …… 66

4.33 Correlation between BDOC and SCOD of the effluent of the AS process 67

4.34 Correlation between BDOC and UV_{254} of the effluent of the RBC process 67

4.35 Correlation between DOC and $SBOD_5$ of the effluent of the AS, TF, and RBC processes …… 68

4.36 Correlation between DOC and SCOD of the effluent of the AS process 68

4.37 Correlation between DOC and UV_{254} of the effluent of the RBC process 69

4.38 Correlation between $SBOD_5$ and SCOD of the effluent of the AS process 69

4.39 Correlation between $SBOD_5$ and UV_{254} of the effluent of the RBC process 70

LIST OF TABLES

		Pages
2.1	Values for design and operational parameters of TF ……..	10
3.1	Feeding rate in each SRT and HLR in AS and TF units ……	39
3.2	Analytical Methods and Instruments ……..	40
3.3	Parameter Determination in each biological process ……..	41
4.1	Precision of BOD and BDOC analysis in biological process …….....	71
A.1	General Description of RBC units of Rockland County Sewer District No.1	81
A.2	Operational condition of Rockland County Sewer District No.1 during sampling period ……...	81
B.1	Flow pattern of section A and B of Rockland County Sewer District No.1	82
C.1	Organic Loading Rate (OLR) of Rockland County Sewer District No.1 …	83
D.1	Hydraulic Loading Rate (HLR) of Rockland County Sewer District No.1	85
E.1	Flow Rate of Rockland County Sewer District No.1 …….	87
F.1	Suspended Solids of Rockland County Sewer District No.1 …….	88
G.1	Total BOD of Rockland County Sewer District No.1 ……	90
H.1	Soluble BOD and CBOD of Rockland County Sewer District No.1 …….	92

NOMENCLATURES

AOC = assimilable organic carbon
AS = activated sludge
BAC = biological granular activated carbon
BAF = biological activated carbon filter
BAR = biofilm based annular reactor
BAS = biologically active sand
BDOC = biodegradable dissolved organic carbon
BF = biostability factor
BOD = biochemical oxygen demand
BOD_5 = biochemical oxygen demand at 5 days
BOM = biodegradable organic matter BOM
BPOC = biodegradable particulate organic carbon
CFSTR = continuous-flow stirred tank activated sludge reactors CFSTR
COD = chemical oxygen demand
DBP = disinfection by-product
DO = dissolved oxygen
DOC = dissolved organic carbon
EBCT = empty bed contact time
F/M = food to microorganism ratio
GAC = granular activated carbon
GF/F = glass fiber filter
HLR = hydraulic loading rate
MCRT = mean cell residence time
MGD = million gallon per day
MLSS = mixed liquor suspended solids
NF = nanofiltration
NOM = natural organic matter
NPDOC = nonpurgeable dissolved organic carbon
OBP = ozone by-product
OLR = organic loading rate

NOMENCLATURES (Cont'd)

POC	=	particulate organic carbon
RBC	=	rotating biological contractor
SBOD	=	soluble biochemical oxygen demand
SCOD	=	soluble chemical oxygen demand
SMP	=	soluble microbial product
SRT	=	solid retention time
T	=	temperature
TBOD	=	total biochemical oxygen demand
TF	=	trickling filter
THM	=	trihalomethane
THMFP	=	trihalomethane formation potential
TOC	=	total organic carbon
TOD	=	total oxygen demand
UV_{254}	=	ultraviolet absorbance at wave length 254 nm
WWTP	=	wastewater treatment plant

CHAPTER 1

INTRODUCTION

1.1 Backgrounds and Motivation

Removal of organic matter is a primary goal of wastewater treatment (Khan *et al.*, 1998a). The treatment efficiency is usually evaluated based on the percent reduction of organic contents through the process. Four traditional measurements used for measuring organic contents in wastewater are biochemical oxygen demand (BOD), chemical oxygen demand (COD), total oxygen demand (TOD) and total organic carbon (TOC). Each measurement has its own strengths and weaknesses. Analysis of TOC is rapid with low detection limits. It provides excellent precision and has fewer disadvantages compared to the other three parameters (Khan *et al.*, 1998a). Nevertheless, TOC does not provide information regarding the biodegradability level of water samples.

For the past fifteen years, biodegradable dissolved organic carbon (BDOC) has been used as a parameter for quantifying the amount of biodegradable organic matter (BOM) in waters. The residual BOM in treated water can serve as a carbon source that promotes the regrowth of heterotrophic microorganisms (Khan *et al.*, 1999). Methods for BDOC analysis can be divided into two major groups; batch or static methods (Joret and Levi, 1986; Joret *et al.*, 1988; Servais *et al.*, 1987 and 1989; Percherancier *et al.*, 1996; Khan *et al.*, 1998a and 1999) and fixed film reactor or dynamic methods (Lucena *et al.*, 1990; Mogren *et al.*, 1990; and Ribas *et al.*, 1991; Frias *et al.*, 1992; Kaplan and Newbold, 1995; Sharp *et al.*, 2001).

The first BDOC method was developed specifically for testing the quality of raw water used for drinking water and for indicating raw water quality and measuring the effect of water treatment processes (Servais *et al.*, 1987). In 1989, Servais *et al.* used BDOC for designing, monitoring, and optimizing operational conditions of biological granular activated carbon (BAC) system. Occasionally, it has been used to

measure the effects of other treatment processes such as coagulation-flocculation, filtration, and ozonation. Interest in BDOC of finished water started to grow when BDOC was linked to microbial proliferation in the distribution systems. The methods for BDOC analysis have been widely used in the drinking water industry, but their applications to wastewater field have been limited. BDOC could be used to characterize secondary treated wastewater effluents from biological processes. A batch BDOC protocol developed by Khan *et al.* (1998a) provided excellent results and was very useful for indicating the quality of secondary treated effluents and reclaimed water. The protocol was capable of measuring BDOC in water samples with moderately low dissolved organic carbon (DOC) concentrations (4-15 mg/L).

For the past several decades, biological wastewater treatment processes have been developed and used. Activated sludge (AS), rotating biological contactor (RBC), trickling filter (TF), stabilization pond, anaerobic pond, and aerated lagoon are the main types of the biological treatment processes utilized nowadays. The most popular process is activated sludge (AS) because of its efficiency. The process provides high-suspended solids and BOD removal while requires small volume. Another process that is commonly used but is less popular than AS process is RBC. The advantages of RBC over other processes are less energy intensive and its capacity to handle shock load with fast recovery. The third common process is TF, a towered fixed film reactor, that is less effective than AS and RBC. Due to the ease of operation, the process is suitable for small communities.

All of the three processes mentioned above have high efficiencies in treating dissolved organic compounds by converting them into carbon dioxide, water, and non-dissolved compounds (microbial cells) that can be separated by sedimentation and removed as sludge. Each of the three processes has a specific control parameter which affects the performance of the system, mean cell residence time (MCRT) or solid retention time (SRT) for AS and organic loading rate (OLR) or hydraulic loading rate (HLR) for RBC and TF. This study will present the effect of control parameter of AS, and TF on BDOC in the effluents using bench scale experiments and the evaluation of BDOC in effluents from two parallel sections of a full scale RBC plant that were operated at two different organic loading rates.

1.2 History of BDOC Development

Servais *et al*. introduced the first BDOC method in 1987 to test the raw water quality used in drinking water facilities. This procedure involved sterilization, reinoculation with a natural assemblage of bacteria, and inoculation in the dark at 20°C for a period of 10-30 days. In 1989, they also proposed a simplified method used for designing, monitoring, and optimizing operational condition of BAC. The measurement of BDOC is based on an estimation of the flux of organic matter utilized by bacteria, deduced from biomass and mortality measurement. BDOC results were obtained after 30 days of incubation. Although the method provides higher sensitive, it is time consuming and labor intensive. Therefore, it is not suitable for use as a routine measurement.

In 1996, Percherancier *et al.* proposed a simple procedure of batch experiments to determine BDOC content of different effluent from outfalls of wastewater treatment plants. The samples were inoculated with natural consortia of bacteria taken from river sediments or aquarium filters. This test could determine BDOC within 8 days or less.

The first batch protocol (Servias *et al.,* 1987) was modified by Khan *et al.* (1998a) to characterize secondary treated wastewater effluents from biological processes. They combined the BDOC procedure with BOD techniques. The inoculated sample was incubated in the dark at 20°C for 28 days. Khan *et al.* (1999) improved their previous protocol by inoculating samples with more microbial mass to reduce the incubation time to 5 days.

A modified version of bioassay to allow routine determination of BDOC within shorter period of time by using a large biomass of bacterial assemblage fixed on a solid support was known as biofilm reactor or dynamic method. The first biofilm procedure was developed by Lucena *et al.* (1990). The water sample was circulated over biofilm attached to sand particles inside a glass column. The BDOC value corresponded to the DOC decrement between inlet and outlet typically measured in 2 hours.

Ribas *et al.* (1991) and Kaplan *et al.* (1995) used a special support for biofilm attachment called Siran® instead of sand particles. BDOC could be analyzed within 2-

3 hours with these two methods. Nevertheless, same as other dynamic methods, they have a limitation of the long acclimation period.

1.3 Problem Statement

BDOC has been applied in wastewater field for the past few years. Khan *et al.* (1998a) modified the batch BDOC method (Servais *et al.*, 1987) for evaluating BDOC in reclaimed and secondary wastewaters. Although it had shown that BDOC could be used successfully to indicate the performance of wastewater reclamation plant and secondary effluent quality, it could not be used as a routine parameter because of its long incubation time. In 1999, Khan *et al.* used different inoculum types and sizes to reduce the incubation time from 28 days to 5 days.

Babcock *et al.* (2001) used a simple BDOC method (Khan *et al.*, 1998a) to evaluate organic content of secondary treated effluent from bench-scale AS reactors treating synthetic wastewater. A strong relationship between effluent BDOC and SRT was obtained. BDOC of secondary effluent from wastewater treatment plants (WWTPs) in Hawaii was also tested. Nevertheless, there was no clear relationship between SRT and BDOC in the effluent of the full-scale plants.

In Babcock *et al.* (2001)'s study, there were doubts about the relationship between effluent BDOC and SRT obtained from the bench scale experiment, if real wastewater were experimented. Khan *et al.* (1998a and b) studied the relationship between effluent BDOC and SRT using secondary wastewater collected from 13 full-scale treatment plants, but BDOCs of the primary treated effluents of the plants were not measured. As a result, the relationship between BDOC removal efficiency and SRT are not known. In addition, there has never been research that addresses the utility of BDOC in characterizing the effluent quality and treatment efficiency of processes other than AS. This study attempts to extend the use of BDOC on less popular biological processes, TF and RBC, and to examine the applicability of BDOC to characterize the efficiency of AS treating actual primary effluent.

1.4 Objectives

The main objectives of this study are to investigate the effect of operational and control parameters of biological wastewater treatment processes on BDOC concentration in the effluents. The specific objectives are as follows:

1. To examine the effect of SRT in AS process on BDOC in treated wastewater and BDOC removal efficiency.

2. To identify the effect of HLR in TF process on BDOC in treated wastewater and BDOC removal efficiency.

3. To investigate the effect of HLR in RBC process on BDOC in treated effluent.

4. To determine correlations between BDOC and other water quality parameters such as soluble BOD at 5 days ($SBOD_5$), soluble COD (SCOD), DOC, and ultraviolet absorbance at 254 nm (UV_{254}).

5. To demonstrate that BDOC is a more precise parameter than BOD for indicating the quality of secondary treated wastewaters.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview of Design and Control Parameters for AS, TF, and RBC

2.1.1 SRT and Kinetic Equations for AS

Activated sludge process is an aerobically biological process treating organic compounds in wastewater by converting them into carbon dioxide, water, and sludge. Figure 2.1 illustrates the activated sludge process. Organic waste is introduced into a reactor for the conversion by active microorganisms. The sludge can be separated by sedimentation and partial removal. To control activated sludge process, operating condition is maintained by returning sludge partially. For the activated sludge system design and control, there are three parameters to apply; mean cell-residence time (MCRT) or solid retention time (SRT), specific utilization rate (U), and food-microorganism (F/M) ratio. The first parameter has been termed sludge age (θ_C) which is calculated as:

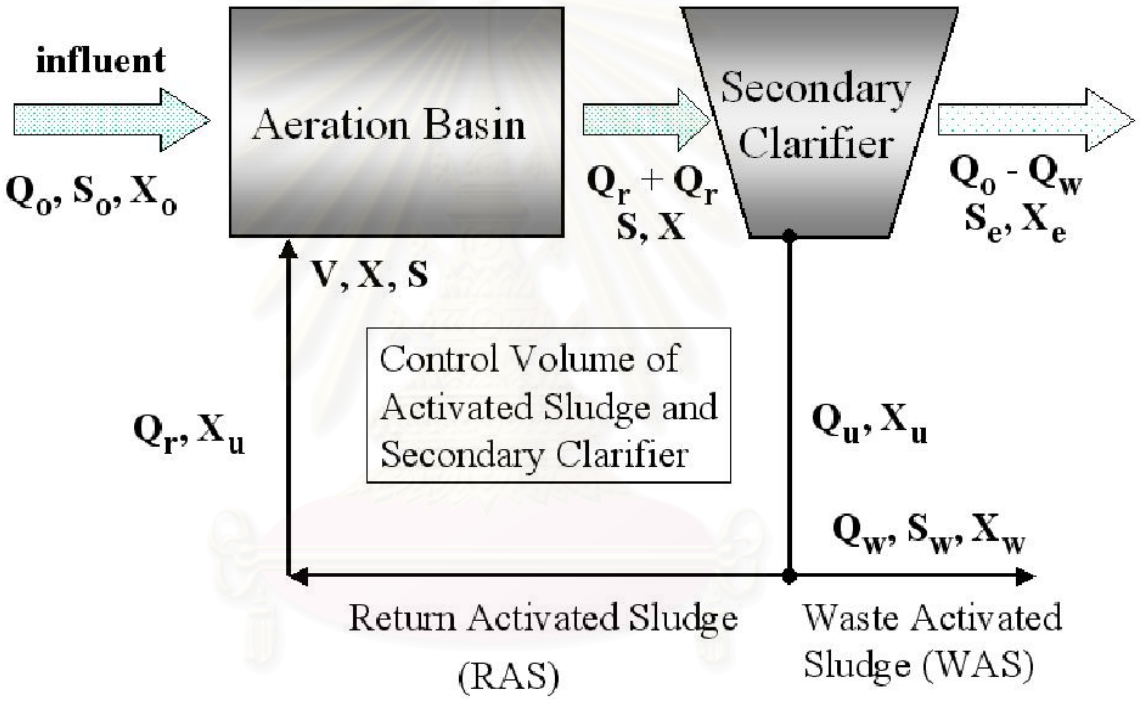
$$\theta_c = \frac{V_r X}{Q_w X_w + Q_e X_e} \qquad (2.1)$$

where V_r is a volume of reactor (L, ft^3), X is the microorganism concentration in the reactor (mg/L), Q_w is a flow rate of liquid containing the biological cells (waste) to be removed from the reactor (L/d, gal/L), X_w is the microorganism concentration in wasted activated sludge (mg/L), Q_e is a flow rate of liquid from sedimentation unit (L/d, gal/L), X_e is the microorganism concentration in the effluence from sedmentation unit (mg/L)

The second parameter is a specific utilization rate (U) which is defined as:

$$U = -\frac{r_{su}}{X} = \frac{(S_0 - S)}{\theta X} = \frac{Q(S_0 - S)}{V_r X} \qquad (2.2)$$

where (S_0-S) is the mass concentration of substrate utilized (mg/L), S_0 is a substrate concentration in influent (mg/L), S is a substrate concentration in effluent (mg/L), and θ is hydraulic retention time (day) which is equal to (V/Q).



Source:http://www.swbic.org/education/envengr/secondary/asequations/asequations.html

Figure 2.1 Schematic of Activated Sludge Process with recycling and wasting

The utilized substrate must be known in order to calculate the specific utilization rate (U). This makes U an impractical control parameter. In contrast, using

SRT to control the activated sludge system is easier because it does not require the the determination of food utilization.

Since the specific utilization rate is not a practical parameter for controlling the activated sludge system, food-microorganism (F/M) ratio which closely relates to the specific utilization rate is used. It is defined as:

$$\frac{F}{M} = \frac{S_0}{\theta X} \tag{2.3}$$

F/M relates to the specific utilization rate according to this equation:

$$U = \frac{(F/M)E}{100} \tag{2.4}$$

where E is a process efficiency (%) which is defined as:

$$E = \frac{(S_0 - S)}{S_0} x\,100 \tag{2.5}$$

The mass concentration of microorganisms (X) in the reactor can be obtained using the following equation:

$$X = \frac{\theta_c}{\theta} Y \left(\frac{S_0 - S}{1 + k_d \theta_c} \right) \tag{2.6}$$

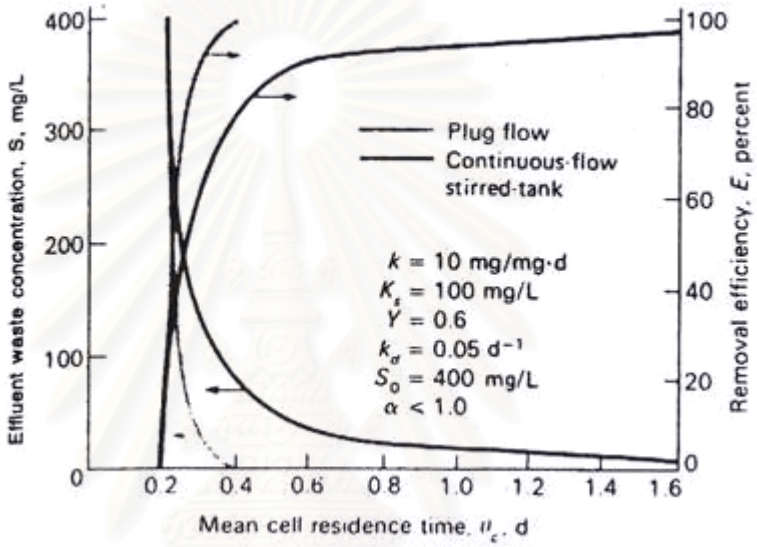
where k_d is the endogenous decay coefficient (day^{-1}) and Y is the yield coefficient (mg VSS/mg BOD_5).

Performing a substrate balance, the effluent substrate concentration is found to be equal to:

$$S = \frac{K_s (1 + \theta_c k_d)}{\theta_c (Y_k - k_d) - 1} \tag{2.7}$$

where K_s is the half velocity constant (mg BOD_5) and Y_k is a yield in the system with recycle sludge (mg VSS/mg BOD_5)

For a specific waste, a particular set of environmental conditions such as the kinetic coefficients Y, k, K_s, and k_d is constant. For given values of coefficients, the effluent-waste concentration from the reactor is a direct function of SRT as shown in Figure 2.2.

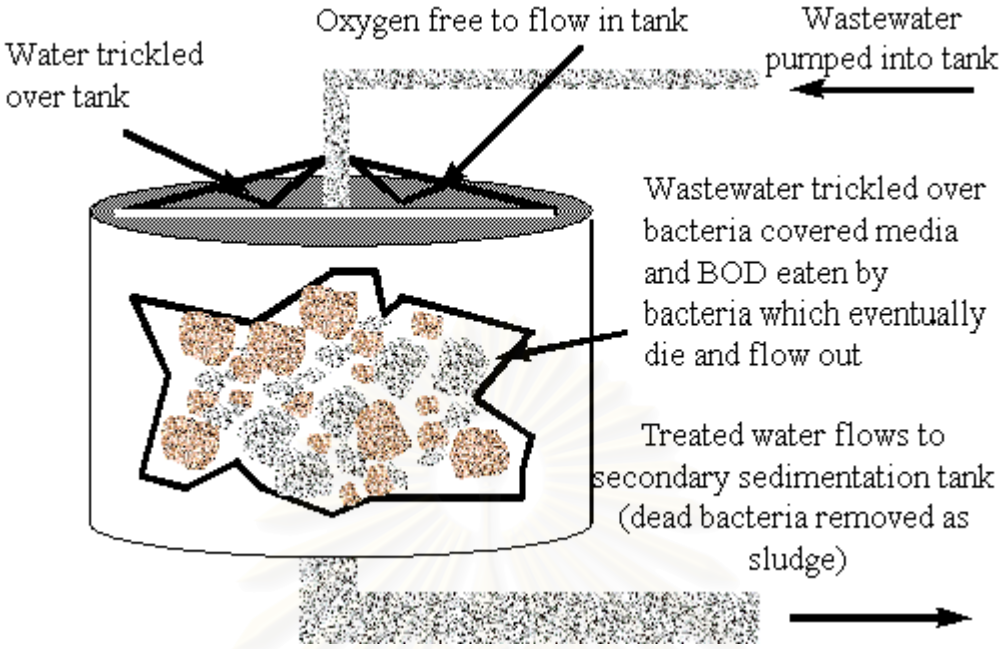


Source: Metcalf & Eddy (1991)

Figure 2.2 Effluent waste concentration and removal efficiency for the complete-mix and plug-flow reactors with recycle versus SRT

2.1.2 HLR and Kinetic Equations for TF

The trickling filter consists of a media-bed. Microorganism attached on the media which usually is rock or plastic media. Figure 2.3 shows a typical schematic of trickling filter system. In designing and operating of trickling filters, the organic and hydraulic loadings are the significant parameters. The hydraulic loading accounts for shear velocities. The organic loading corresponds to the microbial activity rate and it is adjusted to maintain a uniform slime layer during the operation.



Source:http://www.swbic.org/education/envengr/secondary/intro/secondary.html

Figure 2.3 Typical trickling filter process

Trickling filters are classified by the hydraulic or organic loading rates. Classifications are low or standard rate, intermediate rate, high rate, super high-rate and roughing. The range of loadings and other operational characteristics are shown in Table 2.1.

Table 2.1 Values for design and operational parameters of TF

Item	Low-rate	Intermediate rate	High-rate	Super high-rate
Filter medium	Rock, slag	Rock, slag	Rock	Plastic
HLR design (m^3/m^2-d)	1.17-3.52	3.52-9.39	9.39-37.55	11.73-70.4
Depth (ft)	6-8	6-8	3-6	10-40
Recirculation ratio	0	0-1	1-2	1-2

Source: Adapted from Metcalf & Eddy (1991)

Many researchers have proposed the equations for predicting the performance of trickling filter. One of the equations developed from plant study for rock filters is NRC equation, the equation is shown below:

$$E = \frac{100}{1 + 0.056\sqrt{\frac{W}{VF}}} \quad (2.8)$$

where E_1 is the efficiency of BOD removal for process at 20°C, recirculation and sedimentation (%), V is a volume of filter media (10^3 ft^3) and W is BOD loading to filter (lb/day) which is equal to

$$W = \frac{QC}{A} \quad (2.9)$$

and F is a recirculation factor which is calculated by

$$F = \frac{(1+R)}{(1+R/10)^2} \quad (2.10)$$

where R is recirculation ratio = (Q_r/Q), Q_r is a recirculation flow and Q is a wastewater flow.

Substituting (2.10) in (2.9) yields:

$$E = \frac{100}{1 + 0.056\sqrt{\frac{QC}{AVF}}} \quad (2.11)$$

HLR can be defined according to the following equation:

$$HLR = \frac{Q}{A} \quad (2.12)$$

Substitute HLR into (2.11), therefore, the design equation for TF using HLR is equal to:

$$E = \frac{100}{1 + 0.056\sqrt{\frac{(HLR)C}{VF}}} \tag{2.13}$$

For the second stage of filter, the equation is:

$$E_2 = \frac{100}{1 + \frac{0.0561}{1 - E_1}\sqrt{\frac{W'}{VF}}} \tag{2.14}$$

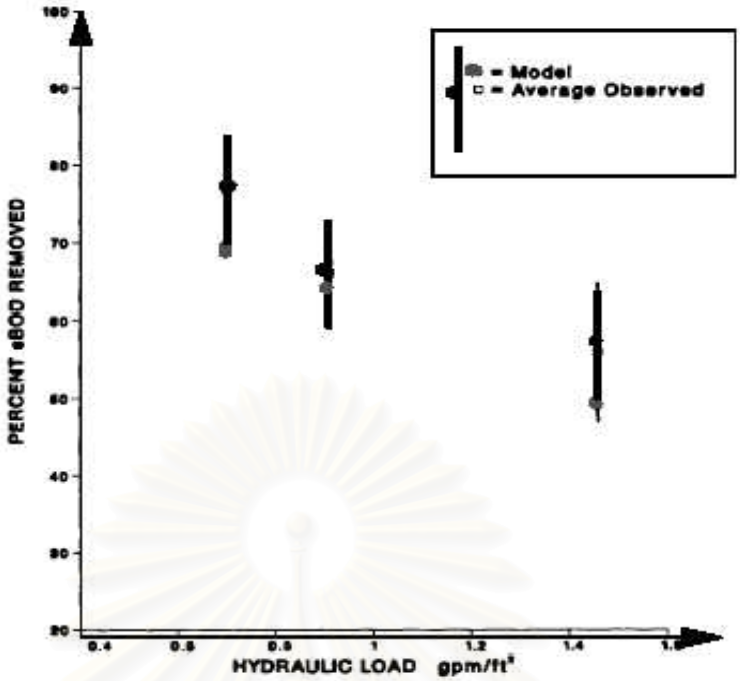
where E_2 is the efficiency of BOD removal for second stage filter at 20°C including recirculation and sedimentation (%), E_1 is a fraction of BOD removal in first stage filter, W' is the BOD loading applied to second stage filter (lb/day)

Another common kinetic equation for stone filter performance when treating municipal wastewaters was developed by Eckenfelder (1961):

$$\frac{S_t}{S_0} = \frac{1}{1 + C\left(\frac{D^{0.67}}{Q_L^{0.50}}\right)} \tag{2.15}$$

where S_t is the BOD_5 in the filter effluent (mg/L), S_0 is the BOD_5 in the wastewater discharged on the filter bed (mg/L), C is equal to 2.5 for USCS units and 5.358 for SI units, D is the filter depth (ft, m) and Q_L is a unit liquid loading, MG/acre-day (m^3/m^2-day)

Eckenfelder *et al.* (1963) studied and investigated the effect of the hydraulic loading rate in TF process. The hydraulic loading rates were plotted against BOD removal as illustrated in Figure 2.4.



Source: http://www.ce.berkeley.edu/~hermanowicz/ce212/notes/bflmre_b.pdf

Figure 2.4 Effect of hydraulic loading rate on the BOD removal efficiency of trickling filter process

2.1.3 HLR and Kinetic Equations for RBC

A main component of a rotating biological contactor (RBC) is a series of circular disks which are submerged and rotated in wastewater. A typical flow diagram of an RBC application for secondary treatment is shown in Figure 2.5

RBCs are usually designed on the basis of loading factors as same as those of trickling filters; hydraulic and organic loadings. The process design is based on a hydraulic loading express in soluble BOD per unit of surface area (lb TBOD/ 10^3 ft^2). RBC process design curves are shown in Figure 2.6. It can be seen that the poor performances suchs as low DO, H_2S odors, and poor first stage removals has been observed where systems are overloaded.

First-order equation for rotary biological contactors has been developed by Eckenfelder (1989). This equation is:

$$-\frac{1}{X}\frac{dS}{dt} = kS \qquad (2.16)$$

where (1/X)(dS/dt) is a specific rate of substrate utilization, dS/dt is the rate of substrate utilization, k is the rate constant and S is the substrate concentration.

