

1-1-2002

The influence of denitrification in clarifiers on biological phosphorus removal at CCSD plant

Prithviraj Vasantryao Chavan
University of Nevada, Las Vegas

Follow this and additional works at: <https://digitalscholarship.unlv.edu/rtds>

Repository Citation

Chavan, Prithviraj Vasantryao, "The influence of denitrification in clarifiers on biological phosphorus removal at CCSD plant" (2002). *UNLV Retrospective Theses & Dissertations*. 1477.
<http://dx.doi.org/10.25669/0ag9-9io8>

This Thesis is protected by copyright and/or related rights. It has been brought to you by Digital Scholarship@UNLV with permission from the rights-holder(s). You are free to use this Thesis in any way that is permitted by the copyright and related rights legislation that applies to your use. For other uses you need to obtain permission from the rights-holder(s) directly, unless additional rights are indicated by a Creative Commons license in the record and/or on the work itself.

This Thesis has been accepted for inclusion in UNLV Retrospective Theses & Dissertations by an authorized administrator of Digital Scholarship@UNLV. For more information, please contact digitalscholarship@unlv.edu.

THE INFLUENCE OF DENITRIFICATION IN CLARIFIERS ON BIOLOGICAL
PHOSPHOROUS REMOVAL AT CCSD PLANT

by

Prithviraj V. Chavan

Bachelor of Engineering (Civil)
Shivaji University, Kolhapur, India
2000

A thesis submitted in partial fulfillment
of the requirements for the

Master of Science Degree in Engineering
Department of Civil and Environmental Engineering
Howard R. Hughes College of Engineering

Graduate College
University of Nevada, Las Vegas
May 2003

UMI Number: 1414518

UMI[®]

UMI Microform 1414518

Copyright 2003 by ProQuest Information and Learning Company.

All rights reserved. This microform edition is protected against
unauthorized copying under Title 17, United States Code.

ProQuest Information and Learning Company
300 North Zeeb Road
P.O. Box 1346
Ann Arbor, MI 48106-1346



Thesis Approval

The Graduate College
University of Nevada, Las Vegas

December 16, 2002

The Thesis prepared by

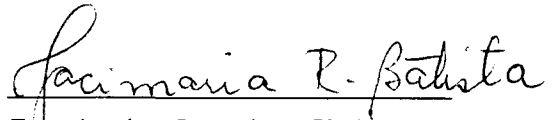
Prithviraj V. Chavan

Entitled


The Influence Of Denitrification In Clarifiers On Biological
Phosphorous Removal At The CCSD Plant.

is approved in partial fulfillment of the requirements for the degree of


Master of Science Degree in Engineering



Jacimaria R. Batista

Examination Committee Chair


Dean of the Graduate College


Examination Committee Member


Examination Committee Member


Graduate College Faculty Representative

ABSTRACT

The Influence of Denitrification in Clarifiers on Biological Phosphorus Removal at the Clark County Sanitation District (CCSD) at Las Vegas, Nevada

by

Prithviraj V. Chavan

Dr. Jacimaria Ramos Batista, Examination Committee Chair
Assistant Professor, Department of Civil and Environmental Engineering
University of Nevada, Las Vegas

Denitrification in biological reactors has been widely studied, whereas, little is known about denitrification occurring in secondary clarifiers. In this study an attempt was made to study denitrification occurring within a secondary clarifier at the Clark County Sanitation District (CCSD) wastewater treatment plant, Las Vegas. The results obtained from this study showed that denitrification and phosphorus (P) release were occurring within the CCSD clarifiers. Dissolved oxygen (DO) and soluble COD concentrations were found to be the most influencing parameters on denitrification and P-release within the clarifiers. The results also showed that sludge blanket height (SBH), solid flux, and state point analysis can be used as operating tools to control denitrification within the clarifiers.

TABLE OF CONTENTS

ABSTRACT.....	iii
ACKNOWLEDGEMENTS.....	viii
CHAPTER 1 : STATEMENT OF THE PROBLEM.....	1
CHAPTER 2 : LITERATURE REVIEW.....	3
2.1.1 Benefits of Adopting BNR Process	5
2.2 Enhanced Biological Phosphorus Removal (EBPR)	7
2.2.1 History of EBPR Systems.....	9
2.2.2 Factors Affecting EBPR	11
2.3 Biological Nitrogen Removal	12
2.3.1 Biological Nitrification	13
2.3.1.1 Classification of Nitrogen Removal Process	15
2.3.1.2 Factors Affecting the Nitrification Process.....	18
2.3.2 Biological Denitrification	19
2.3.2.1 Denitrification in Secondary Clarifiers.....	23
2.3.2.2 Effects of Nitrates on Biological P-removal.....	25
2.3.2.3 Classification of Denitrification System.....	30
2.3.2.4 Factors Affecting the Denitrification Process.....	33
2.4 Secondary Clarifiers.....	34
2.4.1 Secondary Clarifier Components.....	35
2.4.2 Clarifier Design Factors.....	37
2.4.2.1 Clarifier Configuration.....	37
2.4.2.2 Sludge Settling Characteristics	38
2.4.2.3 Surface and Solid Loading Criteria.....	39
2.4.2.4 Side Water Depth (SWD)	39
2.4.2.5 Flow Control	40
2.4.2.6 Structural Factors	40
2.4.3 Clarifier Design Approaches.....	42
2.4.4 Solid Flux Theory	43
2.4.4.1 History and Development of Solid Flux Theory.....	46
2.4.4.2 Application of Solid Flux Theory	49
2.4.4.3 Methods for Calculating Solid Flux.....	50
2.4.4.4 Clarifier Conditions	54
2.4.5 State Point Analysis	56

2.4.5.1	Importance of State Point Analysis.....	58
2.4.5.2	Clarifier Operations Control Strategies	62
2.4.5.3	Consequences to Plant Performance.....	63
CHAPTER 3 : CHARACTERIZATION OF DENITRIFICATION IN SECONDARY CLARIFIERS IN THE CCSD WASTEWATER TREATMENT PLANT		64
3.1	Introduction.....	64
3.2	Materials and Methods.....	66
3.3	Results and Discussions.....	68
3.3.1	Regression Analysis # 1.....	68
3.3.2	Nitrate Profiles.....	69
3.3.3	Dissolved Oxygen (DO) and Oxidation Reduction Potential Profiles.....	71
3.3.4	pH Profiles	74
3.3.5	Total Suspended Solids (TSS) Profiles.....	76
3.3.6	Soluble Chemical Oxygen Demand (SCOD)	77
3.3.7	Temperature	80
3.3.8	Regression Analysis # 2.....	82
3.3.9	Nitrite Profiles.....	83
3.3.10	pH Increase	85
3.3.11	Regression Analysis # 3.....	86
3.3.12	Total Phosphate (TP) and Ortho-Phosphate (OP) Profiles	87
3.4	Conclusions.....	89
CHAPTER 4 : MASS BALANCE EVALUATIONS OF DENITRIFICATION, P-RELEASE, AND ALKALINITY RECOVERY IN THE CCSD TREATMENT PLANT.....		91
4.1	Introduction.....	91
4.2	Materials and Methods.....	94
4.2.1	Mass Balance Calculations	94
4.3	Results and Discussion	97
4.3.1	Relationship between Denitrification and P-release in the Clarifier	97
4.3.2	Relationship between Denitrification and