The rate of substrate utilization (dS/dt) is given by:

$$\frac{dS}{dt} = Q(S_0 - S) \qquad (2.17)$$

where Q is a flow rate, S_0 is a substrate in the flow to the contactor and S is a substrate in the flow leaving the contactor

Substituting Equation (2.17) into (2.16) gives:

$$\frac{1}{X}Q(S_0 - S) = kS \qquad (2.18)$$

The cell mass (X) is proportional to the disc area (A) that gives:

$$\frac{Q}{A}(S_0 - S) = kS \qquad (2.19)$$

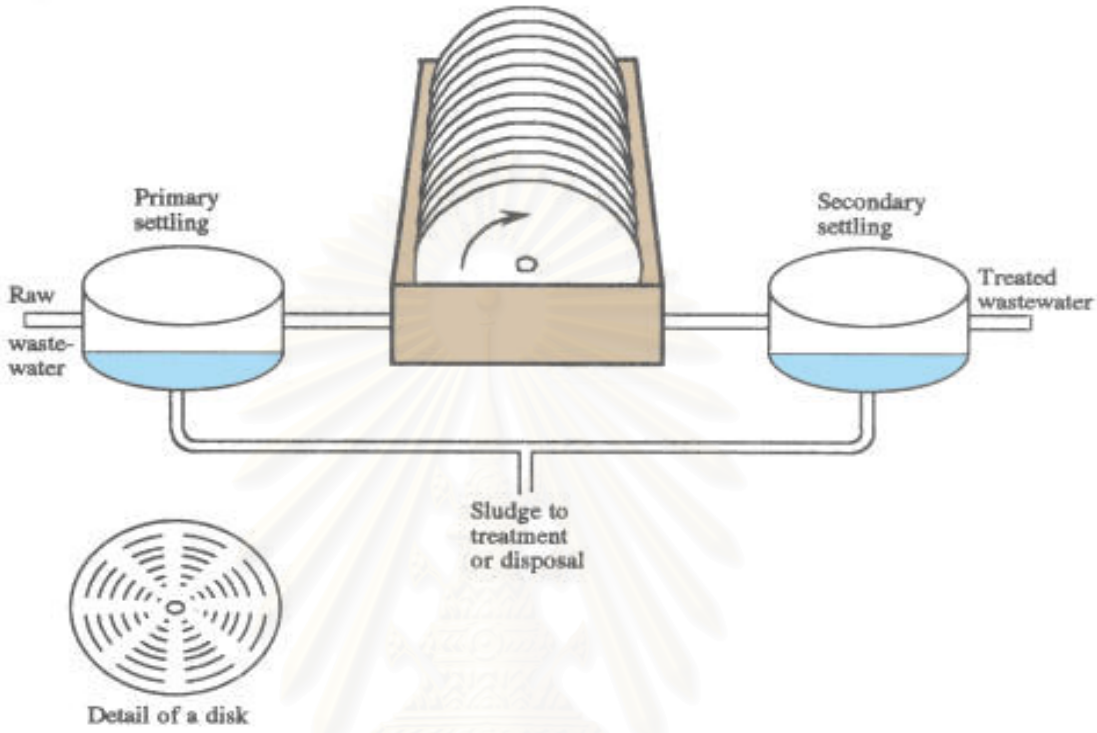
The term $(Q/A)(S_0\text{-}S)$ is equal to the rate of reaction (r). Thus,

$$\frac{Q}{A}(S_0 - S) = r = kS \qquad (2.20)$$

This equation is in the form y = mx, so it can be graphically represented as shown in Figure 2.7. Rearranging Equation (2.20) gives:

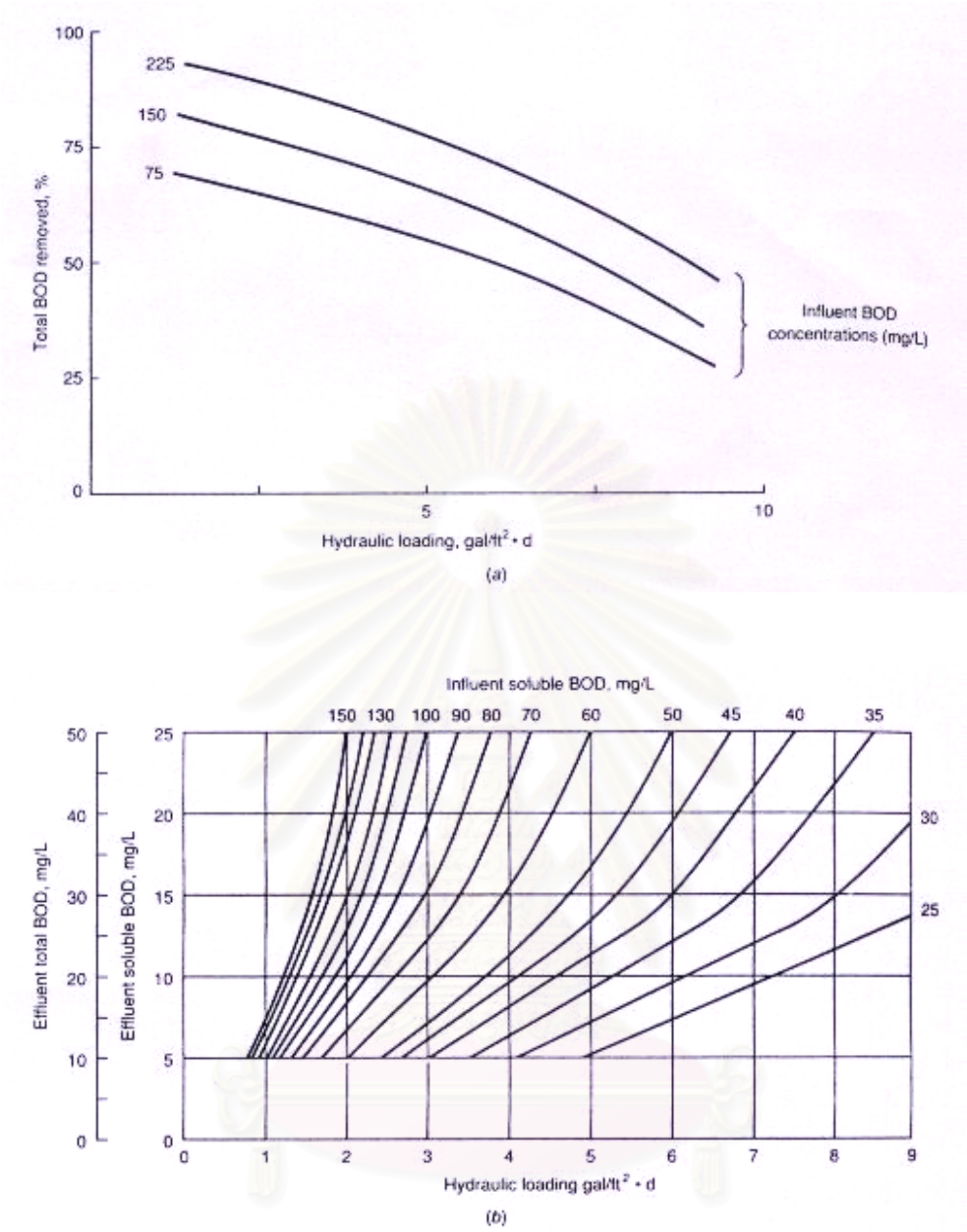
$$\frac{Q}{A} = \frac{r_1}{S_0 - S_1} = slope \qquad (2.21)$$

where r_1 is the rate of reaction for the biological contactor and S_1 is the substrate concentration leaving the contactor.



Source:http://www.fao.org/DOCREP/003/V9922E/V9922E05.htm#4.1.4%20Trickling%20filters

Figure 2.5 Typical RBC flow diagram for secondary treatment



Source: Metcalf & Eddy (1991)

Figure 2.6 RBC process design curve for: (a) total BOD removal and (b) total and soluble effluent BOD (T > 55°F)

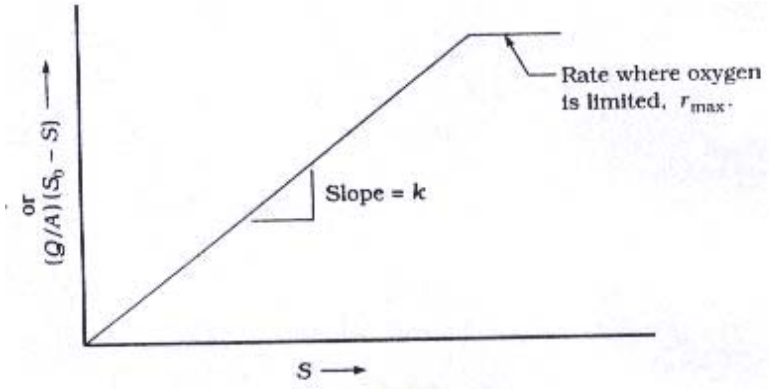
Equation (2.21) can also be represented graphically;a line from S_0 to r_1 has a slope = Q/A. As seen in Figure 2.8, it graphically shows the lines corresponding to Equation (2.20) and (2.21). The line from S_0 to r_1 has a slope (Q/A) equal to the hydrualic loading and the x value at r_1 is S_1, the substrate concentration leaving the contractor. For a series of contractors, Equation (2.21) can be generalized to give Equation (2.22) which represents any stage, n, in the series of multi-stage contactors.

$$\frac{Q}{A} = \frac{r_n}{S_n - S_{n-1}} \qquad (2.22)$$

An alternative method of estimating soluble organic removal in the inter-stages, devised by Opatken (1984), utilizes a second order reaction equation. The equation may be used for RBC design during the summer months; however, a temperature correction factor should be used for the cold winter months. Wastewater temperatures below 15°C decrease shaft rotational speeds and increase loping problems resulting with insufficient biomass sloughing. This equation is as follows:

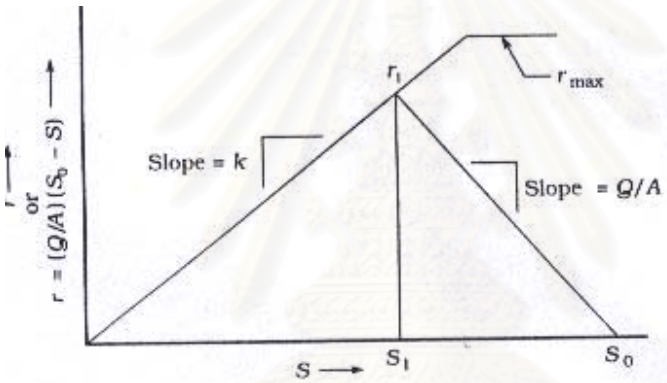
$$C_n = -1 + \frac{\sqrt{1 + 4kt\,(C_{n-1})}}{2kt} \qquad (2.23)$$

Where C_n is the concentration of soluble organics in the n^{th} stage (mg/L), k is the second-order reaction constant of 0.083 (L/mg/hr), t is the average hydraulic residence time in the n^{th} stage (hour) and C_{n-1} is the concentration of soluble organics entering the n^{th} stage (mg/L).



Source: Reynolds and Richards (1996)

Figure 2.7 Plot of Equation (2.20)



Source: Reynolds and Richards (1996)

Figure 2.8 Plot of Equations (2.20) and (2.21)

2.2 Overview of the Classical Measurement of Water Quality

Water quality could be assessed by measuring the treatment efficiency or degree of contamination in the water. The treatment efficiency is usually evaluated based on the percent reduction of organic contents through the process or the reduction of the propensity of contaminants to react with oxygen. Four traditional measurements used for measuring organic contents in wastewater are BOD, COD, TOD and TOC. The most widely used parameter is 5-day BOD (BOD_5). This assessment measures the dissolved oxygen utilized by microorganisms in the

biochemical oxidation of organic matter in 5 days of incubation. While COD measures the amount of oxygen used to oxidize organic compound by strong oxidizing agent. TOD assesses the amount of oxygen that oxidized the total organic matter in the sample when heated and catalyzed in a furnace. TOC is the only method which determines the amount of organic carbon presented in the sample. These determinations have advantages and limitations.

2.2.1 Advantages and Limitations of classical measurement of water quality

BOD is an analysis of both carbonaceous and nitrogenous oxygen demand used by microorganisms to oxidize organic content in water sample. BOD_5 is useful for measuring the biodegradable organic content of wastewater influents and effluents. It provides a good estimate of the bioactivity of organic with oxygen in the sample. However, low accuracy at values less than 4 to 5 mg/L was observed while the detection limit is 2 mg/L (APHA *et al.*, 1998). Moreover, it requires acclimated seed bacteria and a substantial period of time to obtain the result. The COD test has higher accuracy than BOD procedure at low concentrations but determines total organic content (except for pyridines and some aromatic compounds) rather than biodegradable organic content in water. The test also uses toxic chemicals and produces hazardous waste. TOD gives rapid result; however, its major limitation is the same as that of COD. TOD provides no indication of biodegradability. Furthermore, the TOD test could be interfered by organic nitrogen leading to underestimated results. Analysis of TOC is rapid with low detection limits and provides excellent precision and has fewer disadvantages compared to the other three parameters (Khan *et al.,* 1998a). It is applicable to small organic concentrations (0.05 to 0.1 mg/L). Nevertheless, TOC also does not provide information regarding the biodegradability level of water samples.

2.3 Biodegradable Dissolved Organic Carbon (BDOC)

Within the past two decades, BOM in water has become a major concern in water industries. BOM can be used by microorganisms as a carbon and energy source to promote growth and regrowth in the distribution system. In addition to the health risk, BOM in finished water can react with some disinfectants to form disinfection by-products (DBPs) that have been identified as potential carcinogens. Biological

processes can remove some of this organic matter during water treatment, leading to the decrease in disinfectant demand and consequently disinfection by products (Bouwer and Crowe, 1988).

The biodegradability and regrowth potential can be evaluated by many bioassays such as AOC and BDOC methods. Currently, several BDOC procedures have been developed to determine BOM in water. BDOC has been used for indicating finished water quality. High BDOC in finished water verifies poor quality of water and high potential for microbial regrowth. The microbial regrowth can be controlled by limiting BDOC availability for microbial growth. The strategy is not only a direct control of bacterial population, but also an indirect restriction of protozoan population through a trophic food web (Servais *et al.*, 1993).

2.3.1 Definition

Biodegradable dissolved organic carbon (BDOC) is the portion of the organic carbon in water that can be mineralized by heterotrophic microorganisms (Huck, 1990). Khan *et al.* (1998a) defined BDOC as the portion of DOC that is biodegradable.

2.3.2 BDOC Methods

During the last two decades, there has been an increasing interest in the measurement of BDOC in waters, especially in the field of drinking water. Because of its complexity and variability, chemical analysis is not helpful to characterize dissolved organic matter in waters. The use of a bioassay procedure is thus required. BDOC methods can be mainly divided into two types: Static and dynamic.

2.3.2.1 Static Methods

Static methods are sometimes referred to as batch procedures. General procedure consists of sterilization, reinoculation with a natural assemblage of bacteria followed by incubation (the procedure is performed in a closed system) for a period of time.

2.3.2.1.1. Biomass-Based Method

The general principle of the procedure involves quantifying BDOC by measuring the growth of microorganisms which are using dissolved organic matter present in the sample (Servais *et al.*, 1987). Billen-Servais (1987) proposed a procedure involving sterilization (by filtration through a 0.22 μm CA membrane, carefully rinsed first with distilled water and water sample), reinoculation with a natural assemblage of bacteria (same natural environment as the sample), and incubation in the dark at 20°C for a period of 10-30 days. During the incubation, bacterial biomass and bacterial mortality rate is monitored until total mortality and total biomass production is equal. The measurement of BDOC is based on an estimation of the flux of organic matter utilized by bacteria, deduced from biomass and mortality measurement. The values of BDOC found by this method are much higher when compared with the results obtained by other bioassays using a single strain of bacteria as a test organism (van der Kooij *et al.*, 1982). This method is too time-consuming for routine measurements even it provides sensitive and reliable results.

2.3.2.1.2 DOC-Based Methods

The DOC-based methods involve the measurement of a change in DOC concentration after a period of incubation. Joret *et al.* (1988) introduced a batch biofilm protocol. Their method uses pre-washed, biologically active sand (BAS) as an inoculum. The sand is washed until there is no detectable release of DOC. The sample and the sand are then placed in an Erlenmeyer flask and incubated at room temperature under aerated conditions for several days. Daily measurement of DOC is made until there is no further change, normally a period of three to five days. Using fixed flora allows a rapid response because of large quantities of bacteria involved in the biodegradation process. From the methodological point of view, the test is so simple, does not need fastidious microbiological measurements or pretreatment of the samples which can modify the state or the quantities of initial biodegradable organic content of water. It gives reliable results due to the large quantities of inoculated bacteria fixed on BAS.

The method of Servais *et al.* (1989) has the same initial sample preparation is the same as for the method of Billen-Servais (1987). The principle of the method is to sterlize by filtration the water sample containing organic matter to be tested, to inoculate it with autochtonous bacteria population, and to measure the decrease of DOC concentration due to the carbon oxidation by bacteria. In the case of ozonated or chlorinated water, sodium thiosulfate is added to neutralize the oxidant excess before the inoculum is added. The sample is then incubated at approximately 20°C in the dark for four weeks. BDOC value is calculated as the difference between the initial and final DOCs. This method provides no information on the kinetics of biodegradation.

Percherancier *et al.* (1996) introduced a simple procedure of batch experiments allowing the determination of the BDOC content of different effluent outfalls from wastewater treatment plants. The bioassay is based on the DOC reduction of treated wastewater samples inoculated with natural consortia of bacteria taken from river sediments or aquarium filters. This test allows routine determination of BDOC within a short period of time (less than 8 days). BDOC represents a still significant proportion of the treated effluent DOC, from 50% to 70%, depending on the effluent. The origin of bacterial inocula has no influence on the results, but is the main parameter for the rate of biodegradation.

Khan *et al*. (1998a) developed a batch BDOC protocol specifically for reclaimed and secondary-treated wastewater by combining the protocol of Servais *et al*. (1987) with the BOD techniques. Glass-fiber filters are used instead of 0.22-μm CA membrane filters because the membrane filters release a large amount of organic carbon that interferes with the procedure. Dilution and seed control techniques are included in the method to avoid dissolved oxygen depletion and to produce more accurate results. The detailed experimental protocol is as follows. The water sample was filtered through a 0.7 μm glass-fiber-filter (GF/F, Whatman, Whatman International Ltd., Maidstone, England) previously rinsed with deionized water containing less than 0.2 mg/L TOC. A 20-mL of filtered sample was collected, measured for TOC and recorded as DOC$_i$. Dilutions were prepared with dilution water (a commercial BOD nutrient buffer solution (HACH) mixed with deionized water) to produce at least 300 mL. After DO saturation by shaking, the mixture was placed into BOD bottle to measure DO$_i$ with a washed probe. A 2-mL inoculum of unfiltered

water sample was then added and the bottle was filled to the top with diluted sample. The BOD bottle was capped, water sealed with sample, and incubated in the dark for 5 days at 20°C. After 5 days, DO was measured and recorded as DO_5. Then, 100 mL of sample was discarded and the remaining mixture was resaturated by shaking daily and incubated under the same condition for additional 23 days. After the incubation, 20-mL of supernatant was collected and measured for TOC directly, and recorded as DOC*f*. A seed control (sample b) was prepared in the same way except that the 2-mL seed was added to 300 mL of dilution water without water sample, and the values were recorded as DOC*bi* and DOC*bf*. The BDOC and $SBOD_5$ are then calculated using the following equations:

$$BDOC\ (mg/L) = [(DOC_i - DOC_f) - (DOC_{bi} - DOC_{bf})]\ F \qquad (2.24)$$

$$SBOD_5\ (mg/L) = [(DO_i - DO_5) - (DO_{bi} - DO_{b_5})]\ F \qquad (2.25)$$

Where F is equal to (mL of dilution water + mL of sample)/mL of sample

The advantages of this method are reducing variability and increasing precision as compared to BOD and COD analyses. It is also capable of determining DOC, BDOC, and SBOD simultaneously.

2.3.2.2 Dynamic Methods

The methods are also known as biofilm reactor methods. It is a modified version of bioassay to allow routine determination of BDOC within shorter period of time by using a large biomass of bacterial assemblage fixed on a solid support. The sample is passed through the column, and the BDOC value can be calculated from the difference between the DOC values of inlet and outlet samples. The measurement could be accomplished within only 2-3 hours.

The method of Lucena *et al.* (1990) was developed specifically to suit the needs of water industry. It circulates water sample continuously upflow over biofilm attached to sand particles inside a glass column. BDOC value corresponds to the DOC reduction when inlet and outlet water samples are compared. The delay between the two sample collections depends on the retention time of the column. This BDOC

analysis takes about two hours. This method provides slightly lower but similar BDOC values to those obtained with other methods involving indigenous bacteria, free (Servais *et al.*, 1989) or fixed to sand (Joret *et al.*, 1988), for GAC-filtered and distribution waters.

Ribas *et al*. (1991) proposed a dynamic procedure that measures BDOC by circulating water continuously across two glass columns filled with special supports for biofilm attachment called Siran®. The BDOC value corresponds to the difference in DOC between inlet and outlet water samples. The initial assay was performed on one column but the final design consists of two columns in series for the reason of significantly higher effectiveness. The connections between the different parts are made of glass and silicone tubing. The BDOC results provided by this method are not significantly different from other BDOC bioassays based on the use of indigenous bacteria. Although the duration of the analysis is only two to three hours, it is very difficult to standardize the method. There is a high variability in the time required before the good performance of the system was reached (from 15 to more than 40 days). Other advantage over other methods is that it resembles water treatment and distribution processes, where the water is circulating across different biofilm.

Frias *et al.* (1992) modified the protocol of Ribas *et al.* (1991) specifically for measuring the BDOC in discrete samples. The Siran® support was colonized by water mixture for 5 days and the biofilm was adapted to the sample of water within 5 to 8 days. Once this period had passed, the column was ready to perform BDOC determinations. The samples for DOC analyses were taken daily, and the BDOC was calculated as the difference between the initial DOC and the minimum value obtained in the period of analysis (5 days typically). Even this method had reduced the colonization time into 10-20 days, the overall measuring time was still long because it required at least 5 days of analysis.

Kaplan and Newbold (1995) developed plug-flow biofilm reactors colonized by microorganisms indigenous to stream water to measure BDOC. The bioreactor was patterned after a design of Ribas *et al.* (1991) and was constructed of paired borosilicate chromatography columns with polyethylene bed supports (Chromaflex®, Knotes) filled completely with borosilicate glass beads (Siran®, Schott). Two different sized bioreactors were used. The columns were kept in the dark and supplied continuously with water in an upflow mode using a peristatic pump. Water filtered

through a 2-stage glass-fiber cartridge system (Balston) was fed to the bioreactors then stored in a covered 1001-polyethylene reservoir at 12-28°C, depending on the season. Both discrete and continuous DOC measurements of inflow and outflow water were performed. Finally, DOC concentrations between the inflow and outflow water were measured. The advantage of this method is the ability to monitor BDOC concentrations with measurements that can be accomplished within minutes to hours. Nevertheless, biofilm reactor required an extended period of colonization at least 4-6 months. It was found that the biological removal of DOC within the reactors is influenced by hydraulic residence time, DOC concentration, and water temperature.

2.3.3 BDOC applications

2.3.3.1 Indicating Raw Water Quality

BDOC has been used for indicating raw water quality and measuring the effect of water treatment processes. Servais *et al.*(1987) applied a batch BDOC procedure to test raw water from different sources: Two river waters, urban sewage, and seawater. Hascoet *et al.* (1986) applied a static method (Servais *et al*., 1987) to test river water in France and proposed the idea of using BDOC as another parameter for characterizing raw water. Servais *et al.* (1989) measures BDOC in the three Belgian rivers using a revised BDOC method. Two of the rivers were more contaminated by domestic and industrial wastewater than the other. BDOCs of the more contaminated rivers were two to nine times higher than those of the least contaminated river. Morgren *et al*. (1990) applied their dynamic BDOC protocol to test three raw water sources in the United States: Ohio River, Florida ground water, and Delaware River water. They concluded that all three sources had low BDOC concentrations (0.32 mg/L, 0.75 mg/L, and 0.45 mg/L). Ribas *et al.* (1992) used their dynamic bioreactor method (Ribas *et al*., 1991) to monitor BDOC in a Spanish river that served as a water supply for the City of Barcelona. The BDOC and DOC were influenced by the flow of the river. Paode *et al.* (1997) studied the formation of BOM by measuring BDOC concentration in raw and ozoned water. They found that raw water BDOC was a function of DOC and chlorophyll while BDOC in ozoned water was a function of ozone dose.

2.3.3.2 Indicating Finished Water Quality

The use of BDOC has been related to regrowth of microorganisms in the distribution system. Many authors (Rittman *et al.*, 1984 and Le Chevallier *et al.*, 1988) stated that high BDOC in finished water indicated poor quality and a potential for microbial multiplication. Le Chevallier (1988) also reported that maintaining free chlorine residual could prevent the regrowth along the distribution system. However, a large amount of chlorine is required. In addition, chlorine residual cannot completely inactivated fixed bacteria. Thus controlling microbial dynamics by limiting available substrate (BDOC) is an interesting approach. Servais *et al.* (1993) investigated the effect of BDOC on bacterial dynamics in a distribution system in France between 1988 and 1992. The study demonstrated that removal of BDOC to a threshold level of 0.15 mg/L provides a direct control of bacterial growth when there is no residual chlorine in the finished water. Furthermore, it can be an indirect control of protozoan population through a trophic food web.

Gatel *et al.* (2000) stated that it is necessary to decrease the DOC and BDOC to avoid health risks and to have sanitation in drinking water system. Reduction of DOC and BDOC also increased chlorine stability during distribution and reduced the formation of trihalomethanes (THM). The dual approach, based on pilot results, modeling and full-scale studies, was used by Syndicat des Eaux d'Ile de France (SEDIF) for the Paris suburbs. Pilot and modeling studies were conducted to indicate to what degree BDOC should be removed in plants to limit bacterial regrowth. However, the study showed that bacteria such as *Escherichia coli* can survive and even there is low nutrient (BDOC) level in the distribution system. Consequently, biological treatment was introduced by SEDIF into its water plants to optimize BDOC removal, and chlorine booster station was installed to attain a free chlorine residual of 0.1 mg Cl_2/L throughout its supply system. Some small regrowth was still observed in the distribution system, through DOC consumption in the network and increase in viable bacterial counts. Nonetheless, quality control data indicate that a good bacteriological quality was attained, with minimum quantities of disinfection by-products (DBPs).

Niquette *et al.* (2000) used a batch procedure to evaluate the quality of waters in Brussels' distribution systems that were produced from three raw waters: ground

water, treated surface water, and mixed water. They observed that the finished water produced from surface water and mixed waters had the highest potential of bacterial regrowth. The factors that influenced the regrowth included BDOC, chlorine residual, residence time, water temperature, and characteristics of pipes. They also proposed the three threshold indicators to determine the potential of bacterial growth in the distribution system: temperature above 15^{o}C, chlorine residual below 0.07 mg Cl_2/L, and effluent BDOC of more than 0.25 mg/L.

Carlson *et al.* (2000) conducted a study to evaluate the impact of soluble microbial products (SMPs) formed in drinking water biofiltration process. Two approaches were used in the study. First, pilot scale biofilter was developed and the SMPs and BOM were determined according to the accumulation of biomass on filter media. Another approach, synthetic water consisted of known compounds was applied through the biofilter. The differences between known carbon removal and DOC removal were calculated as SMP concentration. The results were compared between the two approaches and indicated that SMPs was significantly related to the DOC removal during biofiltration. Estimation of BOM by measuring DOC removal could result in 17-33 % error when SMPs was found and SMPs could be negligible if the BOM fraction of the filter influent DOC was small. The study also showed that the production of SMPs was dependent upon BOM utilization rate and accumulated biomass.

Volk *et al.* (2000) used two BDOC approaches (Volk *et al.*, 1994 and Kaplan *et al.*, 1993 as cited in Volk *et al.*, 2000) for evaluating biodegradable organic matter accompanied with coliform regrowth measurement in distribution system. It was found that BDOC obtained from the sand method (Volk *et al.*, 1994) was similar to the bioreactor measurement (Kaplan *et al.*, 1993). The bioreactor was useful, however, it suffered from a requirement of long time colonization (6-8 months) and cost of maintenance. They suggested that the sand method could be more preferably applied to a short period experiment. AOC and BDOC should be monitored in water treatment plants and distribution systems because they provided different pieces of information. The three threshold indicators to determine the potential of coliform growth in distribution system were proposed: temperature above 15^{o}C, disinfectant residual below 0.5 mg/L, and AOC effluent of more than 100 μg/L.

2.3.3.3 Designing, Monitoring, and Optimizing Operationing Conditions of Biologically Activated Carbon (BAC) System

Hascoet *et al.* (1986) and Servais *et al.* (1991) conducted a study to evaluate the effect of filer media and depth on BDOC in distribution system and reported that BDOC removal occurred in only the first 20-40% of biological activated carbon filter (BAF) depth and the highest BDOC removal (70%) was reached at the filtration velocity of 6 m/h. Merlet *et al.* (1991) used the BDOC method of Servais *et al.* (1987) to determine parameters to optimize BDOC removal by BAC filtration. They stated that BDOC removal was a function of empty bed contact time (EBCT) and increased with increasing EBCT. They also indicated that the most important compound when optimizing BDOC or chlorine demand removal was amino acid because it provided the most chlorine reactivity.

Malley *et al.* (1993) compared the performance of enhanced slow sand filters in pilot-scale and full-scale treatment plants. BDOC in finished water from the enhanced pilot filter was lower than that from the full-scale plant. The effective O_3 dose for removing nonpurgeable dissolved organic carbon (NPDOC), UV absorbance, and trihalomethane formation potential (THMFP) was 2.0 mg of O_3 consumed/mg of NPDOC. They showed that even most cost-effectiveness ozone dosage would significantly increase BDOC in both pilot and full-scale GAC systems. Hascoet *et al.* (1986) reported that backwashing had an adverse effect on the biomass in the BAF. On the contrary, Servais *et al.* (1991) monitored bacteria populations in the outlet of BAF in a drinking water plant and concluded that backwashing the filter has no significant effect on microbial function.

2.3.3.4 Measuring the Effect of Water Treatment Processes Other than BAC

Many researchers (Hascoet *et al.*, 1986, Servais *et al.*, 1987, Morgren *et al.*, 1990, Ribas *et al.*, 1992, and Ribas *et al.*, 1997) found that BDOC increased after ozonation and optimum ozone dosage varies with water characteristics. Volk *et al.* (1993) stated that a short contact time and a medium to high ozone dosage (0.5-1.0 mg O_3 per mg DOC) was preferred over a long contact time (5 minutes) and a low ozone dosage in optimizing BDOC formation. Volk *et al.* (1996) compared the effect of three different disinfection processes used in water treatment, which were ozone, ozone-hydrogen peroxide, and catalytic ozone on organic carbon in fulvic acids. The

result showed that catalytic ozone could generate the most effective BDOC removal in a synthetic solution. Paode *et al.* (1997) found that BDOC level was a function of raw water characteristic and ozone dosage while AOC level was related to raw water characteristic and aldehydes concentration.

Morgren *et al.* (1990) applied their dynamic BDOC method to evaluate the effect of three different drinking water treatment processes on BDOC. The first treatment plant used raw water from the Ohio River. It was observed that chlorination resulted in a BDOC increase in effluent and had no effect on DOC reduction. For the second plant which its raw water was Florida groundwater, without preozonation, there was insignificant DOC removal in the filter (anthracite/sand). When the lime soften water was ozonated, BDOC increased but DOC remained constant. Samples were collected from the processes of ozonation, super-pulsator and parallel-dual media filters of the third plant which received raw water from the Delaware River. They found that the super-pulsator was very effective in removing BDOC and DOC. The effluent BDOC from filters (packed in different combination of media, anthracite/sand, or GAC/sand) was similar to those from the super-pulsator.

Dossier *et al.* (1996) analyzed BDOC, total amino acids (and humic substances), and chlorine demand monthly at different steps of the water treatment plant of Méry-sur-Oise (270 000 m^3/d) in Paris, France. DOC in raw water reached 5.6 to 6.5 mg C/L during the cold season, and the average yield of elimination through the plant was generally close to 40 %. BDOC, which represents 25 to 50 % of the DOC in the raw water, was partially removed in the plant and only 0.4 to 1.8 mg/L of BDOC concentration was found in treated water. A transitory BDOC increase of 0.2 to 0.5 mg/L was generally observed during the ozonation step. No direct relationship could be demonstrated between amino acid concentrations and the respective values of BDOC or of chlorine demand potential. On account of the BDOC and chlorine demand potential, no correlation could be shown between these two parameters. The results obtained indicate that the small amounts (5 to 25% of the BDOC value) of total dissolved amino acids present in treated water. About 5 to 23% of total dissolved amino acid originated from the total chlorine demand potential. It was noticed that only 2 to 7% of total amino acids was contributed to the DOC values of treated water, but they may account for a larger proportion of BDOC or chlorine demand potential (5 to 25%).

Siddiqui *et al.* (1997) used a biofilm reactor (Morgren *et al.*, 1990) and proposed the ratio of applied ozone dose to DOC at 2:1 (mg/mg) to obtain good results of BDOC removal and reduction of DBPs formation. Applying this dose ratio, the reduction of DOC was 40-50%, aldehydes was decreased as much as 90-100%, and trihalomethane (THM) formation potential was reduced 40-60%.

Ribas *et al.* (1997) used several BDOC procedures (Joret and Levi, 1988, Servais *et al.*, 1987, and Ribas *et al.*, 1991) to characterize the performance of various water treatment processes in a new drinking water plant at Barcelona. The results demonstrated that GAC and ozonation added to the conventional processes (break-point prechlorination, flocculation-sedimentation, and sand filtration) led to a higher efficiency in DOC and BDOC removal.

Carlson *et al.* (1998) conducted a pilot-scale biofiltration experiment to determine how EBCT and hydraulic loading rate (HLR) affected the removal of biological organic matter by using BDOC, biomass, and ozone by-products (OBPs) as indicators. The removal of DOC during biofiltration could be controlled by biomass concentration which was a function of EBCT. Thus biomass concentration could be a better parameter for optimizing and operating filter design than BDOC. Results also indicated that HLR had no effect on BDOC even when the biomass profile was different.

Escobar *et al.* (1999) conducted a study to evaluate the effect of various operational conditions of nanofiltration (NF) on the bacterial growth potential as indicated by AOC and BDOC concentration in distribution system. Three treatment process types were compared in the study; NF alone, NF with lime softening, and lime softening alone. The order of effectiveness for removal BDOC is nanofiltration alone, nanofiltration with lime softening, and lime softening alone, respectively. Although NF attained high efficiency of BDOC removal, it was less effective in reduction of AOC.

Volk *et al.* (1999) evaluated the effect of enhanced optimized coagulation and compared the performance of different coagulants on BDOC removal. They stated that DOC and BDOC removal were improved through the application of optimized coagulation. Ferric coagulants usually performed better DOC removal than alum or poly aluminum chloride.

Shaw *et al.* (2000) applied the BDOC method of Servais *et al.* (1989) to evaluate the effects of UV irradiation on organic matter of two surface water and two

ground water sources. No significant BDOC difference was observed between pre and post UV treatment. However, BDOC increased from the addition of nutrient in some cases.

Carlson *et al.* (2001) integrated data from a previous study (Carlson and Amy, 1998) that used bench-scale and pilot-scale testing for optimizing ozonation and biofiltration processes. They applied a shaker method (Wang *et al.*, 1995) to determine BDOC and DOC during the study. BDOC formed during ozonation was classified as either biofilter removable ($BDOC_{rapid}$) or not removable ($BDOC_{slow}$) and thus was released to the distribution system. The two BDOC fractions are defined as follow:

$$BDOC_{total} = BDOC_{5\ days} = DOC_0 - DOC_{5\ days} \quad (2.26)$$

$$BDOC_{rapid} = BDOC_{60\ min} = DOC_0 - DOC_{60\ min} \quad (2.27)$$

$$BDOC_{slow} = BDOC_{total} - BDOC_{rapid} \quad (2.28)$$

They found that limiting ozone (O_3) could affect only $BDOC_{rapid}$ in the distribution system and applying the ozone dose beyond the optimized dose (1.0 mg O_3 /mg DOC) would increase cost detriment. Their data in the previous study also showed that longer contact time was more necessary for optimizing DOC and BOM removal than for the removal of OBPs.

2.3.3.5 Indicating the Quality of Reclaimed and Secondary Treated Wastewater

Servais *et al.* (1998) conducted a study to investigate impact of the waste waster effluents from three treatment plants of the city of Paris and its bounds on the river Seine by using a BDOC procedure (Servais *et al.*, 1995 as cited in Servais *et al.*, 1998). The treatment plants used different processes including the decantation, nitrification biofiltration, and activated sludge process. The wastewater was analyzed for DOC, particulate organic carbon (POC), BDOC, biodegradable particulate organic carbon (BPOC), and BOD. POC was mainly removed by decantation process. They also found that the particulate organic matter in activated sludge process was lower

than that produced from decantation process. BDOC removal could be improved by increasing the residence time in activated sludge process.

Khan *et al.* (1998a) applied their BDOC protocol to characterize the quality of the municipal reclaimed and secondary treated wastewaters with moderately low DOC concentration (4-15 mg/L). The results provided by incubation temperatures of 20°C and 37°C were not different for ultimate BDOC in reclaimed water. BDOC at 20°C was 75% of BDOC at 37°C for the secondary treated effluents. BDOC provided more sensitivity than SBOD. Khan *et al.* (1998b) observed that higher BDOC concentrations were found in lower SRT wastewater treatment plants. They proposed that BDOC could be used as a water quality parameter for secondary effluents. Strong relationships among three parameters (BDOC, DOC, and SCOD) were obtained. For reclaimed wastewater reclamation, the biodegradability was increased during ozonation. The measurement of SBOD and BDOC provided similar results; however, the data demonstrated that BDOC was more accurate and precise.

Khan *et al.* (1999) studied factors influencing BDOC measurement. In order to facilitate BDOC use as a routine parameter for characterizing plant performance, inocula requirement, temperature and other experimental conditions for its procedure were investigated and optimized. They used four different types of inocula (2 mL effluent inoculum, 10 mL effluent inoculum, 2 mL commercial inoculum, and 2 mL MLSS inoculum) to characterize four types of water samples (standard solution, secondary effluent and non-ozonated and ozonated secondary effluent). The fastest BDOC exertion rate was attained when using 2 mL MLSS inoculum. They concluded that it was possible to measure BDOC within 5 days using a larger volume of MLSS inoculum.

Babcock *et al.* (2001) used a simple BDOC method (Khan *et al.*, 1998a) to evaluate wastewater effluent organic content and to derive a relationship between BDOC and SRT of bench-scale and full-scale activated sludge process. Relationships that enabled the prediction of effluent BDOC from SRT, initial DOC (DOC_i), and DOC remaining after 5 days (of BDOC incubation) for bench-scale continuous-flow stirred tank activated sludge reactors treating synthetic wastewater, were presented. However, there were doubts about the prediction when treating the real wastewater. There was no clear relationship between SRT and effluent BDOC from the full-scale WWTPs. It was found that BDOC values correlated well with DOC, $SBOD_5$, and

SCOD values. They also compared secondary wastewater quality provided by WWTPs in Hawaii and California and reported that the BDOC, DOC, SCOD, and $SBOD_5$ concentrations were slightly higher in the effluents from the plants in Hawaii.

CHAPTER 3

METHODOLOGY

3.1 Activated Sludge and Trickling Filter Studies

3.1.1 Sample collection and preparation

Primary wastewater from the Red Hook Water Pollution Control Plant (Brooklyn, New York) was used as raw water in both systems. The treatment plant is a step aeration activated sludge wastewater treatment plant with a capacity of 60 MGD. The actual flow is 40 MGD and SRT is 5 days. Mixed-liquor suspended solid (MLSS) from the aeration tank of this plant was also collected and used as a seed during the start-up period of activated sludge unit.

3.1.2 Experimental set up and operation

3.1.2.1 Activated Sludge

3.1.2.1.1 Experimental set-up

A bench-scale activated sludge unit was constructed from a plexiglass as shown in Figure 3.1. The unit had a 6.25-liter completely mixed aeration zone and a 3.5-liter internal sedimentation zone. Aeration was provided by sparging air. The air went through fine bubble ceramic diffusing stones to maintain DO at 3 to 4 mg/L.

3.1.2.1.2 Experimental operation

At the beginning, the bioreactor was seeded by using MLSS from the aeration tank of the Red Hook Water Pollution Control Plant. Before each experiment, the wastewater sample was fed through the unit until a steady state condition was reached (The pH and MLSS variations were less than ±10%). Each wastewater sample was continuously pumped through the reactor at seven different SRTs: 0.5, 1, 3, 5, 8, 10, and 15 days with feeding rates as shown in Table 3.1.

Influent samples were collected from the inflow pipe of the reactor after1 hour of new feeding. After that, the influent samples were taken at 10, 15, 30, and 60 minutes passed, then every hour for three hours.

At each SRT tested, the unit was operated until at least 20 representative influent samples were collected. Solids were constantly recycled from the sedimentation to the aeration zones by pumping at the same flow rates as the influent feeding rates shown in Table 3.1.

To control the SRT, sludge was manually wasted by removing sufficient mixed liquor from the aeration zone. Each SRT was performed until steady state was reached. (It should not have more than 10% variation of mixed liquor biomass and effluent substrate concentrations). Then, effluent samples were collected at 15, 30, 45, and 60 minutes and every hour for 3 hours. Operation was continued until at least 20 effluent samples were obtained. Figure 3.2 shows a set up of AS unit. The unit was operated at room temperature.

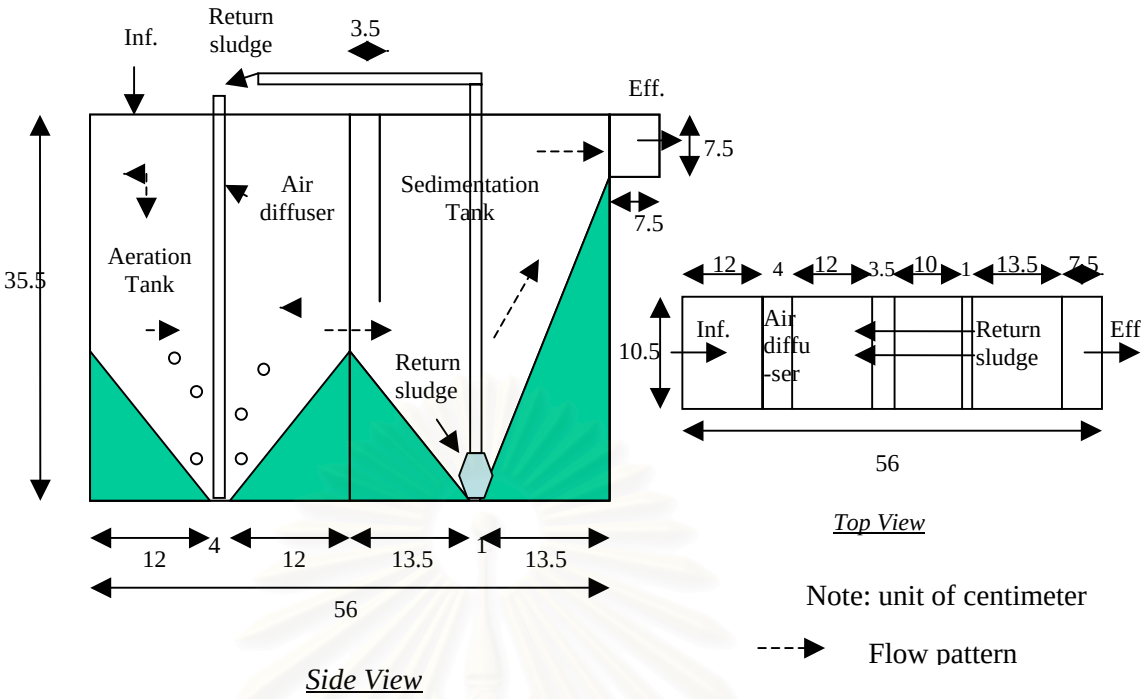


Figure 3.1 Dimensions of activated sludge bench-scale unit

Figure 3.2 The bench-scale AS unit during normal operation

3.1.2.2 Trickling Filter

3.1.2.2.1 Experimental set-up

A packed tower of rock media was constructed from a plexiglass tube with an inside diameter of 43 cm and a height of 61 cm laid on a square collecting basin. The collecting basin was 50 x 50 x 20 cm (WxLxH). The distributor was made of plastic tube with an inside diameter of 0.5 cm connected above the filter. The entire filter bed was 25 cm in depth comprising rock media with an approximate diameter of 12.25 mm. The base of media support was constructed by overlapping sheet of plastic net and a sturdy plastic mesh into a cylinder. The plastic mesh holds the filters and plastic net in place. Figure 3.3 shows a schematic of the TF bench scale unit and its dimensions.

3.1.2.2.2 Experimental operation

Figure 3.4 illustrates the bench-scale TF unit during normal operation. In the first experiment, primary wastewater was circulated through the biofilter for three weeks (A new batch of primary wastewater was used every week to maintain sufficient substrate in the reactor) to grow the attached microorganisms. The primary wastewater was pumped through the distributor at five different hydraulic loading rates (HLRs): 0.5, 3, 5, 10, and 15 m^3/m^2-d. HLRs tested represent typical HLRs used for full-scale TFs: 0.5 m^3/m^2-d for low rate TFs, 3 and 5 m^3/m^2-d for intermediate rate TFs, 10 m^3/m^2-d for high rate TFs, and 15 m^3/m^2-d for super high-rate TFs. Influent samples were collected from the distributor 1 hour after feeding, then at 30, 60, 120, 180 minutes, respectively. Sedimentation occurred in the collecting basin and the effluent overflow to the recirculating tank, where it was pumped to the filter at the same rate as the feeding rate in order to dilute the strength of the incoming wastewater and to maintain the biological slime layer in a moist condition. Each HLR was performed until steady state was reached (pH and effluent substrate concentration variations were less than 10%) Effluent samples were collected from the effluent outlet at 15, 30, 45, and 60 minutes after the steady state of the new feeding was reached. After that, it was taken every 30 minutes. Each experiment was performed until at least 20-representative influent and effluent samples were taken.

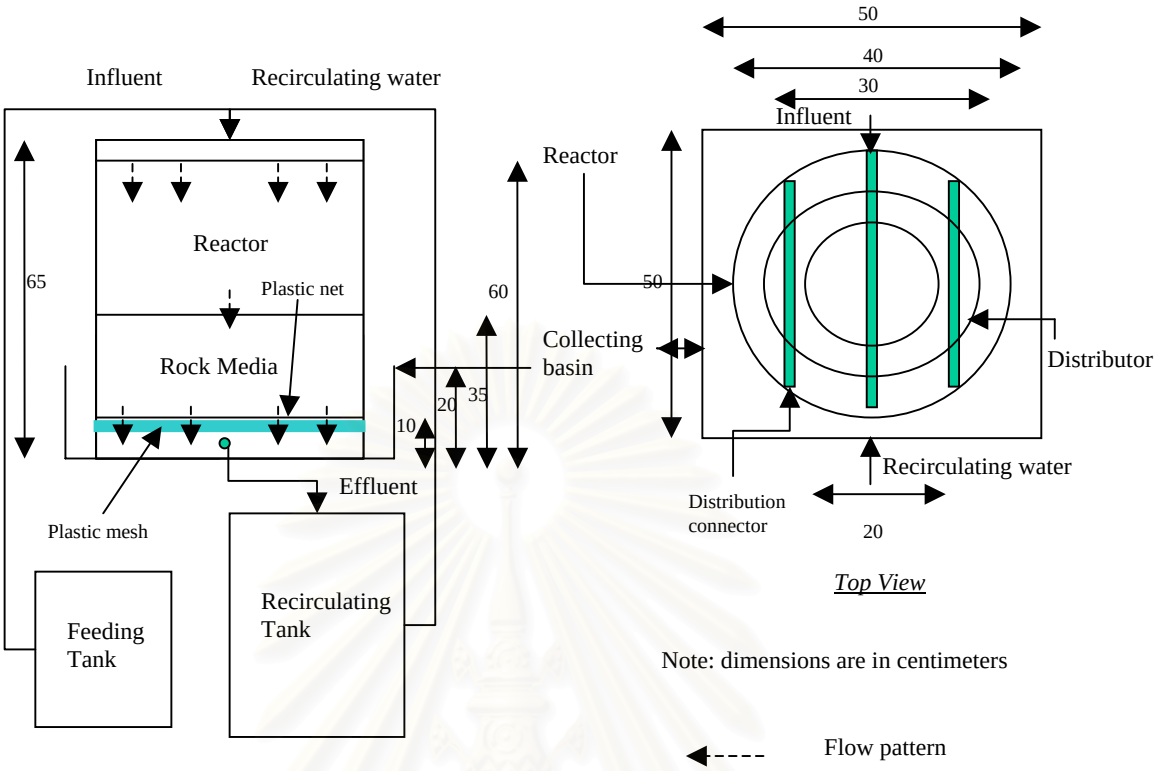


Figure 3.3 Schematic and dimensions of trickling filter bench-scale unit

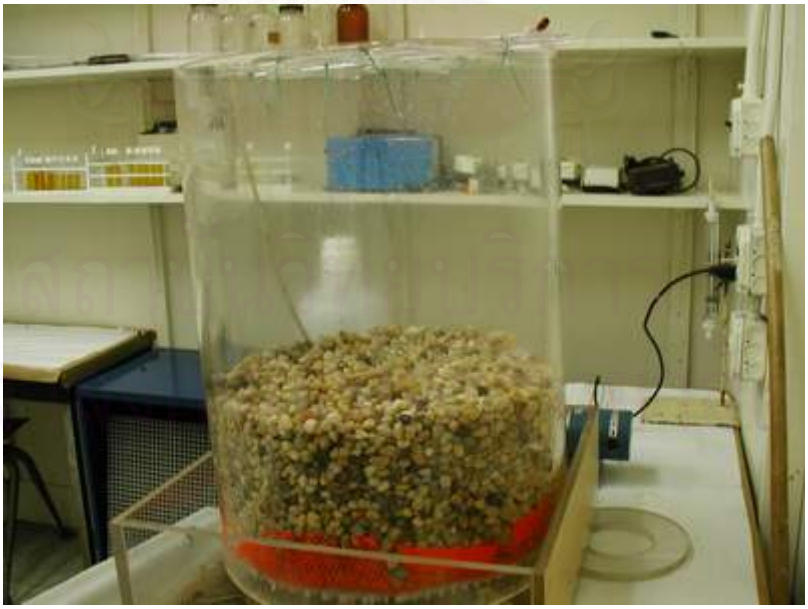


Figure 3.4 The bench-scale TF unit during normal operation

Table 3.1 Feeding rate in each SRT and HLR in AS and TF units

SRT (days)	Feeding rate (L/d)	HLR (m^3/m^2-d)	Feeding rate (L/d)
0.5	135.3	0.5	15.7
1	135.3	3	94.2
3	50.2	5	157.1
5	33.2	10	314.2
8	23.6	15	471.0
10	20.4		
15	16.2		

Note: Feeding rates and return sludge rates were the same in AS
Feeding rates and recirculation rates were the same in TF

3.2 Rotating Biological Contactor (RBC) Studies

3.2.1 Sample collection

Composite samples of treated wastewater were collected daily from secondary settling tanks of the Rockland County Sewer District No.1 Treatment Plant. The facility is located in Orangeburg, New York. The district sewer service is served people in the Towns of Ramapo, Clarkstown and some of parcels in the Town of Orangetown. The original capacity of the wastewater treatment plant was 10 MGD, and it was expanded to 26 MGD in the mid 1980s. The treatment process comprises mechanical screens, grit chamber, primary sedimentation, rotating biological contractors, the secondary sedimentation, and chlorination. The treated wastewater was then discharged into the Hudson River through an outfall sewer. The secondary treated effluents were collected daily from two parallel sections, A and B, for 50 consecutive days. Section B (new section) was originally designed to handle BOD loading approximately twice from section A (old section).

3.3 Analyses

BDOC was measured simultaneously with $SBOD_5$ according to Khan *et al.* (1998a). Other analyses were conducted according to *Standard Methods* (APHA *et al.*, 1998) as indicated in Table 3.1. For $SBOD_5$, SCOD, DOC and UV_{254}, the samples were filtered through a 0.7 μm glass-fiber-filter (GF/F, Whatman, Whatman International Ltd., Maidstone, England) prior to the analyses. Each of wastewater samples was analyzed in duplicate. Table 3.2 illustrates the parameters which were studied for each biological process.

Table 3.2 Analytical Methods and Instruments

Analytical Measurement	**Method, Reference**
1. pH	pH meter (ORION, model 710A), *Standard Methods* (Method 2310A and B; APHA *et al.*, 1998)
2. MLSS	TSS measurement, *Standard Methods* (Method 2540 D; APHA *et al.*, 1998)
3. $SBOD_5$	*Standard Methods* (Method 5210B; APHA *et al.*, 1998).
4. SCOD	Closed reflux method, *Standard Methods* (Method 5220C; APHA *et al.*, 1998)
5. DOC	combustion infrared method, *Standard Methods* (Method 5310B; APHA *et al.*, 1998)
6. BDOC	Method of Khan *et. al* (1998a)
7. UV_{254}	Spectrophotometer (SPECTRONIC GENESY-2), *Standard Methods* (Method 5910B; APHA *et al.*, 1998)

Table 3.3 Parameter Determination in each biological process

Process	Sample	pH	MLSS	SBOD	SCOD	DOC	BDOC	UV_{254}
AS	Influent	*	*	*	*	*	*	
	Effluent	*		*	*	*	*	
TF	Influent	*		*		*	*	
	Effluent	*		*		*	*	
RBC	Influent	*		*		*	*	*
	Effluent	*		*		*	*	*

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Effect of SRT on BDOC and other parameters in Activated Sludge Process Study

The bench-scale AS unit was initially seeded with active activated sludge and operated continuously for 10 to 20 days with a constant HRT of 0.25 day. COD, MLSS and pH were monitored in each experiment until a steady state was reached. Figure 4.1 shows the relationship between MLSS and SRT. The error bars illustrate the standard deviations of each experiment. The standard deviations were calculated based on the 20 representative samples as described in Chapter 3. It was observed that longer SRT resulted in larger MLSS values. This was because the mass concentration of microorganisms should increase with SRT as shown in Equation (2.7).

Figure 4.2 shows the influent and effluent pH on different experiments (SRT); pH slightly increased after the process. The increasing pH was resulted from ammonia produced from both ammonification and endogenous respiration of microorganisms which could react with H_2O and formed some basic compounds (ammonium ion).

An average SCOD concentration of the influent (primary treated wastewater) was 123 mg/L (ranged from 116 to 131 mg/L). Effluent SCOD values were between 28 and 47 mg/L with an average of 35.6 mg/L as presented in Figure 4.3.

The SCOD removal is illustrated in Figure 4.4. The removal decreased as a function of an increasing SRT. This is unusual when compared to previous studies (Kim and Jeong, 1997; Seo *et al.*, 1997) because the removal efficiency should be higher with a larger SRT. This was resulted from the errors of the SCOD method.

Figure 4.5 presents influent and effluent $SBOD_5$ of the AS process at different SRTs. The $SBOD_5$ in influent was fairly scattered and varied from 18 to 32 mg/L while the mean value was 23 mg/L. After the treatment, $SBOD_5$ was reduced to an average of 2.19 mg/L (ranged from 2.00 to 3.67 mg/L). It is noted that at SRT of 5, 8, 10, and 15 days, the $SBOD_5$ detection limit of 2 mg/L was used to represent the effluent $SBOD_5$ which were lower than the detection limit. This shows the insensitivity of BOD at low organic concentrations provided by the system at higher SRTs.

Figure 4.6 shows the relationship between $SBOD_5$ removal and SRT. The efficiency of $SBOD_5$ removal was very high (86 to 94%). $SBOD_5$ removal increased with increasing SRT at lower SRTs and slightly dropped from 94 to approximately 91% at SRT of 10 and 15 days. The relationship between BDOC removal and SRT was similar to those obtained from a previous study (Kim and Jeong, 1997).

Figure 4.7 illustrates a plot of influent and effluent BDOCs against SRT. The influent BDOC ranged from 11.18 to 18.59 mg/L with an average of 14.84 mg/L. BDOC dropped to 3.59 mg/L (0.59 to 6.57 mg/L) in the effluent. The effluent BDOC profile was similar to that obtained from the study of Babcock *et al.* (2001). The effluent BDOC decreased nonlinearly when SRT was increased. Unlike BOD, BDOC was able to distinguish the amount of biodegradable organic at lower organic concentrations.

The BDOC removal efficiency is illustrated in Figure 4.8. Higher BDOC removal was observed at higher SRT. The BDOC removal profile shows a sharp increase at the initial SRTs and its trend line stabilizes at higher SRTs.

Figure 4.9 shows DOC concentrations in both influent and effluent versus SRT. Influent DOC fluctuated while DOC in effluent was relatively constant at lower SRTs. Both influent and effluent DOCs slightly decreased at the SRTs of 10 and 15 days.

The relationship between DOC removal and SRT is shown in Figure 4.10. The removal efficiency fluctuated at lower SRTs and increased between SRT of 5 to 10 days and slightly dropped at an SRT of 15 days.

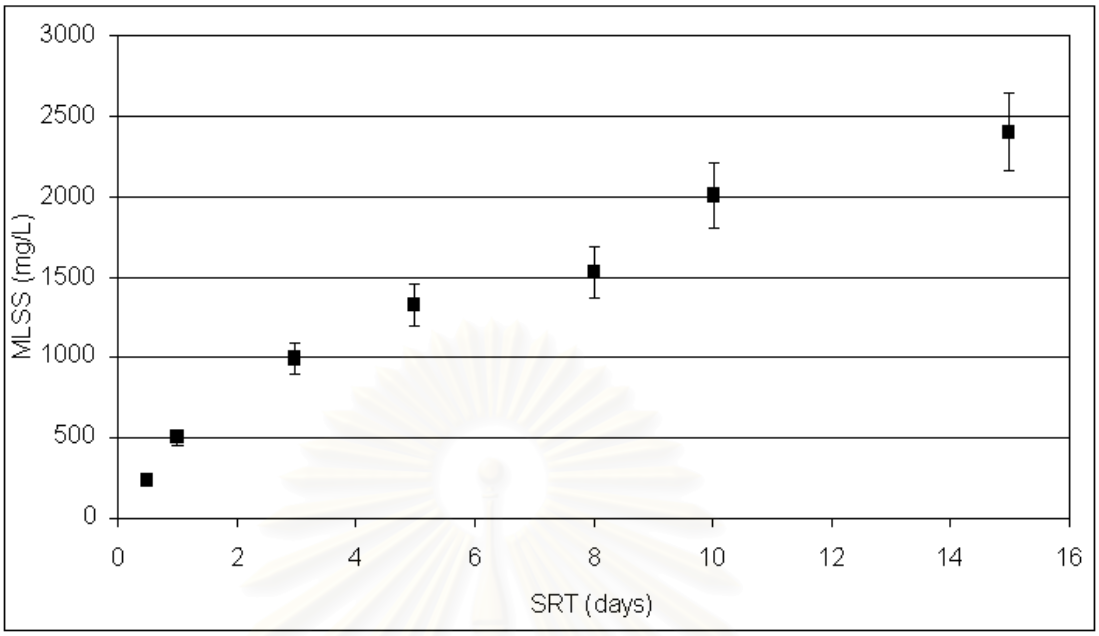


Figure 4.1 Relationship between MLSS and SRT

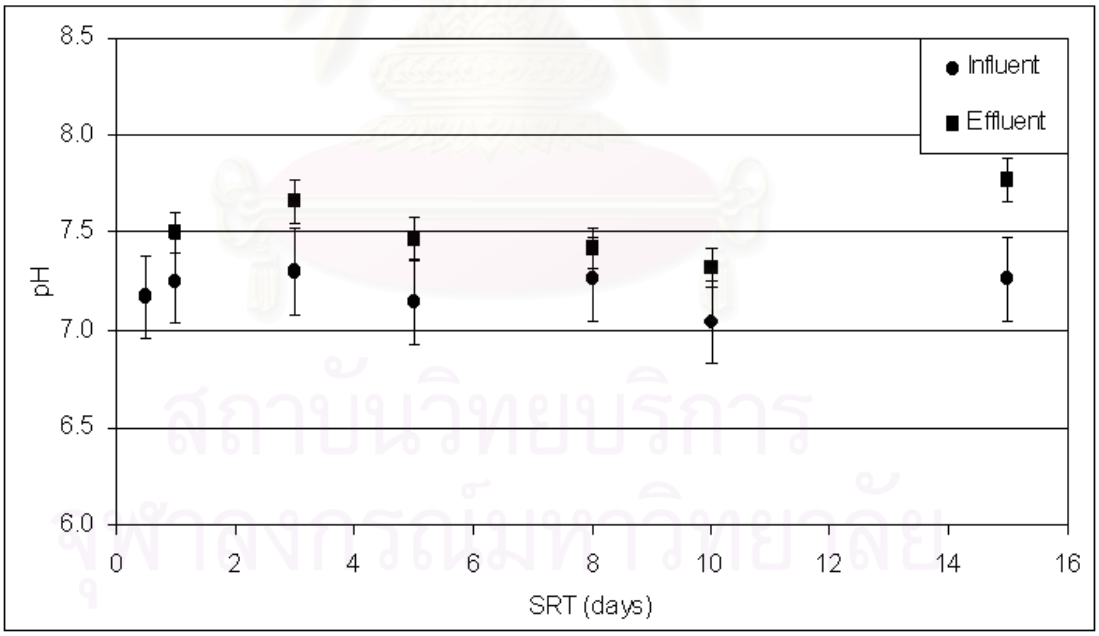


Figure 4.2 Influent and effluent pH versus SRT

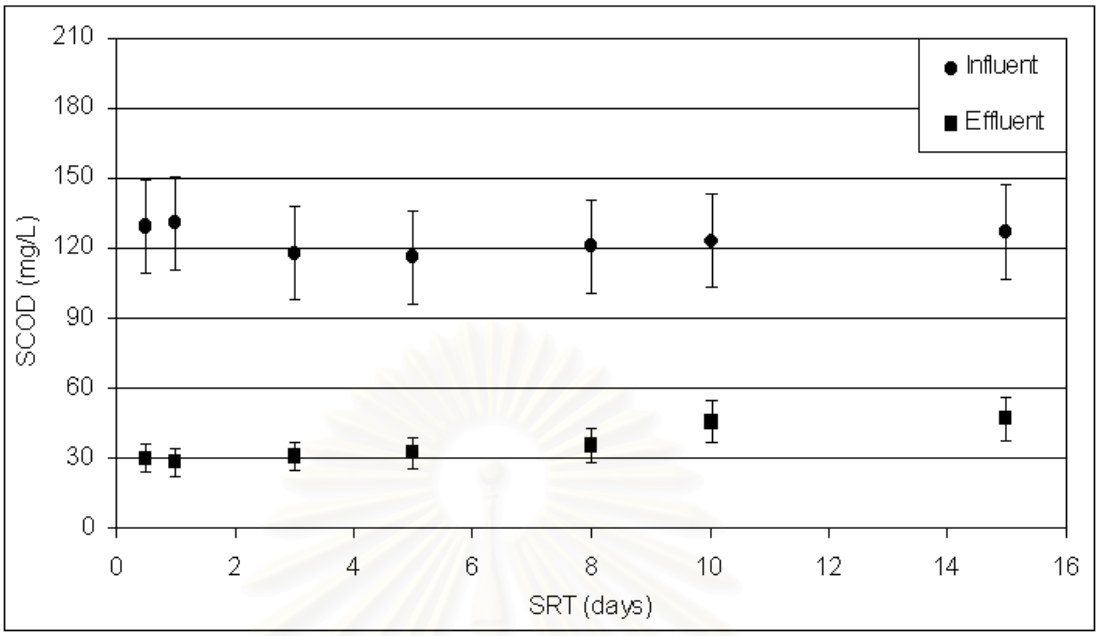


Figure 4.3 Influent and effluent SCOD versus SRT

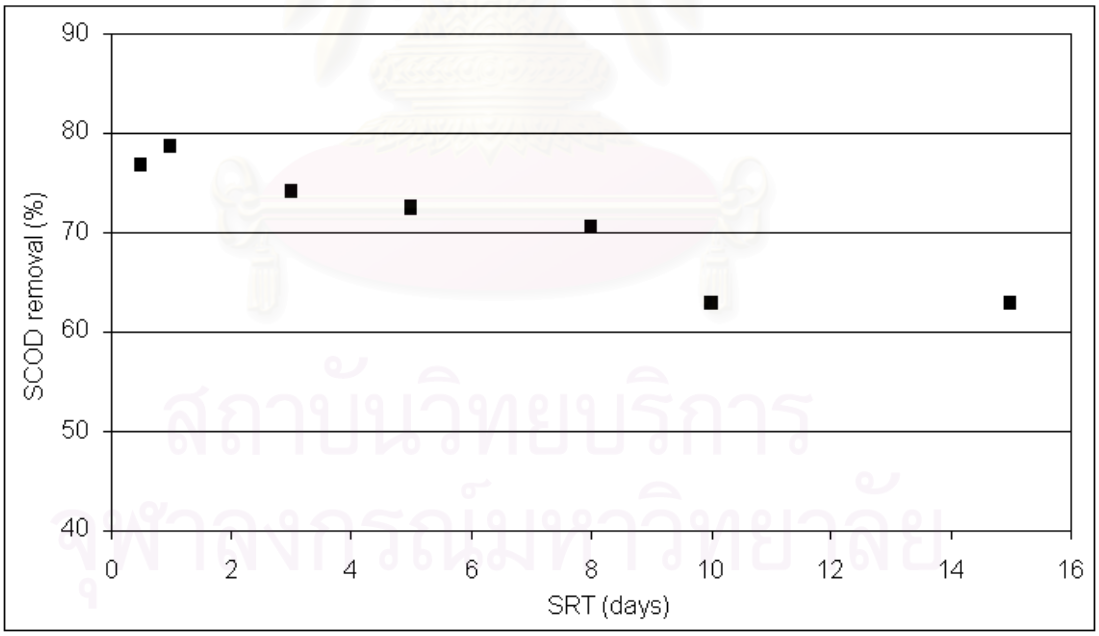


Figure 4.4 Relationship between SCOD removal and SRT

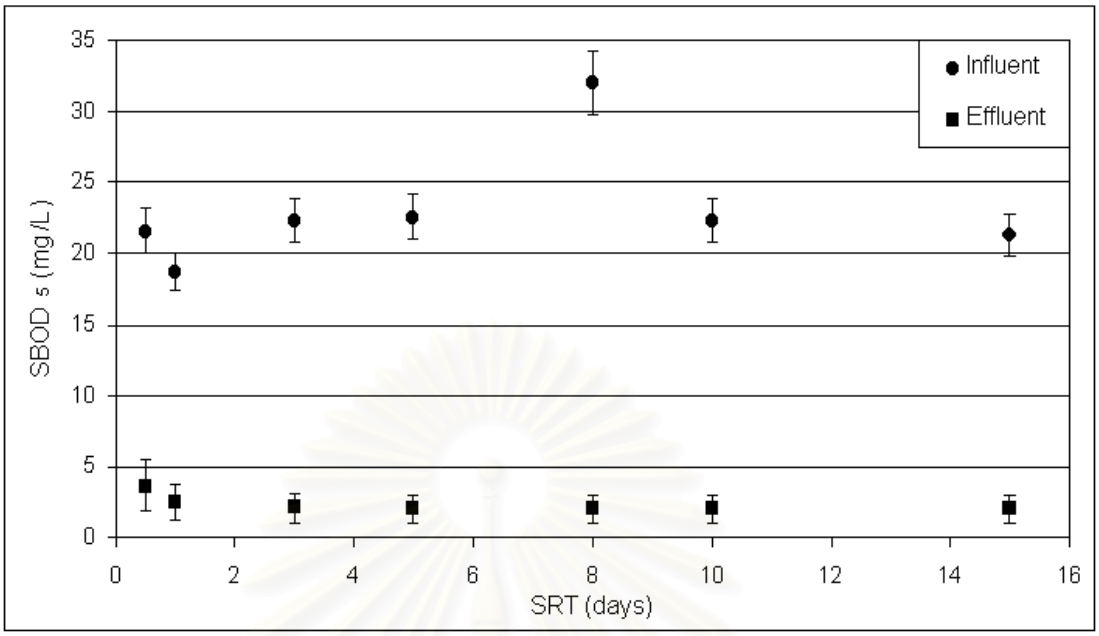


Figure 4.5 Influent and effluent $SBOD_5$ versus SRT

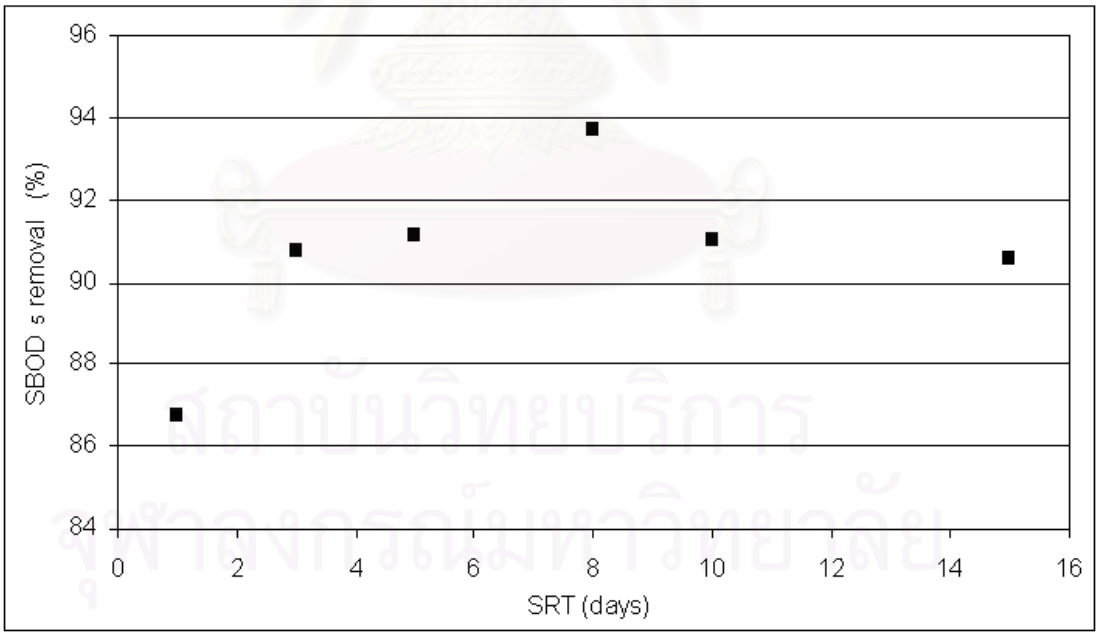


Figure 4.6 Relationship between $SBOD_5$ removal and SRT

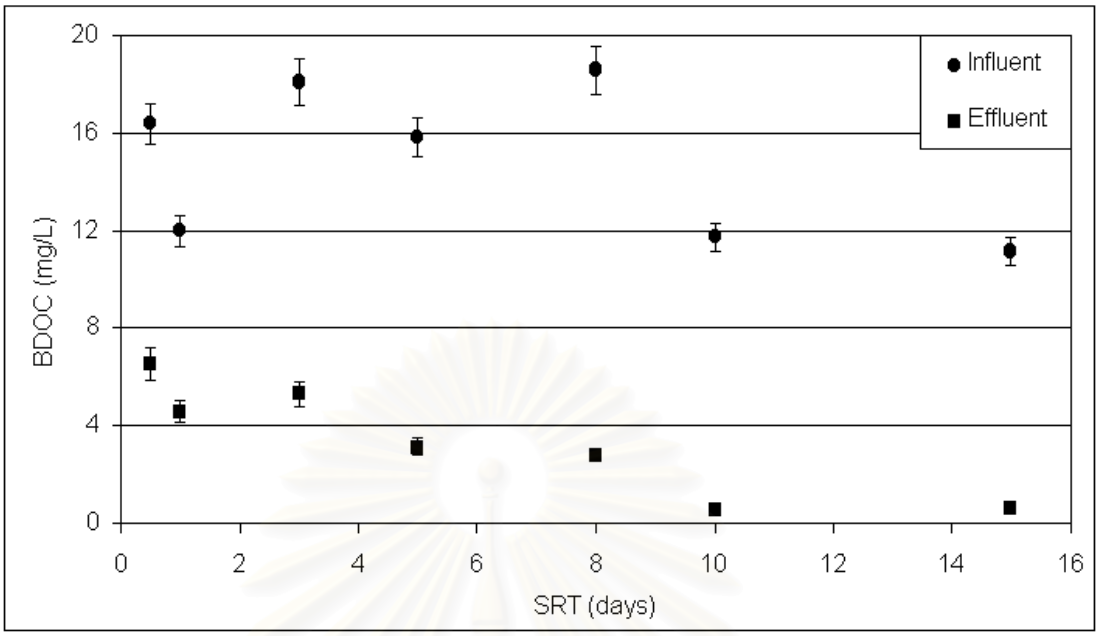


Figure 4.7 Influent and effluent BDOC versus SRT

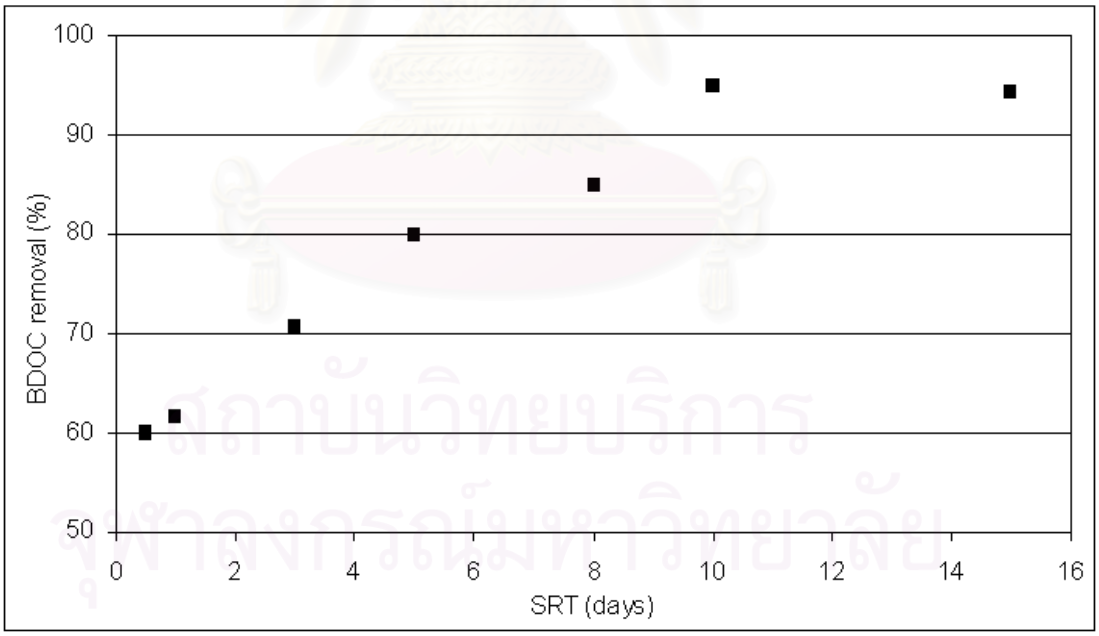


Figure 4.8 Relationship between BDOC removal and SRT

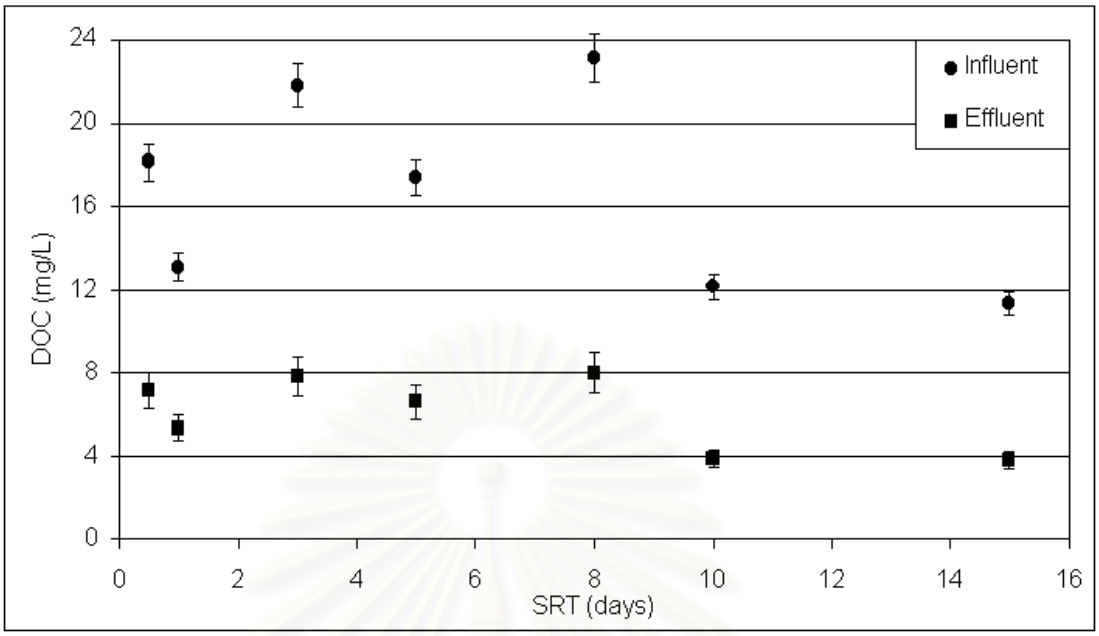


Figure 4.9 Influent and effluent DOC versus SRT

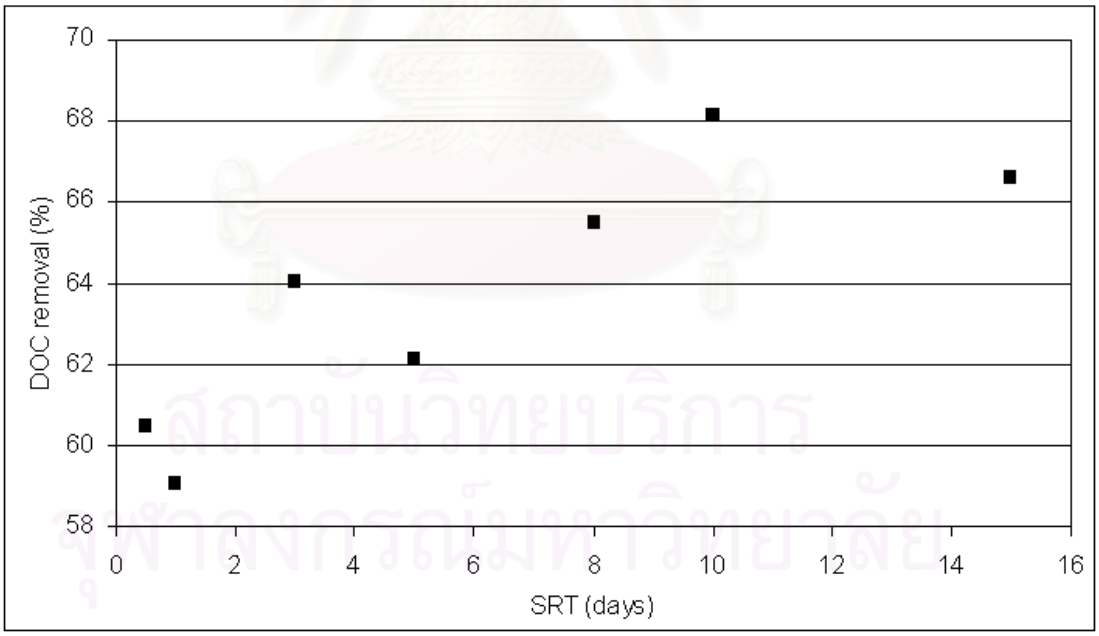


Figure 4.10 Relationship between DOC removal and SRT

Biodegradability in water could be determined by several measurements such as BOD/COD, AOC/DOC, and BDOC/DOC. Figures 4.11 and 4.12 show results when $SBOD_5$/COD and BDOC/DOC were plotted against SRT, respectively. The biodegradability indicated by $SBOD_5$/COD was much lower than that represented by BDOC/DOC. This was expected because the incubation time of $SBOD_5$ was less than that of BDOC. Although the effect of SRT on effluent BDOC/DOC was clearly apparent, the profiles of both indicators exhibited a similar trend. Biodegradability of the influent was fairly constant while that of the effluent decreased with increasing SRT. This suggests that biodegradable organics in influent were removed throughout the AS process and the proportion of biodegradable organics in the effluent was less or there was a recalcitrant portion at higher SRTs.

In summary, it can be seen that the secondary treated effluent BDOC decreased nonlinearly with increasing SRT. BDOC in primary and secondary treated wastewater was between 11.18 to 18.59 mg/L and 0.59 to 6.57 mg/L respectively. Effluent $SBOD_5$ was undetectable and was reported as a detection limit. This resulted in an unreasonable relationship between $SBOD_5$ and SRT. It was observed that BDOC removal was higher at the higher SRTs. Biodegradability of the treated effluent was between 0.2 and 0.9. It also decreased nonlinearly when SRT was enhanced. The biodegradability indicated by using $SBOD_5$/SCOD was much lower than using BDOC/DOC ratio. This resulted from low precision and sensitivity of $SBOD_5$ measurement at low organic concentrations.

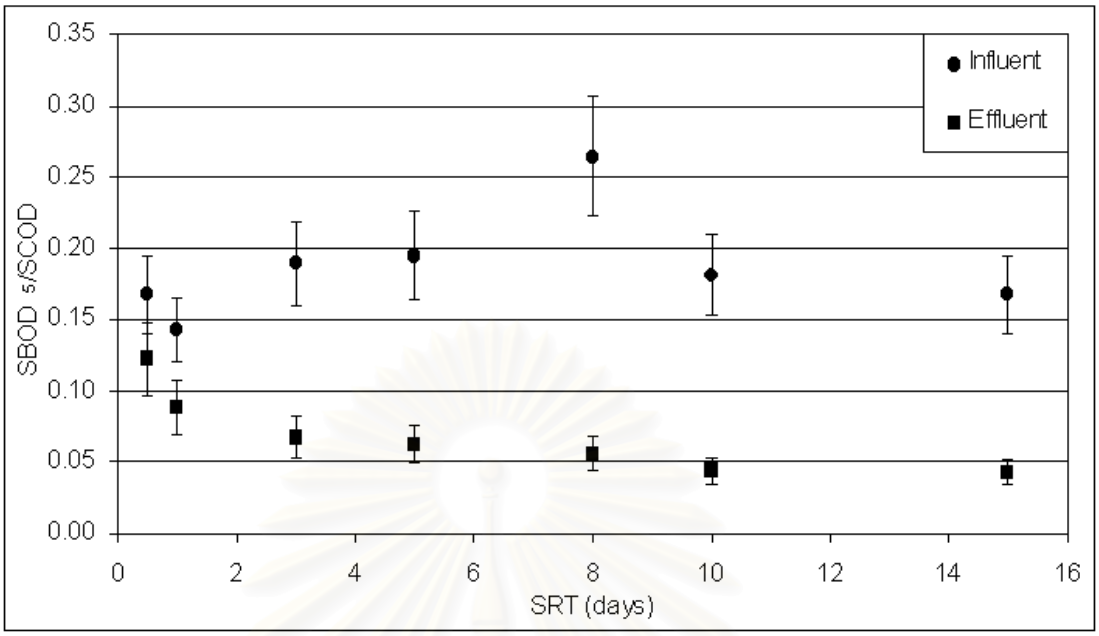


Figure 4.11 Influent and effluent $SBOD_5$/SCOD versus SRT

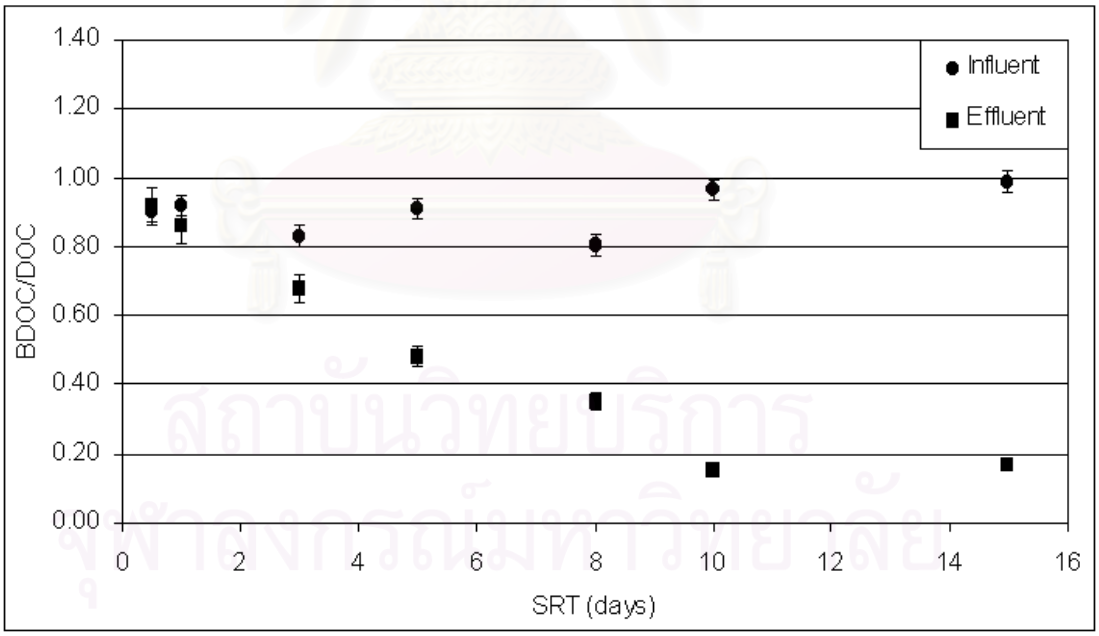


Figure 4.12 Influent and effluent BDOC/DOC versus SRT

4.2 Effect of HLR on BDOC and other parameters in Trickling Filter Process

The TF reactor was initially seeded by recirculating the primary wastewater for 3 weeks to establish active microorganisms and then operated continuously for a total 14 to 20 days at each HLR. Figure 4.13 shows pH of influent and effluent of the bench-scale TF. Influent pH ranged from 6.96 to 7.40 and after the treatment, pH increased to a range of 7.54 to 7.85. The increasing pH might be resulted from bacterial oxidation and respiration by-product (ammonia). However, this should not have significant effect to the system since the pH was quite neutral (6-8).

Figure 4.14 illustrates the relationship between $SBOD_5$ and HLR in TF process. At different HLRs, the influent $SBOD_5$ varied between 16.6 and 52.0 mg/L with an average of 32.4 mg/L and was removed to a range of 2.9 to 22.6 mg/L in the effluent. The significant variation of the samples in the influent quality was because New York City has a combined sewer system and it was raining occasionally during the sampling period. When influent $SBOD_5$ was high, effluent $SBOD_5$ tended to be high. Both influent and effluent $SBOD_5$s were relatively constant at lower HLRs and slightly dropped at an HLR of 5 m^3/m^2-d and tended to increase at higher HLRs.

Figure 4.15 shows the effect of HLR on BDOC of the influent and effluent in TF process. Both influent and effluent BDOC increased when HLR increased. The average influent BDOC was 14.21 mg/L and was reduced to 7.82 mg/L in the effluent.

As shown in Figure 4.16, both influent and effluent DOCs tended to increase with increasing HLR. DOC in the influent was between 15.80 and 29.10 mg/L while that in the effluent was in a range of 6.77 to 11.25 mg/L. DOC concentrations in the influent and effluent were similar to those of BDOC at different HLRs but BDOC concentrations were lower than DOC concentrations. Although effluent concentrations had the same reasonable trend (higher at higher HLRs), this was because influent organic concentrations were high at higher SRTs.

The $SBOD_5$, BDOC, and DOC removal efficiencies are presented in Figure 4.17. $SBOD_5$ removal was about the same at HLRs of 0.5 and 3 m^3/m^2-d, increased substantially from 65 to 80% at HLRs of 5 and 10 m^3/m^2-d, and dropped to 56.4% at an HLR of 15 m^3/m^2-d. Unlike the $SBOD_5$ removal which had no obvious relationship

with HLR, BDOC removal decreased from approximately 70 to 50% as HLR was increased. In contrast, more DOC removal was observed at higher HLRs.

When the loading is higher, TF provides lower treatment (lower organic removal). It can be seen from Figure 4.17 that BDOC removal obviously relates to HLR under this rule. It is evident that BDOC is the most effective parameter for characterizing the performance of TF. This resulted from its high precision, especially compared to $SBOD_5$ method. Although DOC precision level is known to be the same as that of BDOC, its removal could be different from that of BDOC removal. It is noted that the TF unit treated biodegradable organic matter when HLR increased while its overall DOC removal was quite stable (the lower treatment affected only biodegradable portion).

Influent and effluent BDOC/DOC (biodegradability) versus HLR is illustrated in Figure 4.18. BDOC/DOC of the influent was consistent around 75%. Biodegradability in effluent increased from approximately 40% to 70% when initial increase of HLR from 0.5 to 3 m^3/m^2-d. At HLR of 5 m^3/m^2-d or above, constant effluent biodegradability at around 80% was observed. Biodegradability significantly increased with HLR at low HLRs and tended to stabilize at higher HLRs. This result is similar to the results obtained from the AS experiments. At higher HLRs or low SRTs, the systems are less effective in removing biodegradable organics resulting in large proportions of biodegradable organics remaining in the effluents.

For all three organic parameters analyzed ($SBOD_5$, BDOC, and DOC), the overall removal efficiencies of TF were less than those of AS process. $SBOD_5$, BDOC, and DOC concentrations were higher at higher HLRs. $SBOD_5$ was relatively constant at lower HLRs then increase at higher HLRs. Effluent $SBOD_5$ ranged from 2.9 to 22.6 mg/L. Similar to $SBOD_5$ profile, BDOCs were relatively constant at lower HLRs and increased at higher HLRs ranging from 3.74 to 9.69 mg/L. Unlike $SBOD_5$, BDOC removal dropped from 70 to 50% at HLR from 0.5 to 3 m^3/m^2-d and remained relatively constant at higher HLRs. Biodegradability (BDOC/DOC) increased from 0.4 to 0.8 when increasing HLR from 0.5 to 3 m^3/m^2-d. At above an HLR of 5 m^3/m^2-d, biodegradability was relatively constant.

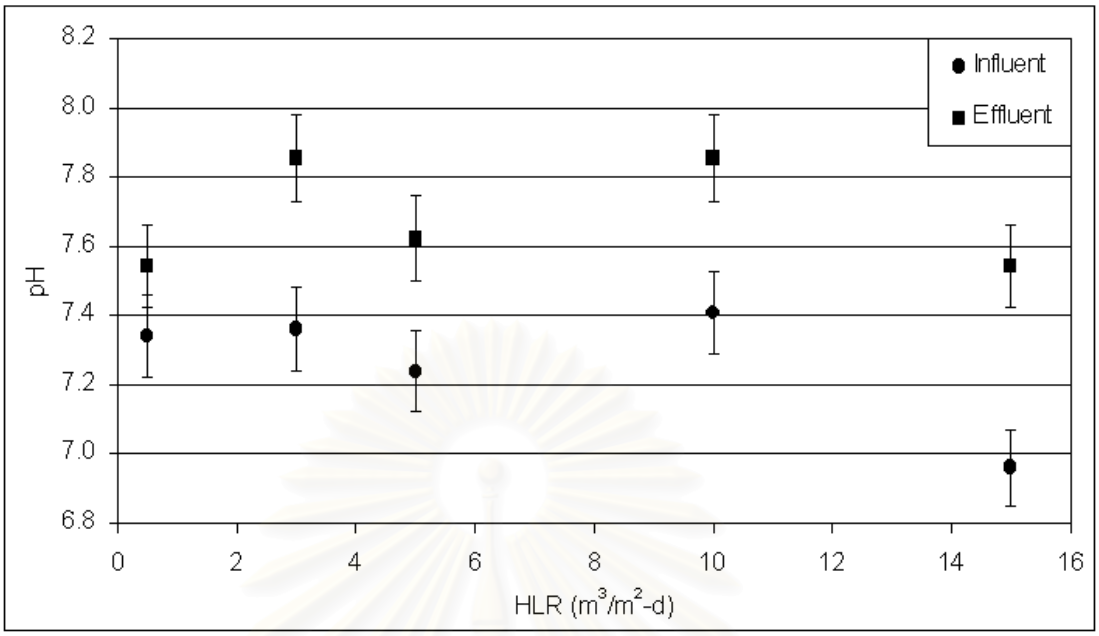


Figure 4.13 Influent and effluent pH versus HLR

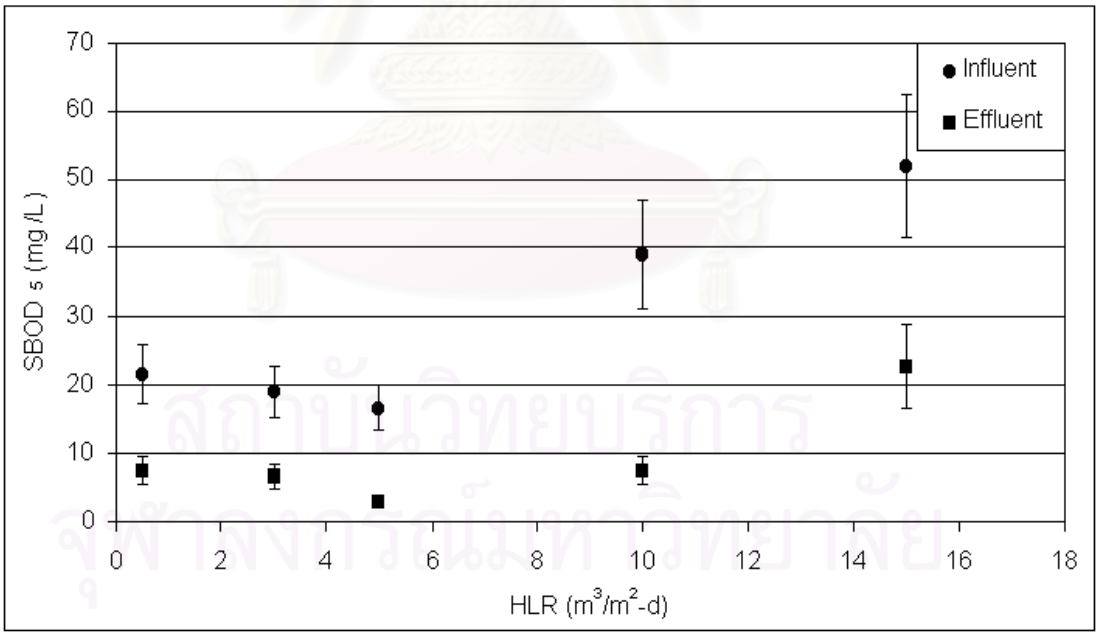


Figure 4.14 Influent and effluent $SBOD_5$ versus HLR

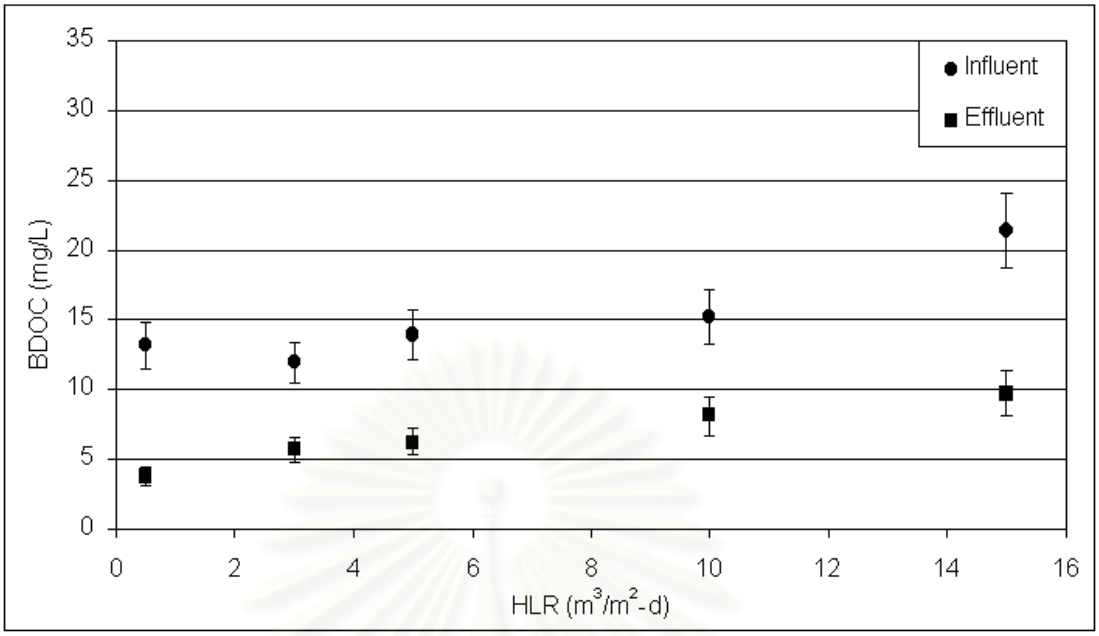


Figure 4.15 Influent and effluent BDOC versus HLR

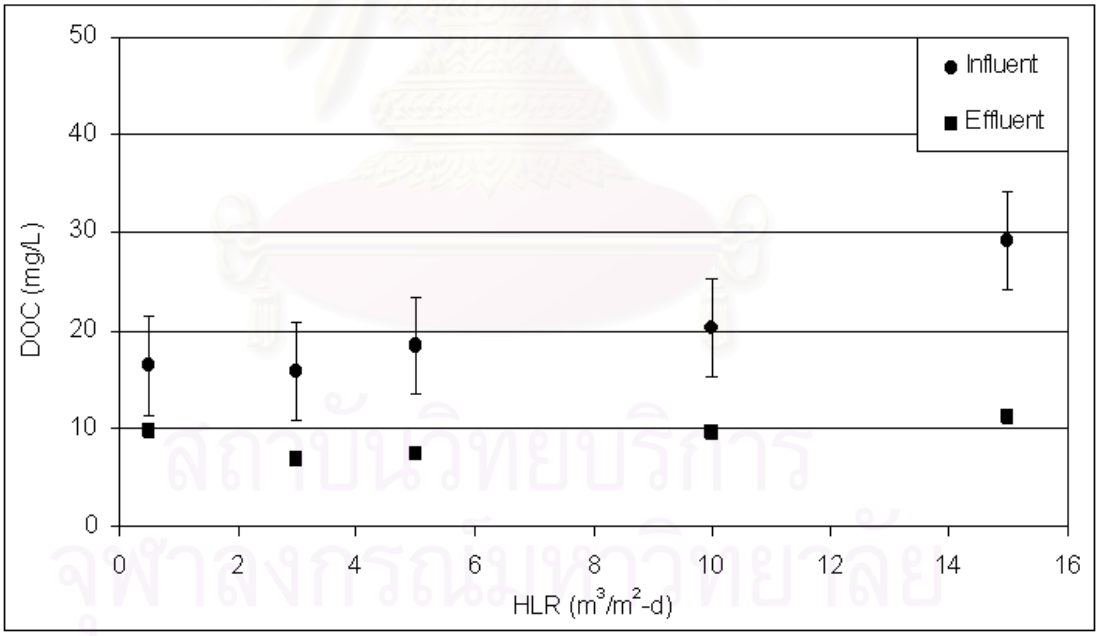


Figure 4.16 Influent and effluent DOC versus HLR

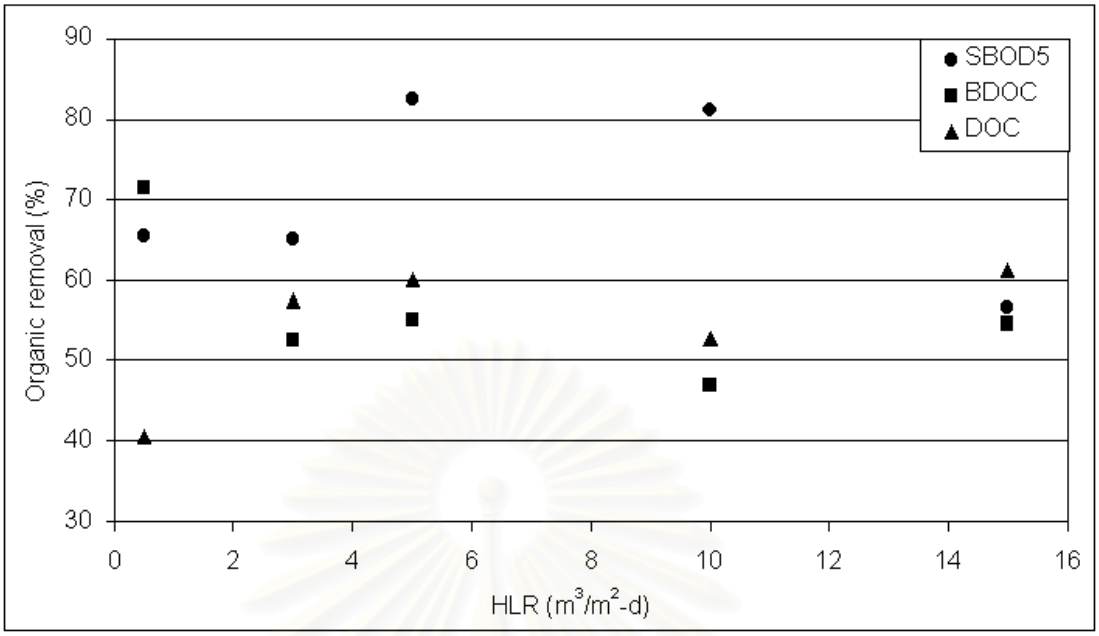


Figure 4.17 Relationship between $SBOD_5$, DOC, and BDOC removal and SRT

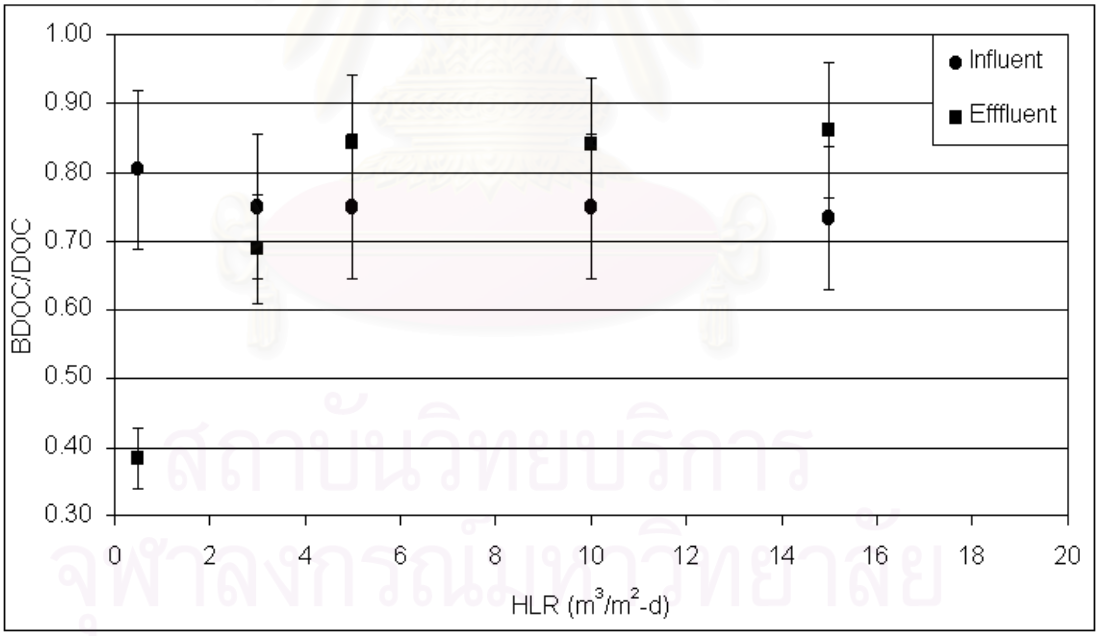


Figure 4.18 Influent and effluent BDOC/DOC versus HLR

4.3 Rotating Biological Contractor (RBC) Study

Organic loading rates (OLRs) of the plant were calculated from plant data (Appendix C). They are illustrated in Figures 4.19 and 4.20 respectively. The OLR of the plant was relatively constant with an average of 14.8 lb TBOD/$10^3$$ft^2$-d while the typical design OLR ranges from 2.0 to 3.5 lb TBOD/$10^3$$ft^2$-d (Metcalf & Eddy, 1991). This suggests that the plant was overloaded during the sampling period. The two parallel sections (old and new sections) were originally designed to balance both hydraulic and organic loading. The new section typically handles twice of OLR and HLR that are provided to the old section. As illustrated in Figure 4.20, OLRs of the new section were obviously higher than that of the old section during the sampling period.

HLRs of the plant and each section were calculated and plotted against the day of sampling as shown in Figures 4.21 and 4.22 respectively. It can be clearly seen that HLR in the new section was higher than that of the old section.

Figure 4.23 shows pH of the wastewater samples during the sampling period. pH of the treated wastewater of both old and new section was relatively constant between 7.40 and 7.80. As illustrated in Figure 4.24, $SBOD_5$ of the new section effluent was higher than that of the old section effluent with an average of 3.48 mg/L and 2.47 mg/L respectively. It was because of the hydraulic overloading of the new section. Moderate fluctuation of effluent $SBOD_5$ observed was due to inconsistent operation conditions such as flow, hydraulic loading, organic loading, and the variation of the quality of primary wastewater as shown in Figure 4.24. Effluent SBOD concentrations in the first and the sixth weeks were obviously higher than the other weeks because of the variation of the plant operation time; some trains of RBC units were shut down during the sampling period. The detail of operation is shown in Appendices A and B. It should be noted that SBOD of primary wastewater, OLR, and HLR are higher during the first two weeks of the sampling period.

Figure 4.25 shows a relationship between HLR and $SBOD_5$ of the effluent of old and new sections. The effluent $SBOD_5$ was scattering but tended to increase with an increase of HLR. BDOC of the effluent from the old and new sections versus HLR are shown in Figure 4.26. Similar to the SBOD data, except for the first few data points, a very weak trend of positive relationship between effluent BDOC and HLR

was observed. Average BDOCs of the effluent of the old and new sections were 9.93 mg/L and 10.05 mg/L, respectively. The variation of effluent BDOC was resulted from fluctuation of the influent organics (SBOD) in the plant as shown in Figure 4.24.

Effluent BDOCs were plotted against day of sampling period as illustrated in Figure 4.27. The effluent BDOCs of the old section were higher in the second week which were similar to the profile of SBOD of primary effluent. In addition to the effluent BDOCs of the new section, they were higher in the third week.

Figure 4.28 illustrates DOC of the samples versus HLR during the sampling period. DOCs of the treated wastewater of both old and new sections were relatively constant approximately in the range of 10 to 25 mg/L, regardless of HLR. High DOC but low $SBOD_5$ indicates that the organic compounds in those samples are not biodegradable. BDOC/DOC (biodegradability) of the effluent of the old and new sections is shown in Figure 4.29. It ranged from 0.2 to 0.8 with averages of 0.55 and 0.53 for the old and new sections, respectively.

There is no trend between biodegradability and HLR. Some organic compounds are found in water and wastewater, such as lignin, tannin, humic substance, and various aromatic compounds, strongly absorbed UV. UV_{254} has been used mainly in the field of water treatment to indicate relative abundance of unsaturated or organic in water.

Figure 4.30 illustrates a relationship between UV_{254} of the effluent and HLR of the RBC process. There was not much difference between UV_{254} of the old and new sections. The new section which was operated at higher HLRs produced secondary effluent with slightly higher UV_{254} than the old section. This suggests that the effluent from the new section contains more UV absorbing compounds such as some unsaturated organics and aromatics. Since the new section produces the effluent with worse quality than the old section does, it is evident that UV_{254} can be used to indicate the wastewater quality.

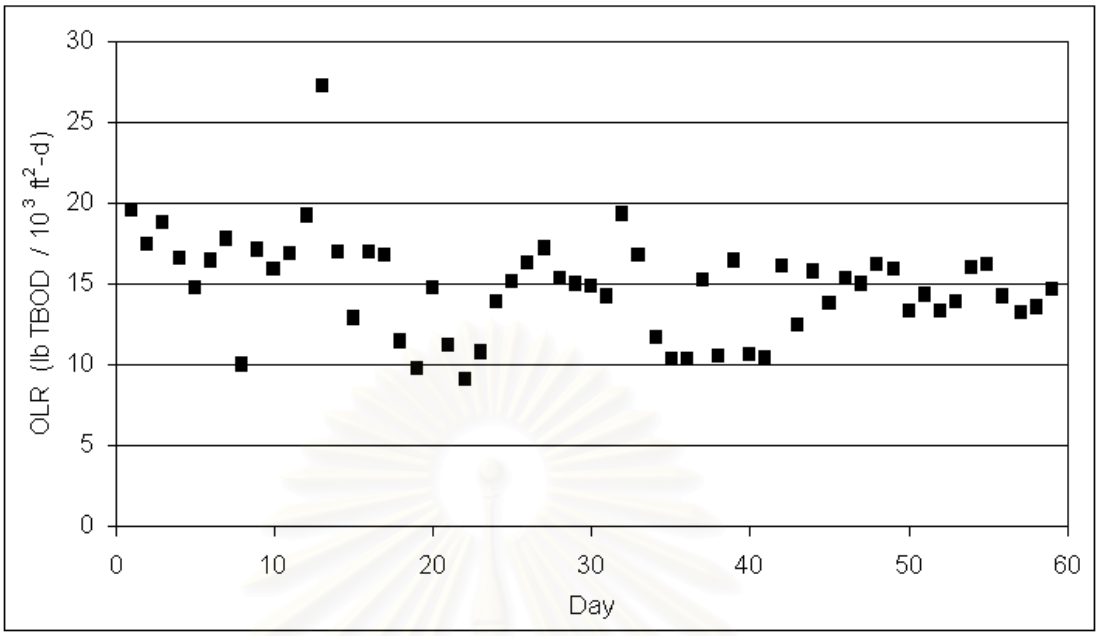


Figure 4.19 OLR of the RBC plant

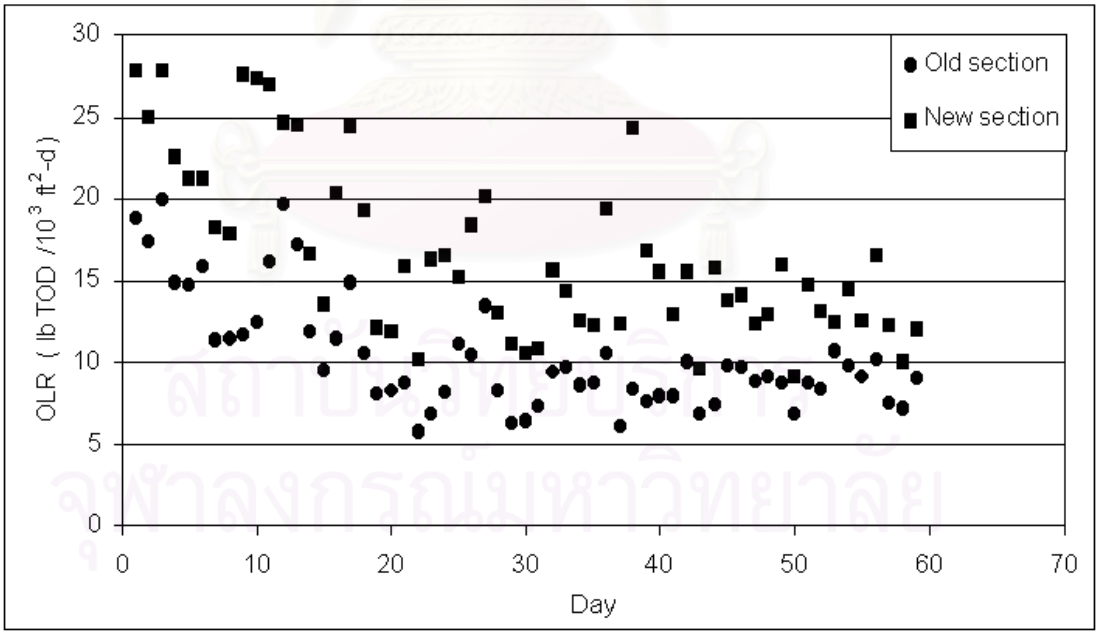


Figure 4.20 OLR of the two parallel sections of the RBC plant

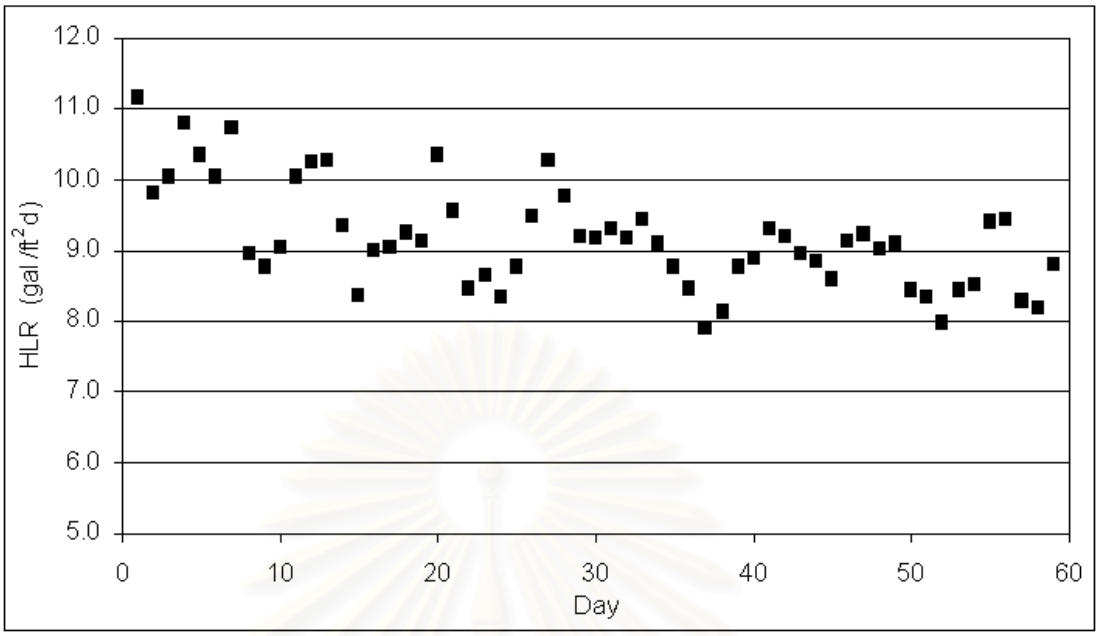


Figure 4.21 HLR of the RBC plant

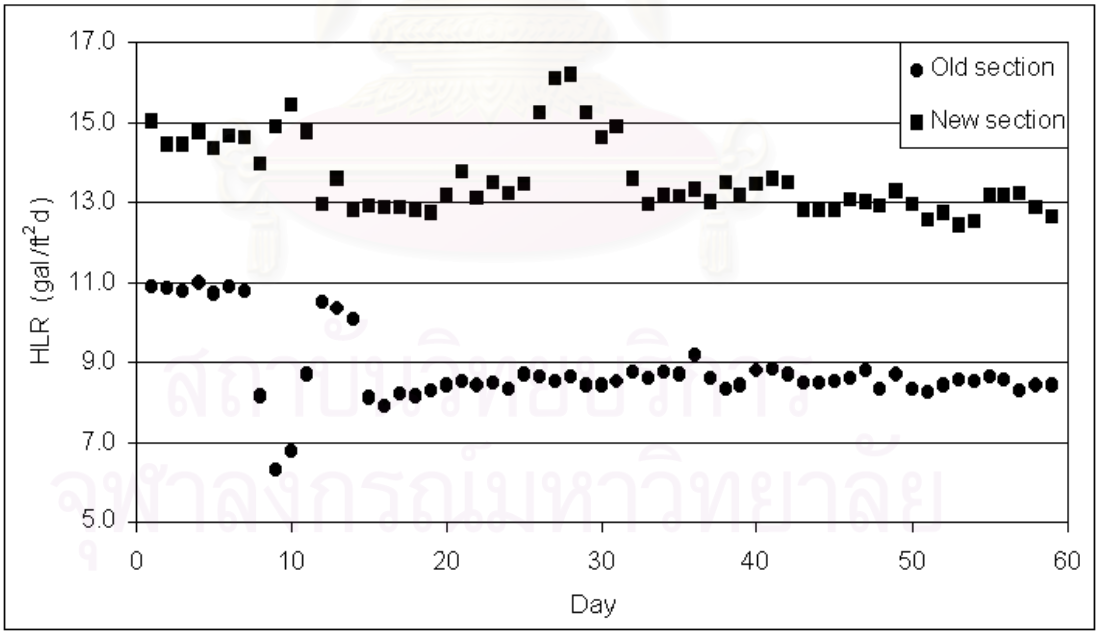


Figure 4.22 HLR of the two parallel sections of the RBC plant

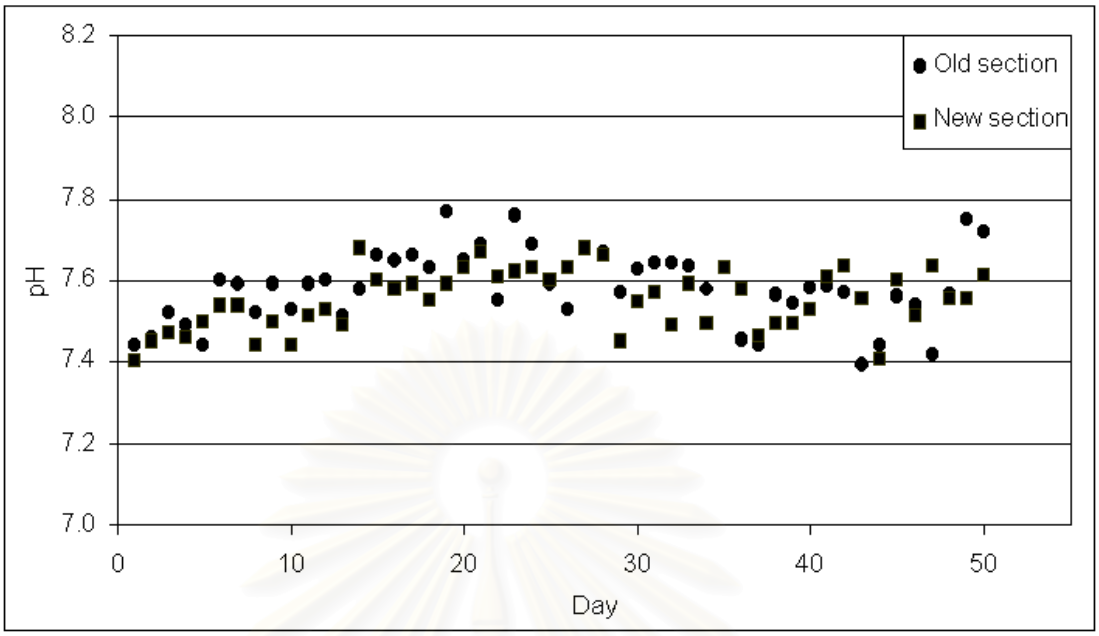


Figure 4.23 Secondary effluent pH of the two parallel sections of the RBC plant

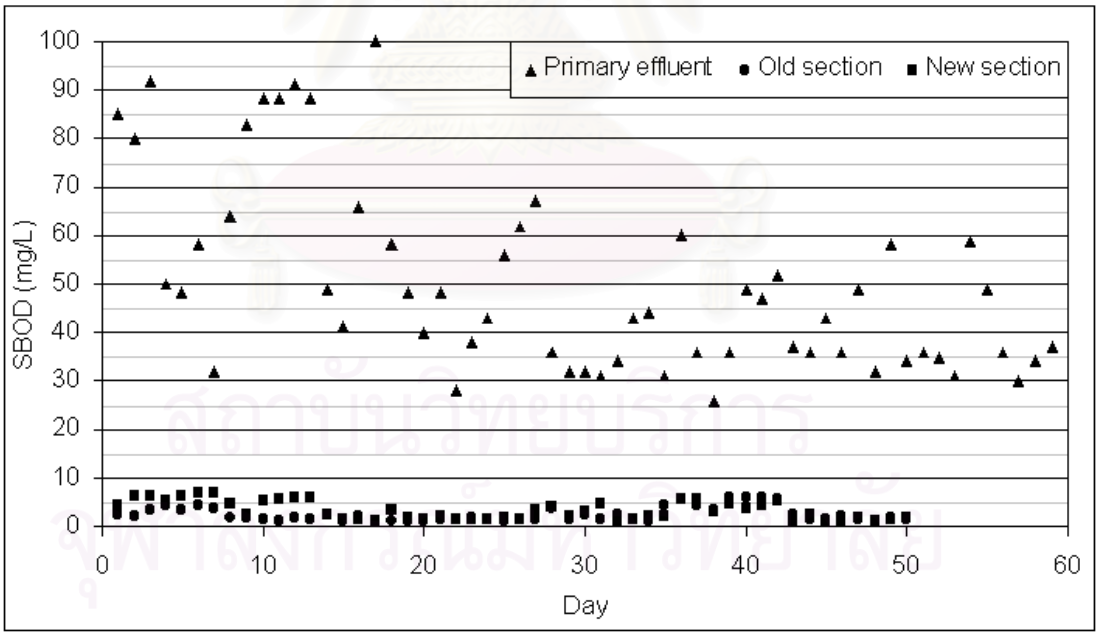


Figure 4.24 SBOD of primary effluent and secondary effluent from the two parallel sections of the RBC plant

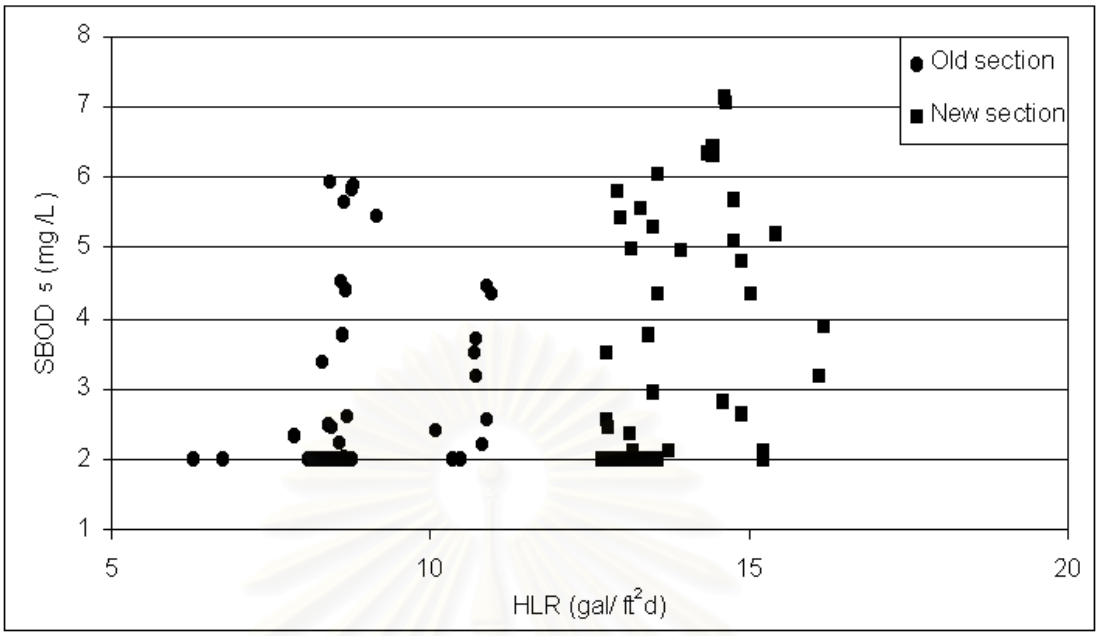


Figure 4.25 $SBOD_5$ of the secondary effluent versus HLR of the two parallel sections of the RBC plant

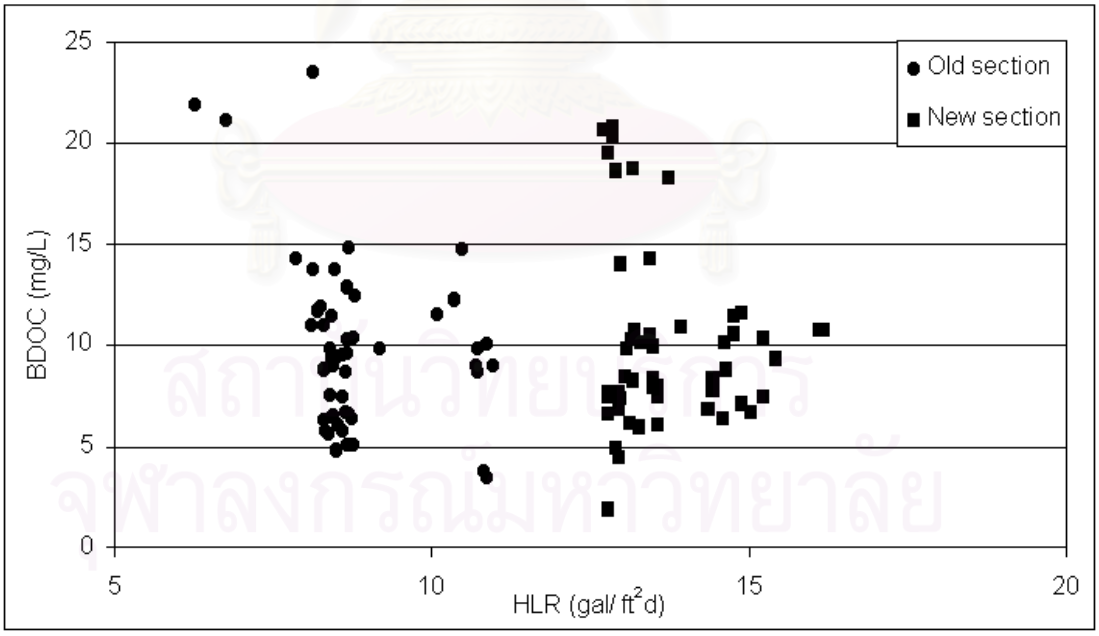


Figure 4.26 BDOC of the secondary effluent versus HLR of the two parallel sections of the RBC plant

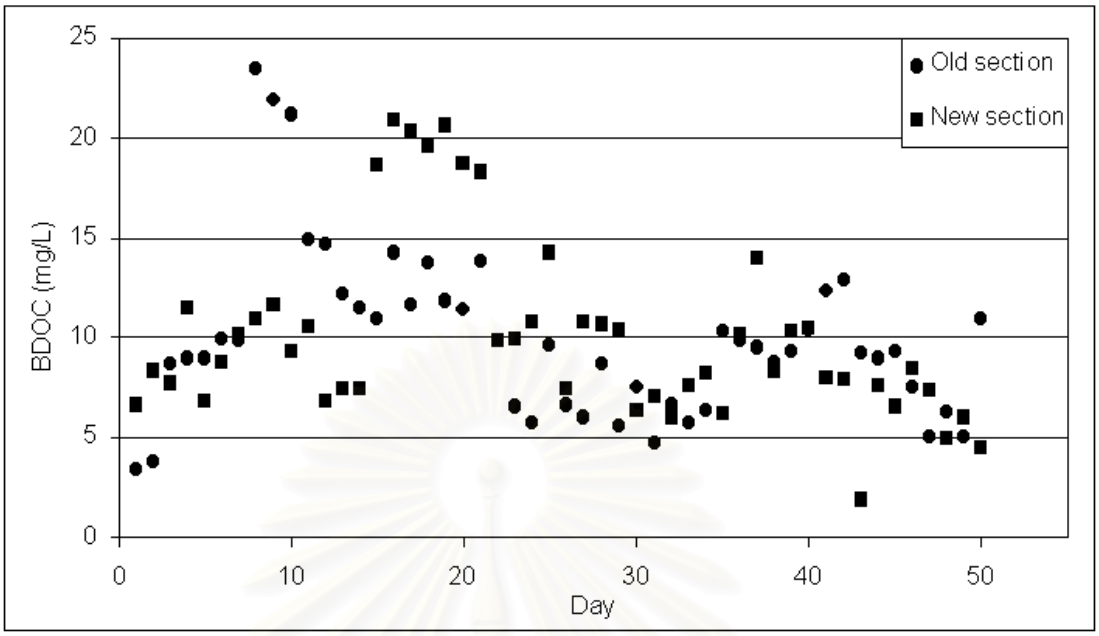


Figure 4.27 BDOC of the secondary effluent of the two parallel sections of the RBC plant

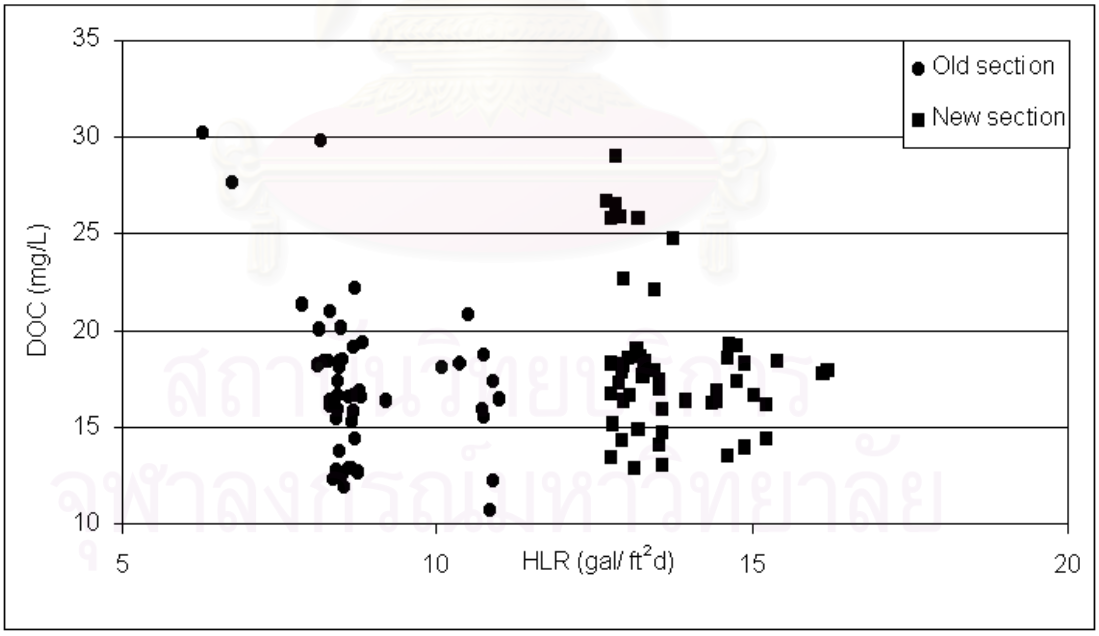


Figure 4.28 DOC of the secondary effluent of the two parallel sections of the RBC plant

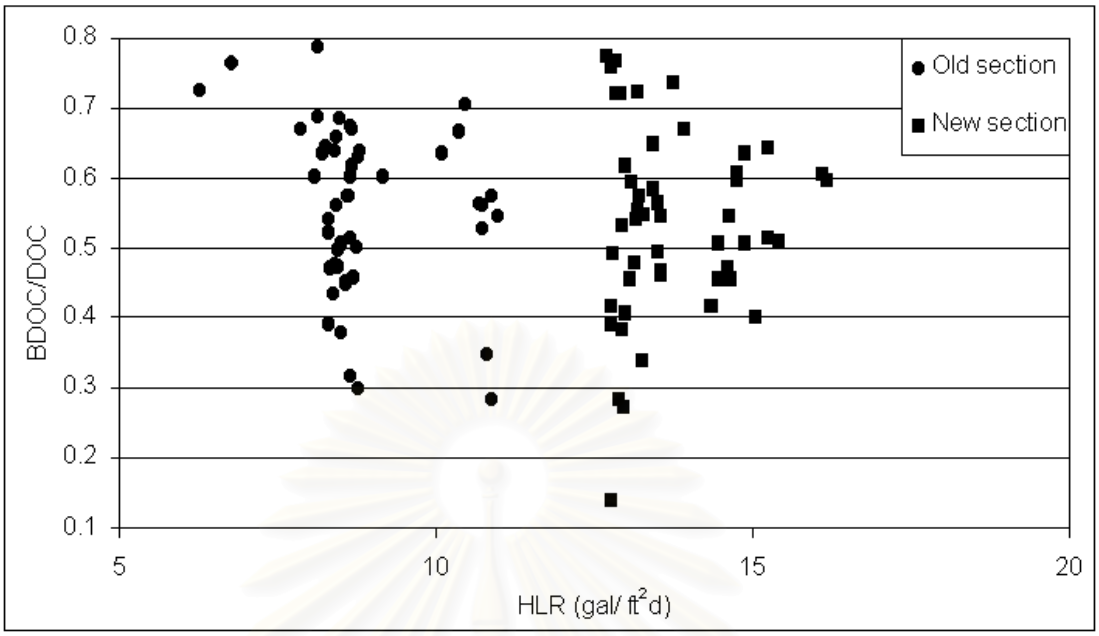


Figure 4.29 Secondary effluent BDOC/DOC of the two parallel sections of the RBC plant

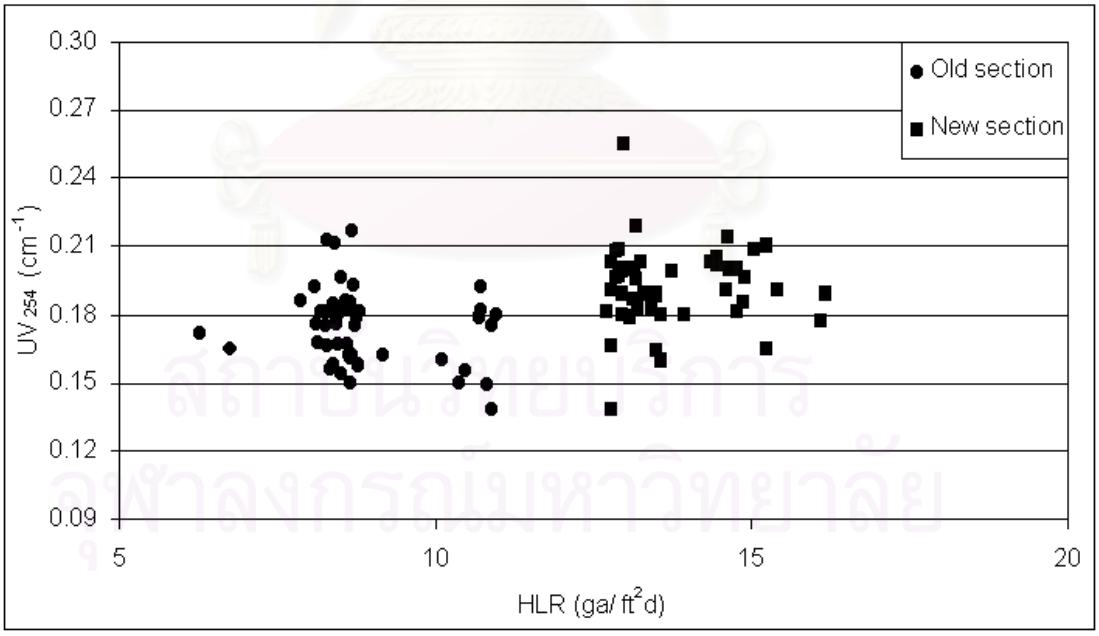


Figure 4.30 UV_{254} of the secondary effluent of the two parallel sections of the RBC plant

In the study of RBC process, the new section of the RBC plant produced worse effluent quality than the old section during the sampling period based on the effluent organic concentrations ($SBOD_5$, BDOC, DOC, and UV_{254}). A weak trend between effluent BDOC and HLR was observed. The averages of BDOC in the old and new sections were 9.93 and 10.05 mg/L respectively. The variation of data resulted from the fluctuation of the primary effluent samples. Similar to the profile in AS process, biodegradability of RBC treated effluent varied approximately from 0.3 to 0.8 regardless of HLR. Aromatics and other UV-absorbed organic compounds in the RBC study were evaluated by the determination of UV_{254}. UV_{254} value was slightly higher when HLR increased.

4.4 Correlations between BDOC and other parameters in biological wastewater treatment processes

Correlations of BDOC and other organic content parameters were evaluated by using secondary treated effluent BDOCs, SBODs, and DOCs of the three systems studied and SCOD of the primary and secondary effluent samples from the AS unit. Secondary effluent samples from the RBC plant were used to evaluate correlations between UV_{254} and the organic content parameters except for SCOD. An extremely weak positive relationship between BDOC and $SBOD_5$ was obtained as illustrated in Figure 4.31. At low concentrations, $SBOD_5$ remained the same when BDOC increased. It was resulted from the low precision of the $SBOD_5$ method at low concentrations. There were many unreliable $SBOD_5$ data points using a detection limit of 2 mg/L.

Figure 4.32 shows a strong relationship between BDOC and DOC. This is because both of two parameters are very sensitive and have low detection limits compared to $SBOD_5$. Figure 4.33 shows a correlation between BDOC and SCOD of the effluent from the AS study. SCOD increased with increasing BDOC as a linear function with R^2 of 0.68. UV_{254} of the RBC effluent was correlated with BDOC as the result is shown in Figure 4.34. It can be concluded that BDOC has no relationship with UV_{254} for the RBC effluent. However, the data are based on a limited number and only one type of biological wastewater samples. A relationship between BDOC and UV_{254} of wastewater may exist.

Correlations between DOC and $SBOD_5$, SCOD, and UV_{254} were determined as shown in Figure 4.35 to 4.37 respectively. Correlation between DOC and $SBOD_5$ was similar to that of BDOC-$SBOD_5$ correlation. It is apparent that $SBOD_5$ method begins to suffer from poor precision at the concentration of 5 mg/L.

Figure 4.36 illustrates a linear relationship with R^2 of 0.68 between DOC and SCOD of the effluent from the AS study. However, more data points are required to assure the correlation. There was no significant relationship between DOC and UV_{254} as shown in Figure 4.37, although UV_{254} was likely to increase with increasing DOC.

Figure 4.38 presents a strong correlation between $SBOD_5$ and SCOD in AS process. However, the certainty of the relationship needs to be verified due to the abnormal distribution of the data points.

Figure 4.39 presents a correlation between $SBOD_5$ and UV_{254} of the effluent of the RBC process. The relationship between $SBOD_5$ and UV_{254} was unclear. The poor correlations for some cases were unexpected and could be caused by several factors. A relatively small sample set of SCOD (which was analyzed only in the AS study) made the correlations not as strong as it should be. The other poor overall correlations were resulted from differences in wastewater characteristics among plants and the sampling periods as well as the differences in treatment processes. The weak correlations between $SBOD_5$ and other parameters were resulted from its low precision and high detection limit.

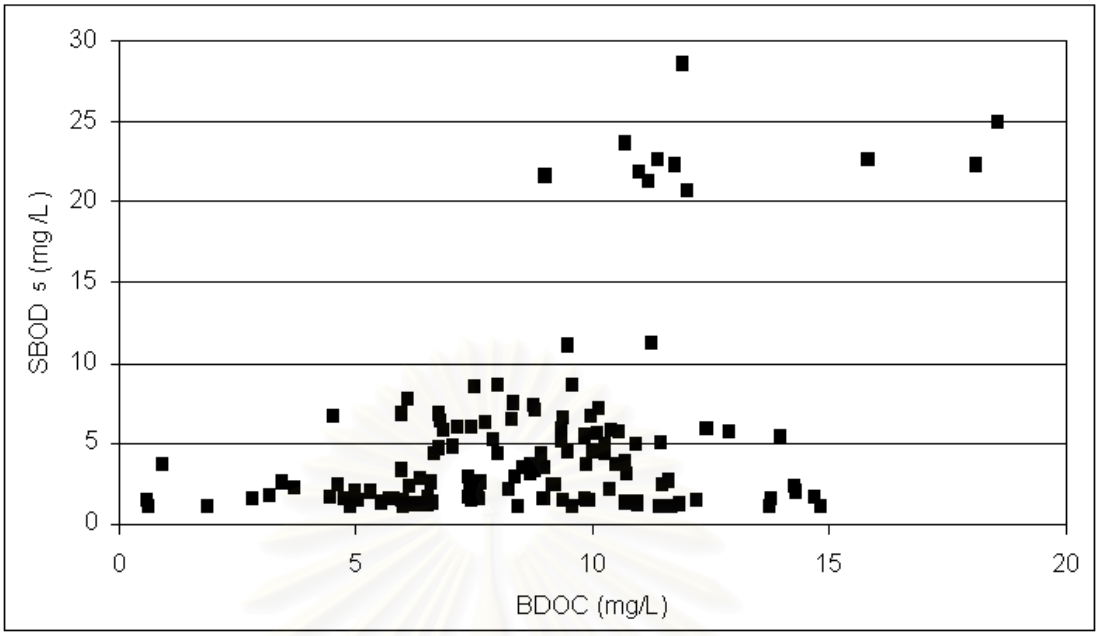


Figure 4.31 Correlation between BDOC and $SBOD_5$ of the effluent of AS, TF, and RBC processes

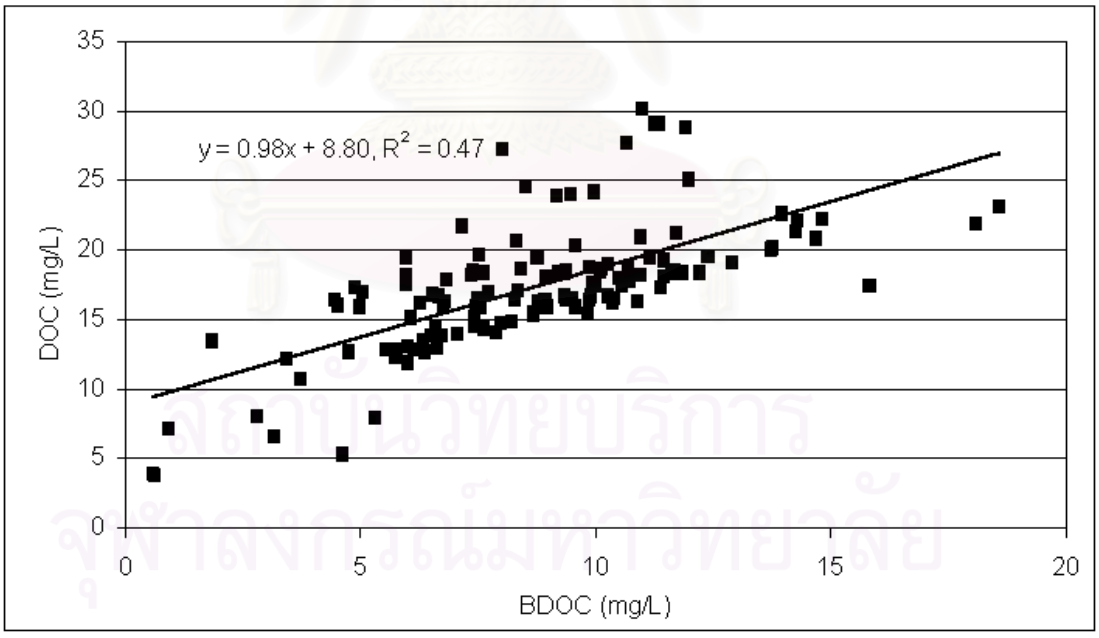


Figure 4.32 Correlation between BDOC and DOC of the effluent of AS, TF, and RBC processes

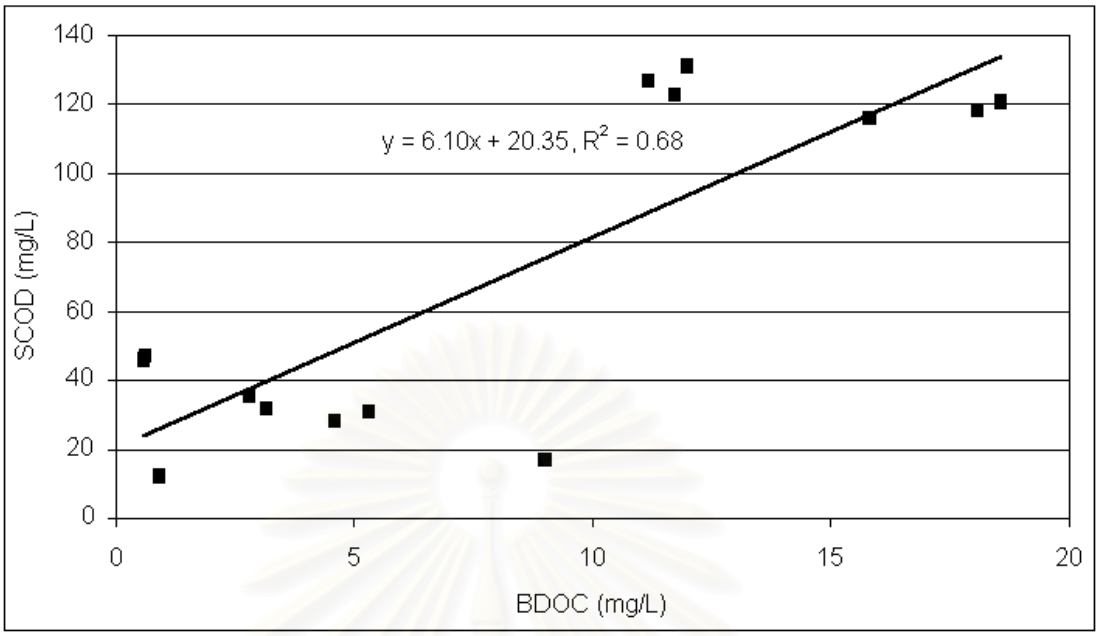


Figure 4.33 Correlation between BDOC and SCOD of the effluent of the AS process

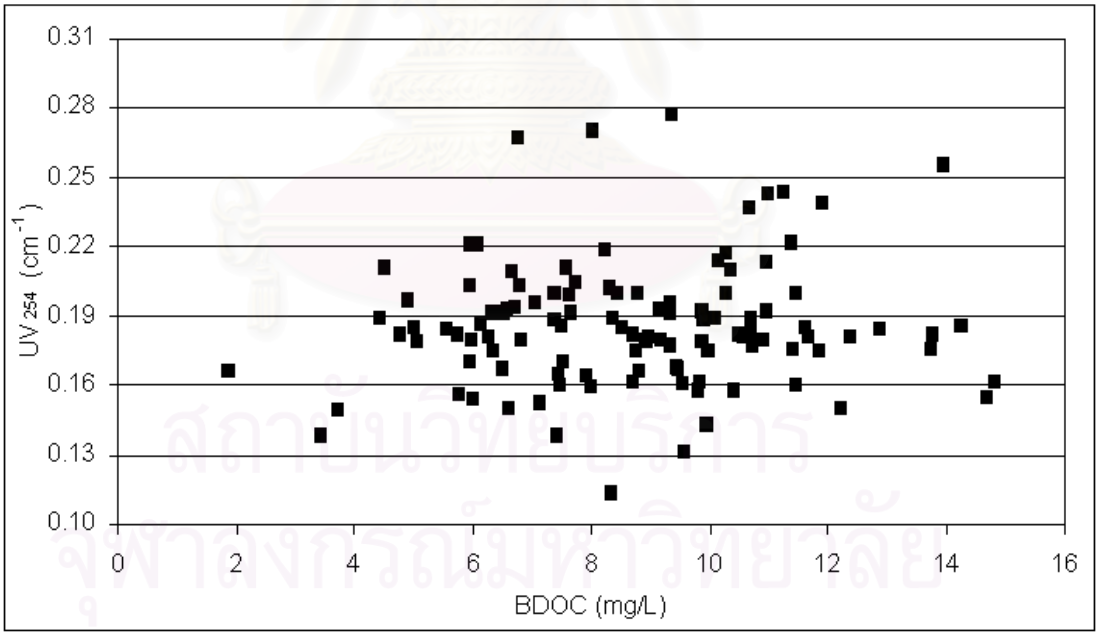


Figure 4.34 Correlation between BDOC and UV_{254} of the effluent of the RBC process

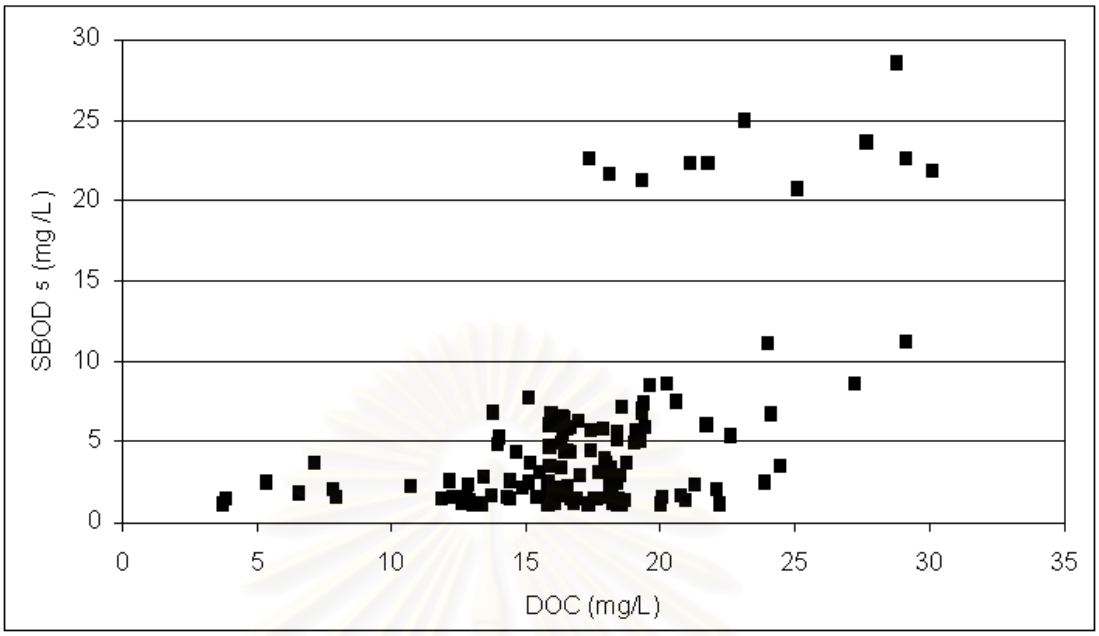


Figure 4.35 Correlation between DOC and $SBOD_5$ of the effluent of the AS, TF, and RBC processes

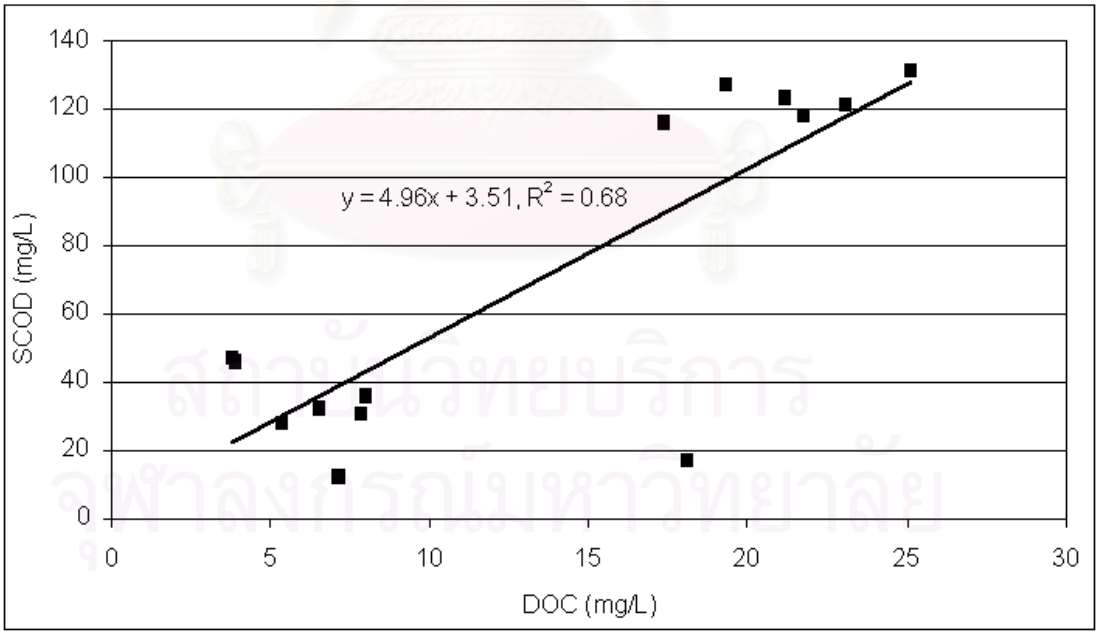


Figure 4.36 Correlation between DOC and SCOD of the effluent of the AS process

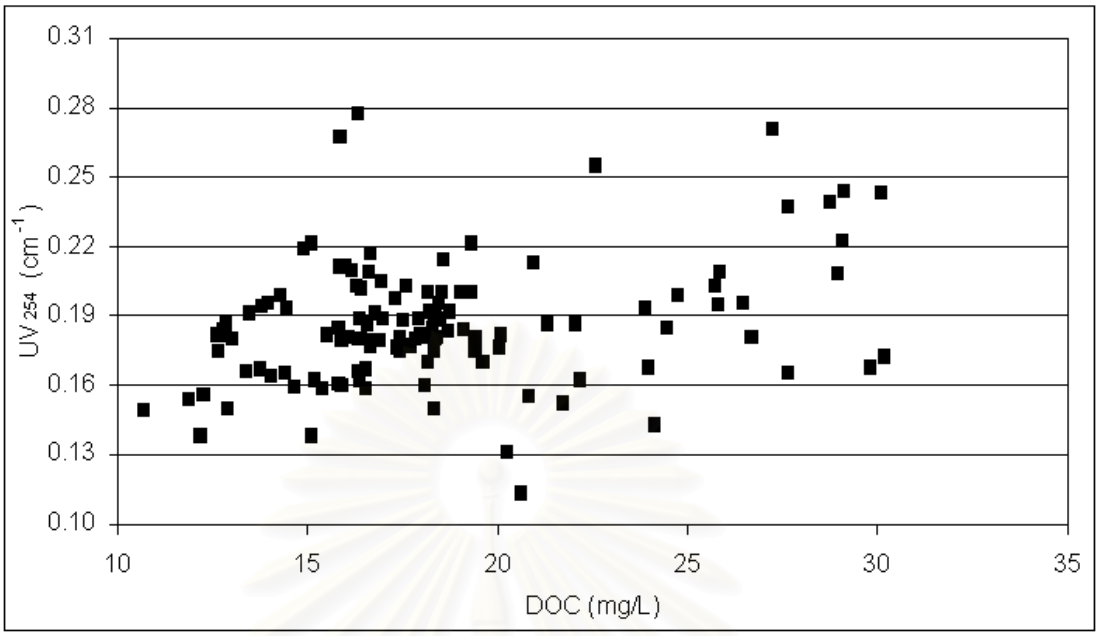


Figure 4.37 Correlation between DOC and UV_{254} of the effluent of the RBC process

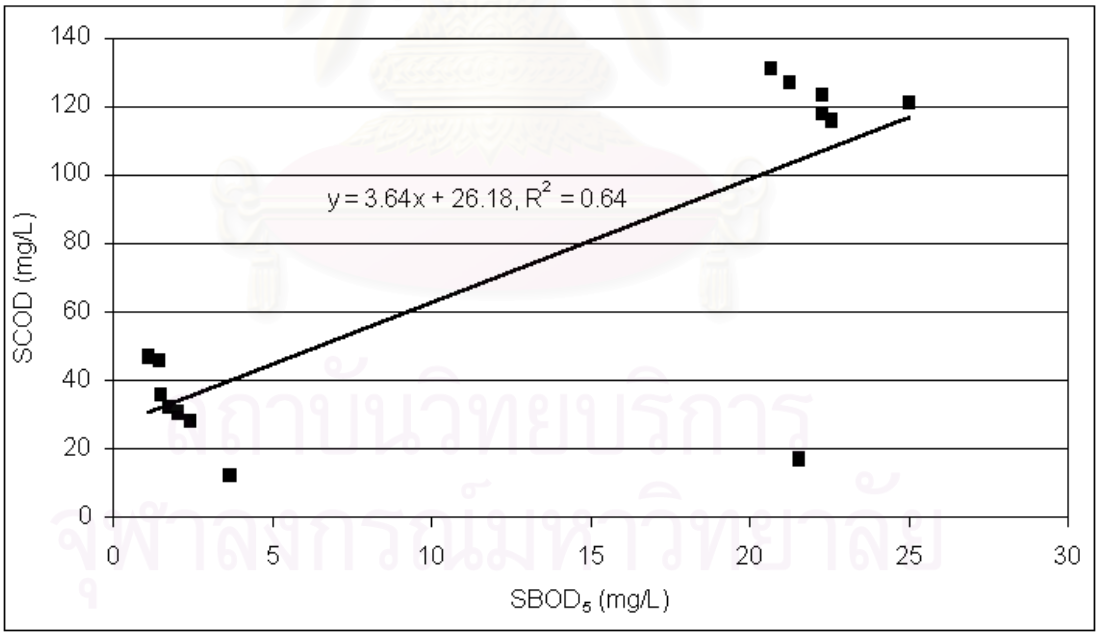


Figure 4.38 Correlation between $SBOD_5$ and SCOD of the effluent of the AS process

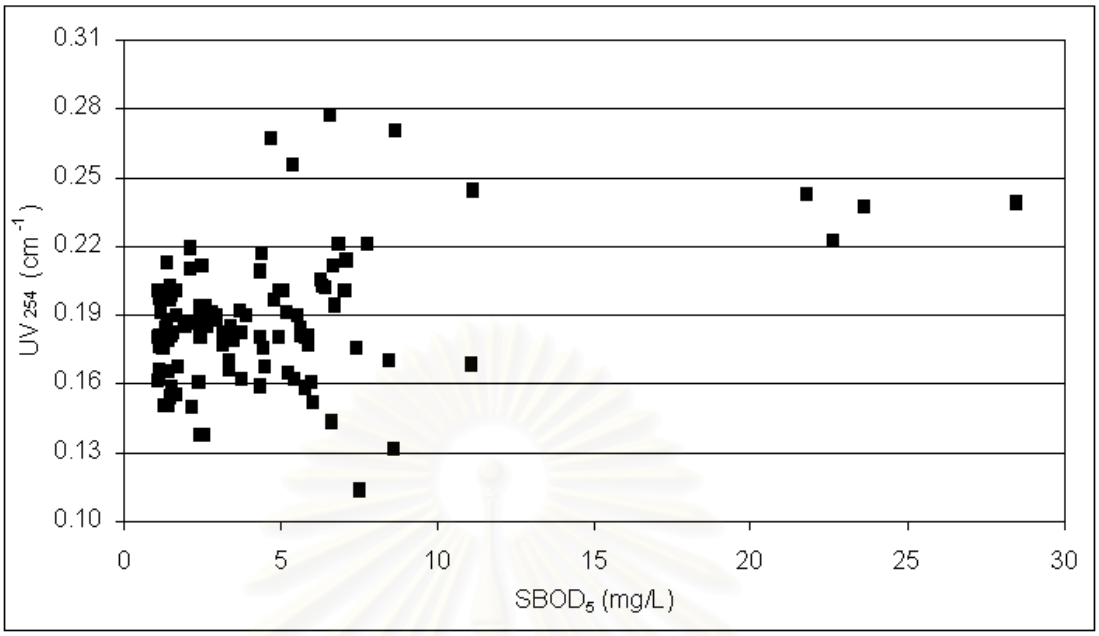


Figure 4.39 Correlation between $SBOD_5$ and UV_{254} of the effluent of the RBC process

4.5 Precision of BDOC and $SBOD_5$ methods

The precision of the BDOC and BOD methods was determined. The relative standard deviations (%RSD) was calculated and illustrated in Table 2.1. The standard deviations were calculated based on 5 analyses. The average BDOC concentration data of the biological treated wastewater varied from 0.63 to 19.55 mg/L. The standard deviation of BDOC was between 0.09 and 3.11 mg/L which corresponds to a range of RSD of 3.55% to 20.22%. The average SBOD concentration data varied from 2.00 to 32.22 mg/L. The standard deviation of SBOD ranged from 0.49 to 8.24 mg/L which corresponds to a range of RSD of 2.84% to 54.86%. Based on the ranges of RSD, it is apparent that the BDOC protocol is more precise than BOD method.

Table 4.1 Precision of BOD and BDOC analyses

Sample	BOD	SD	RSD	BDOC	SD	RSD
1	21.60	0.83	3.84	16.40	0.95	5.79
2	22.30	0.97	4.35	18.10	0.78	4.31
3	22.60	0.98	4.34	15.83	1.12	7.08
4	32.00	0.91	2.84	18.59	0.66	3.55
5	2.48	0.61	24.64	6.57	0.39	5.88
6	2.06	0.60	29.22	6.02	0.39	6.45
7	2.00*	0.72	40.86	5.32	0.40	7.46
8	2.00*	0.79	51.57	3.17	0.44	13.72
9	2.00*	0.81	54.86	0.63	0.09	14.33
10	23.17	5.24	22.62	14.13	2.03	14.37
11	24.58	6.95	28.27	12.46	1.86	14.93
12	23.50	5.91	25.15	14.14	2.54	17.96
13	32.22	8.24	25.57	15.38	3.11	20.22
14	7.25	2.10	28.98	4.31	0.51	11.83
15	6.65	1.24	18.64	6.53	0.64	9.81
16	3.65	0.89	24.37	8.39	0.66	7.86
17	8.64	2.91	33.70	10.13	1.15	11.36
18	3.42	1.12	32.76	7.66	1.11	14.49
19	2.00*	0.58	29.00	17.11	2.93	17.13
20	2.00*	0.66	33.00	12.53	1.83	14.61
21	2.00*	0.49	24.50	7.57	1.20	15.85
22	2.18	0.86	39.50	6.70	0.85	12.69
23	5.24	2.06	39.33	10.46	1.58	15.11
24	2.00	0.77	38.50	7.79	1.36	17.46
25	6.10	2.56	41.94	8.56	1.49	17.41
26	4.68	1.11	23.70	9.17	1.15	12.55
27	2.00	0.58	29.00	19.55	2.87	14.68
28	2.10	0.65	30.95	10.52	1.54	14.63
29	2.42	0.89	36.78	7.40	1.33	17.98
30	4.61	1.32	28.63	9.87	1.49	15.09
31	2.00	0.64	32.00	5.90	0.77	13.05
RSD avg.			28.50			12.57

Note: * is not detectable ($SBOD_5$ was lower than detection limit)

%RSD = (SD/mean) × 100

CHAPTER 5

CONCLUSIONS

This research investigates the effect of operational and control parameters of biological wastewater treatment processes, including AS, TF, and RBC on BDOC concentration in the effluents. The bench-scale units of AS and TF were constructed and used to study the effect of SRT and HLR on effluent BDOC, respectively. Primary treated wastewater from a wastewater treatment plant was used as influent of the treatment units. BDOC, SBOD, SCOD, DOC, MLSS and UV_{254} were analyzed during the research. For the RBC study, the effect of HLR was determined by analyzing BDOC in the secondary treated wastewater from two parallel sections (old and new sections) of an RBC plant. This research provides some insights into the potential utilization of BDOC for the characterization of secondary treated wastewater.

The results obtained from the study confirm the utility of the BDOC method to determine biodegradable organic content in the treated wastewater as well as characterize the performance of AS, TF, and RBC processes. Secondary treated effluent BDOC decreased nonlinearly with increasing SRT in AS process. In contrast, effluent $SBOD_5$ was mostly undetectable and its detection limit was reported. This resulted in the insensitivity of $SBOD_5$ to the SRT changes and no meaningful relationship between the two parameters.

The DOC measurement could not distinguish the performance of the AS process during the study. Effluent DOCs fluctuated and had no trend with increasing SRT. In the TF study, higher HLRs provided higher BDOCs. This is true throughout the range of HLRs studied. Although $SBOD_5$ and DOC tended to increase with HLR, increasing HLR did not necessarily result in higher $SBOD_5$ and DOC. Thus, BDOC is more appropriate parameter than $SBOD_5$ or DOC for indicating wastewater quality and the treatment performance especially when high quality secondary effluent is produced. Unfortunately, there was no obvious curve between organic parameter as well as biodegradability and

HLR in the RBC study due to the limitation and variation of RBC samples. However, the average organic content was higher at higher HLR. Significant and strong positive linear correlations among BDOC, DOC, and SCOD were obtained.

BDOC removal increased nonlinearly and tended to stabilize at higher SRT or lower HLR. Although BDOC, $SBOD_5$, and DOC removal provided similar profile in AS study, $SBOD_5$ was less accurate and less precise than the others because of its high detection limit. Furthermore, in the TF study, a trend that shows less BDOC removal at higher HLRs, was observed, while there are no clear relationships between HLR and the other two organic parameters. Hence, BDOC removal can be used as a reliable parameter for evaluating the efficiency of biological wastewater treatment process such as AS and TF processes.

The relationships between biodegradability of the treated effluent represented by $SBOD_5$/SCOD and BDOC/DOC and HLR and SRT show that the proportion of biodegradable organics in the secondary effluent was less at higher SRTs or lower HLRs. Even though both measurements shared a similar profile for AS treated wastewater, the biodegradability represented by BDOC/DOC was more reliable and sensitive than that represented by $SBOD_5$/SCOD as indicated by the standard deviations and the ranges of biodegradability covered by the two quotients.

UV_{254} in the RBC effluent samples was determined. Results show that it might be possible to use UV_{254} to indicate the wastewater quality; however, more data and studies are required. Because the BDOC method is easy and offers more sensitivity and precision than BOD, BDOC can be useful for designing and characterizing the performance of biological wastewater treatment processes.

CHAPTER 6

RECOMMENDATIONS FOR FUTURE STUDIES

One of the problems found in this study is the weak correlations between some parameters. It would be more appropriate to test more samples to obtain more reliable relationships. In this study, UV_{254} was measured only for the RBC effluent obtained from limited HLR values. The utility of UV_{254} as a treated wastewater quality indicator may be possible and should be studied thoroughly using more numbers and types of samples. Another interesting research project that should be conducted is a study of the effect of HLR of RBC process on effluent BDOC and BDOC removal efficiency using a laboratory scale RBC unit. The study will ensure that BDOC is applicable to RBC process.

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APPENDICES

Appendix A

Table A.1 General Description of RBC units of Rockland County Sewer District No.1

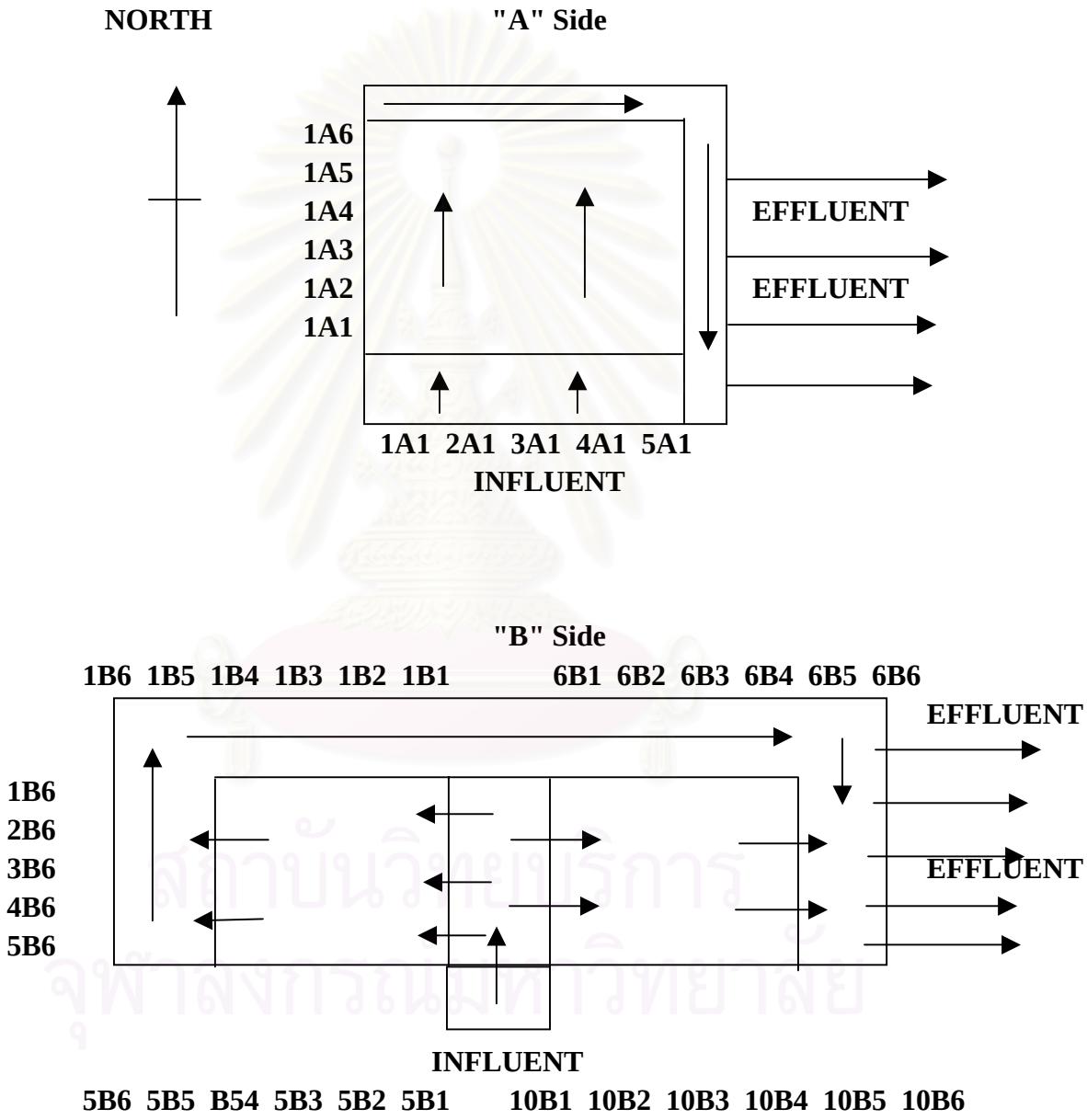
General Description of RBC units:		
RBC Arrangement:	"A" side RBC (Old side) - 5 trains (rows), 6 RBCs per train, total of 30 RBCs,	"B" side RBC (New side) - 10 trains (rows), 6 RBCs per train, total of 60 RBCs,
Surface Area: ft^2	"A" side - 1st three RBC on each Train = 114,000 , Last three RBC = 150,000	"B" side - 1st three RBC on each Train = 100,000 Last three RBC = 150,000
Flow: MGD	10 MGD in "A" Side	Balance of Flow in "B" side

Table A.2 Operational condition of Rockland County Sewer District No.1 during sampling period

Date	**No of Trains out of service**	
	Side "A" (Old Side)	**Side "B" (New Side)**
1/1/02 to 1/2/02	1	
1/1/02 to 1/7/02		1
1/3/02 to 1/14/02	1	
1/1/02 to 1/31/02		1
1/26/02 to 2/28/02		1
1/1/02 to 2/28/02		1

Appendix B

Table B.1 Flow pattern of section A and B of Rockland County Sewer District No.1



Appendix C

Table C.1 Organic Loading Rate (OLR) of Rockland County Sewer District No.1

Date	AREA (ft^2)	OLR (lb TBOD/10^3ft^2-d)	OLR-A (lb TBOD/10^3ft^2-d)	OLR-B (lb TBOD/10^3ft^2-d)
1 Jan 02	1683600	19.567	18.801	27.843
2 Jan 02	1683600	17.431	17.337	24.942
3 Jan 02	1683600	18.825	19.871	27.834
4 Jan 02	1683600	16.508	14.841	22.530
5 Jan 02	1683600	14.739	14.725	21.201
6 Jan 02	1683600	16.492	15.803	21.256
7 Jan 02	1683600	17.724	11.278	18.288
8 Jan 02	1833600	10.008	11.411	17.790
9 Jan 02	1833600	17.093	11.659	27.541
10 Jan 02	1833600	15.865	12.367	27.386
11 Jan 02	1833600	16.849	16.101	26.956
12 Jan 02	1833600	19.219	19.665	24.625
13 Jan 02	1833600	27.265	17.123	24.455
14 Jan 02	1833600	17.015	11.878	16.642
15 Jan 02	1992000	12.881	9.465	13.466
16 Jan 02	1992000	17.050	11.481	20.362
17 Jan 02	1992000	16.740	14.785	24.435
18 Jan 02	1992000	11.497	10.579	19.178
19 Jan 02	1992000	9.813	8.070	12.083
20 Jan 02	1992000	14.770	8.230	11.882
21 Jan 02	1992000	11.240	8.704	15.825
22 Jan 02	1992000	9.095	5.681	10.148
23 Jan 02	1992000	10.814	6.773	16.223
24 Jan 02	1992000	13.883	8.144	16.524
25 Jan 02	1992000	15.149	11.069	15.134
26 Jan 02	1842000	16.383	10.402	18.300
27 Jan 02	1842000	17.228	13.434	20.159
28 Jan 02	1842000	15.322	8.223	12.963
29 Jan 02	1842000	14.947	6.302	11.056
30 Jan 02	1842000	14.921	6.321	10.593
31 Jan 02	1842000	14.202	7.239	10.801

Table C.1 Organic Loading Rate (OLR) of Rockland County Sewer District No.1 (Cont'd)

Date	AREA (ft^2)	OLR (lb TBOD/$10^3 ft^2$-d)	OLR-A (lb TBOD/$10^3 ft^2$-d)	OLR-B (lb TBOD/$10^3 ft^2$-d)
1 Feb 02	1992000	19.287	9.373	15.624
2 Feb 02	1992000	16.765	9.681	14.256
3 Feb 02	1992000	11.620	8.538	12.542
4 Feb 02	1992000	10.313	8.694	12.166
5 Feb 02	1992000	10.383	10.579	19.300
6 Feb 02	1992000	15.242	6.033	12.344
7 Feb 02	1992000	10.587	8.315	24.334
8 Feb 02	1992000	16.393	7.597	16.790
9 Feb 02	1992000	10.689	7.915	15.470
10 Feb 02	1992000	10.468	7.938	12.907
11 Feb 02	1992000	16.134	9.983	15.547
12 Feb 02	1992000	12.446	6.773	9.589
13 Feb 02	1992000	15.731	7.408	15.662
14 Feb 02	1992000	13.762	9.794	13.744
15 Feb 02	1992000	15.282	9.681	14.049
16 Feb 02	1992000	15.006	8.782	12.344
17 Feb 02	1992000	16.260	9.146	12.910
18 Feb 02	1992000	15.864	8.681	15.933
19 Feb 02	1992000	13.294	6.860	9.084
20 Feb 02	1992000	14.387	8.664	14.738
21 Feb 02	1992000	13.389	8.403	13.071
22 Feb 02	1992000	13.865	10.694	12.443
23 Feb 02	1992000	15.995	9.780	14.387
24 Feb 02	1992000	16.171	9.089	12.542
25 Feb 02	1992000	14.168	10.067	16.503
26 Feb 02	1992000	13.179	7.449	12.251
27 Feb 02	1992000	13.504	7.143	9.973
28 Feb 02	1992000	14.662	9.061	12.019

Appendix D

Table D.1 Hydraulic Loading Rate (HLR) of Rockland County Sewer District No.1

Date	AREA (ft^2)	HLR (gal/ft^2d)	HLR-A (gal/ft^2d)	HLR-B (gal/ft^2d)
1 Jan 02	1683600	11.172	10.890	15.038
2 Jan 02	1683600	9.812	10.827	14.448
3 Jan 02	1683600	10.032	10.732	14.448
4 Jan 02	1683600	10.816	10.985	14.762
5 Jan 02	1683600	10.335	10.701	14.362
6 Jan 02	1683600	10.038	10.890	14.648
7 Jan 02	1683600	10.733	10.732	14.619
8 Jan 02	1833600	8.955	8.144	13.942
9 Jan 02	1833600	8.759	6.297	14.875
10 Jan 02	1833600	9.059	6.771	15.417
11 Jan 02	1833600	10.051	8.696	14.758
12 Jan 02	1833600	10.242	10.480	12.950
13 Jan 02	1833600	10.280	10.369	13.575
14 Jan 02	1833600	9.359	10.101	12.792
15 Jan 02	1992000	8.348	8.106	12.917
16 Jan 02	1992000	9.006	7.866	12.850
17 Jan 02	1992000	9.041	8.207	12.850
18 Jan 02	1992000	9.252	8.131	12.775
19 Jan 02	1992000	9.121	8.270	12.708
20 Jan 02	1992000	10.356	8.434	13.192
21 Jan 02	1992000	9.558	8.485	13.750
22 Jan 02	1992000	8.454	8.409	13.083
23 Jan 02	1992000	8.645	8.460	13.508
24 Jan 02	1992000	8.323	8.346	13.208
25 Jan 02	1992000	8.775	8.674	13.442
26 Jan 02	1842000	9.490	8.662	15.238
27 Jan 02	1842000	10.277	8.523	16.114
28 Jan 02	1842000	9.772	8.649	16.190
29 Jan 02	1842000	9.191	8.396	15.238
30 Jan 02	1842000	9.175	8.422	14.600
31 Jan 02	1842000	9.305	8.510	14.886

Table D.1 Hydraulic Loading Rate (HLR) of Rockland County Sewer District No.1 (Cont'd)

Date	AREA (ft^2)	HLR (gal/ft^2d)	HLR (A) (gal/ft^2d)	HLR (B) (gal/ft^2d)
1 Feb 02	1992000	9.177	8.712	13.575
2 Feb 02	1992000	9.438	8.598	12.950
3 Feb 02	1992000	9.106	8.750	13.192
4 Feb 02	1992000	8.770	8.687	13.142
5 Feb 02	1992000	8.469	9.192	13.300
6 Feb 02	1992000	7.912	8.611	12.983
7 Feb 02	1992000	8.138	8.308	13.508
8 Feb 02	1992000	8.775	8.434	13.158
9 Feb 02	1992000	8.901	8.788	13.442
10 Feb 02	1992000	9.297	8.813	13.575
11 Feb 02	1992000	9.212	8.674	13.508
12 Feb 02	1992000	8.936	8.460	12.775
13 Feb 02	1992000	8.855	8.460	12.775
14 Feb 02	1992000	8.594	8.510	12.775
15 Feb 02	1992000	9.116	8.598	13.058
16 Feb 02	1992000	9.227	8.775	12.983
17 Feb 02	1992000	9.026	8.308	12.900
18 Feb 02	1992000	9.101	8.674	13.267
19 Feb 02	1992000	8.434	8.308	12.967
20 Feb 02	1992000	8.333	8.245	12.533
21 Feb 02	1992000	7.987	8.396	12.742
22 Feb 02	1992000	8.439	8.548	12.433
23 Feb 02	1992000	8.524	8.497	12.500
24 Feb 02	1992000	9.413	8.649	13.192
25 Feb 02	1992000	9.438	8.561	13.192
26 Feb 02	1992000	8.273	8.270	13.233
27 Feb 02	1992000	8.178	8.396	12.858
28 Feb 02	1992000	8.790	8.422	12.642

Appendix E

Table E.1 Flow Rate of Rockland County Sewer District No.1

Date	Flow (MGD)			Date	Flow (MGD)		
	plant	section-A	section-B		plant	section-A	section-B
1 Jan 02	18.81	6.9	15.79	1 Feb 02	18.28	6.9	16.29
2 Jan 02	16.52	6.86	15.17	2 Feb 02	18.8	6.81	15.54
3 Jan 02	16.89	6.8	15.17	3 Feb 02	18.14	6.93	15.83
4 Jan 02	18.21	6.96	15.5	4 Feb 02	17.47	6.88	15.77
5 Jan 02	17.4	6.78	15.08	5 Feb 02	16.87	7.28	15.96
6 Jan 02	16.9	6.9	15.38	6 Feb 02	15.76	6.82	15.58
7 Jan 02	18.07	6.8	15.35	7 Feb 02	16.21	6.58	16.21
8 Jan 02	16.42	5.16	16.73	8 Feb 02	17.48	6.68	15.79
9 Jan 02	16.06	3.99	17.85	9 Feb 02	17.73	6.96	16.13
10 Jan 02	16.61	4.29	18.5	10 Feb 02	18.52	6.98	16.29
11 Jan 02	18.43	5.51	17.71	11 Feb 02	18.35	6.87	16.21
12 Jan 02	18.78	6.64	15.54	12 Feb 02	17.8	6.7	15.33
13 Jan 02	18.85	6.57	16.29	13 Feb 02	17.64	6.7	15.33
14 Jan 02	17.16	6.4	15.35	14 Feb 02	17.12	6.74	15.33
15 Jan 02	16.63	6.42	15.5	15 Feb 02	18.16	6.81	15.67
16 Jan 02	17.94	6.23	15.42	16 Feb 02	18.38	6.95	15.58
17 Jan 02	18.01	6.5	15.42	17 Feb 02	17.98	6.58	15.48
18 Jan 02	18.43	6.44	15.33	18 Feb 02	18.13	6.87	15.92
19 Jan 02	18.17	6.55	15.25	19 Feb 02	16.8	6.58	15.56
20 Jan 02	20.63	6.68	15.83	20 Feb 02	16.6	6.53	15.04
21 Jan 02	19.04	6.72	16.5	21 Feb 02	15.91	6.65	15.29
22 Jan 02	16.84	6.66	15.7	22 Feb 02	16.81	6.77	14.92
23 Jan 02	17.22	6.7	16.21	23 Feb 02	16.98	6.73	15
24 Jan 02	16.58	6.61	15.85	24 Feb 02	18.75	6.85	15.83
25 Jan 02	17.48	6.87	16.13	25 Feb 02	18.8	6.78	15.83
26 Jan 02	17.48	6.86	16	26 Feb 02	16.48	6.55	15.88
27 Jan 02	18.93	6.75	16.92	27 Feb 02	16.29	6.65	15.43
28 Jan 02	18	6.85	17	28 Feb 02	17.51	6.67	15.17
29 Jan 02	16.93	6.65	16				
30 Jan 02	16.9	6.67	15.33				
31 Jan 02	17.14	6.74	15.63				

Appendix F

Table F.1 Suspended Solids of Rockland County Sewer District No.1

Date	Suspended Solids (mg/L)					
	Raw water	section-A		section-B		Plant Final
		1' Effluent	2' Effluent	1' Effluent	2' Effluent	
1 Jan 02	195	116	30	118	52	28
2 Jan 02	248	98	30	104	34	34
3 Jan 02	193	106	22	122	46	27
4 Jan 02	185	86	24	120	54	30
5 Jan 02	186	94	12	102	24	25
6 Jan 02	280	98	28	84	38	41
7 Jan 02	209	90	28	120	46	26
8 Jan 02	197	60	18	132	30	28
9 Jan 02	178	88	36	112	20	20
10 Jan 02	210	114	32	114	48	29
11 Jan 02	177	104	32	124	48	24
12 Jan 02	179	80	10	104	20	21
13 Jan 02	195	80	28	102	38	20
14 Jan 02	269	158	26	122	40	19
15 Jan 02	205	108	28	152	30	21
16 Jan 02	207	86	14	126	20	15
17 Jan 02	153	64	10	100	22	27
18 Jan 02	151	76	16	104	20	18
19 Jan 02	178	82	18	112	28	20
20 Jan 02	222	74	12	86	30	20
21 Jan 02	167	98	18	104	30	25
22 Jan 02	191	72	16	96	28	23
23 Jan 02	185	92	10	152	20	20
24 Jan 02	228	90	16	128	24	28
25 Jan 02	263	98	22	104	26	16
26 Jan 02	186	54	14	66	22	21
27 Jan 02	107	82	26	98	32	24
28 Jan 02	273	100	22	106	30	27
29 Jan 02	258	56	24	70	14	18
30 Jan 02	232	92	20	104	28	22
31 Jan 02	177	84	14	60	42	18

Table F.1 Suspended Solids of Rockland County Sewer District No.1 (Cont'd)

Date	Suspended Solids (mg/L)					
	Raw water	section-A		section-B		Plant Final
		1' Effluent	2' Effluent	1' Effluent	2' Effluent	
1 Feb 02	290	110	18	124	30	23
2 Feb 02	212	84	24	124	20	23
3 Feb 02	117	56	16	74	6	15
4 Feb 02	164	102	40	90	28	22
5 Feb 02	136	96	16	134	82	31
6 Feb 02	443	68	18	92	28	25
7 Feb 02	284	106	48	172	40	33
8 Feb 02	261	64	20	154	36	35
9 Feb 02	127	54	28	94	16	29
10 Feb 02	111	54	22	76	12	27
11 Feb 02	252	96	14	142	36	26
12 Feb 02	185	68	22	76	16	29
13 Feb 02	240	56	26	148	14	29
14 Feb 02	202	100	34	124	34	29
15 Feb 02	228	102	24	108	36	23
16 Feb 02	192	42	14	76	14	30
17 Feb 02	208	92	32	98	30	27
18 Feb 02	243	72	18	88	16	26
19 Feb 02	215	58	14	44	26	25
20 Feb 02	245	96	14	114	24	25
21 Feb 02	209	86	22	92	38	27
22 Feb 02	231	98	14	106	46	22
23 Feb 02	201	82	10	102	16	23
24 Feb 02	238	68	20	86	32	28
25 Feb 02	225	80	16	98	32	26
26 Feb 02	228	66	28	64	40	23
27 Feb 02	303	72	24	88	18	23
28 Feb 02	246	90	10	88	32	35

Appendix G

Table G.1 Total BOD of Rockland County Sewer District No.1

Date	Total BOD (mg/L)					
	Raw water	section-A		section-B		Plant Final
		1' Effluent	2' Effluent	1' Effluent	2' Effluent	
1 Jan 02	210	207	69	222	73	80
2 Jan 02	213	192	41	207	41	64
3 Jan 02	225	222	46	231	47	77
4 Jan 02	183	162	41	183	42	44
5 Jan 02	171	165	33	177	42	44
6 Jan 02	197	174	38	174	66	58
7 Jan 02	198	126	33	150	41	30
8 Jan 02	134	168	36	153	40	30
9 Jan 02	234	222	59	222	60	26
10 Jan 02	210	219	43	213	43	41
11 Jan 02	201	222	67	219	64	71
12 Jan 02	225	225	37	228	45	46
13 Jan 02	318	198	36	216	44	64
14 Jan 02	218	141	36	156	38	23
15 Jan 02	185	140	25	125	25	23
16 Jan 02	227	175	37	190	35	23
17 Jan 02	222	216	33	228	42	23
18 Jan 02	149	156	26	180	35	41
19 Jan 02	129	117	23	114	35	29
20 Jan 02	171	117	21	108	32	26
21 Jan 02	141	123	17	138	35	28
22 Jan 02	129	81	18	93	25	30
23 Jan 02	150	96	19	144	25	24
24 Jan 02	200	117	19	150	32	35
25 Jan 02	207	153	30	135	31	26
26 Jan 02	207	144	26	144	30	28
27 Jan 02	201	189	22	150	33	31
28 Jan 02	188	114	14	96	28	34
29 Jan 02	195	90	21	87	16	25
30 Jan 02	195	90	21	87	16	25
31 Jan 02	183	102	19	87	25	27

Table G.1 Total BOD of Rockland County Sewer District No.1 (Cont'd)

Date	Total BOD (mg/L)					
	Raw water	section-A		section-B		Plant Final
		1' Effluent	2' Effluent	1' Effluent	2' Effluent	
1 Feb 02	252	129	24	138	26	26
2 Feb 02	213	135	36	132	35	30
3 Feb 02	153	117	35	114	23	27
4 Feb 02	141	120	26	111	35	31
5 Feb 02	147	138	29	174	38	38
6 Feb 02	231	84	21	114	32	34
7 Feb 02	156	120	29	216	37	33
8 Feb 02	224	108	25	153	39	43
9 Feb 02	144	108	35	138	36	42
10 Feb 02	135	108	35	114	25	43
11 Feb 02	210	138	33	138	40	35
12 Feb 02	167	96	27	90	15	30
13 Feb 02	213	105	29	147	18	30
14 Feb 02	192	138	34	129	38	35
15 Feb 02	201	135	29	129	33	33
16 Feb 02	195	120	23	114	28	42
17 Feb 02	216	132	38	120	34	41
18 Feb 02	209	120	24	144	32	25
19 Feb 02	189	99	24	84	22	32
20 Feb 02	207	126	24	141	24	36
21 Feb 02	201	120	29	123	36	37
22 Feb 02	197	150	26	120	31	33
23 Feb 02	225	138	31	138	29	34
24 Feb 02	206	126	22	114	34	36
25 Feb 02	180	141	26	150	39	33
26 Feb 02	191	108	33	111	37	30
27 Feb 02	198	102	24	93	24	25
28 Feb 02	200	129	20	114	32	41

Appendix H

Table H.1 Soluble BOD and CBOD of Rockland County Sewer District No.1

Date	Soluble BOD (mg/L)				CBOD (mg/L)	
	Raw water	section-A 1' Effluent	section-B 1' Effluent	Plant Final	Raw water	Plant Final
1 Jan 02	55	74	85	24	14	27
2 Jan 02	80	80	80	20	165	32
3 Jan 02	94	94	92	23	144	30
4 Jan 02	43	50	50	23	159	30
5 Jan 02	46	47	48	20	102	29
6 Jan 02	71	60	58	19	177	24
7 Jan 02	36	43	32	13	135	20
8 Jan 02	47	47	64	16	99	18
9 Jan 02	84	82	83	21	111	29
10 Jan 02	88	85	88	22	123	21
11 Jan 02	89	84	88	24	111	20
12 Jan 02	91	90	91	23	141	28
13 Jan 02	88	85	88	20	135	17
14 Jan 02	59	43	49	11	168	17
15 Jan 02	48	45	41	9	81	19
16 Jan 02	84	83	66	15	147	17
17 Jan 02	106	100	100	17	87	19
18 Jan 02	66	62	58	16	123	19
19 Jan 02	42	57	48	12	96	19
20 Jan 02	48	43	40	10	141	12
21 Jan 02	55	48	48	12	108	20
22 Jan 02	30	25	28	13	93	17
23 Jan 02	36	34	38	12	114	16
24 Jan 02	66	41	43	13	168	23
25 Jan 02	62	54	56	15	150	19
26 Jan 02	72	65	62	17	153	21
27 Jan 02	72	68	67	14	120	21
28 Jan 02	60	42	36	15	141	21
29 Jan 02	41	37	32	14	144	19
30 Jan 02	41	37	32	14	144	19
31 Jan 02	41	36	31	14	132	20

Table H.1 Soluble BOD and CBOD of Rockland County Sewer District No.1 (Cont'd)

Date	Soluble BOD (mg/L)				CBOD (mg/L)	
	Raw water	section-A 1' Effluent	section-B 1' Effluent	Plant Final	Raw water	Plant Final
1 Feb 02	43	38	34	12	171	21
2 Feb 02	88	56	43	15	162	23
3 Feb 02	48	44	44	16	114	21
4 Feb 02	50	41	31	16	102	21
5 Feb 02	43	43	60	13	111	27
6 Feb 02	31	35	36	11	174	23
7 Feb 02	30	36	26	12	120	23
8 Feb 02	43	48	36	17	135	30
9 Feb 02	78	60	49	15	117	30
10 Feb 02	60	52	47	17	105	25
11 Feb 02	76	60	52	14	162	23
12 Feb 02	53	42	37	10	132	20
13 Feb 02	55	44	36	11	162	23
14 Feb 02	72	59	43	13	159	24
15 Feb 02	60	47	36	14	174	25
16 Feb 02	77	60	49	20	162	28
17 Feb 02	62	48	32	18	180	28
18 Feb 02	62	54	58	15	171	20
19 Feb 02	53	37	34	12	144	21
20 Feb 02	59	40	36	13	174	21
21 Feb 02	82	42	35	15	150	25
22 Feb 02	60	34	31	14	162	22
23 Feb 02	83	54	59	15	138	19
24 Feb 02	72	53	49	15	158	22
25 Feb 02	66	44	36	14	150	24
26 Feb 02	53	38	30	14	162	25
27 Feb 02	56	37	34	12	138	19
28 Feb 02	60	50	37	15	153	27

BIOGRAPHY

Miss Pischa Wanaratna was born in Ubonratchathani, Thailand, on August 17, 1979. She went to Dara Academy, Chiang Mai, Thailand for her pre-college education and graduated in 1996. She received her Bachelor of Engineering Degree majoring in Environmental Engineering from Chiang Mai University, Thailand in 2000. She ranked first in grade point average in her major filed class. At the time of this study, she was an M.S. student with a major in Environmental Management at the National Research Center for Environmental and Hazardous Waste Management, Chulalongkorn University, Bangkok, Thailand.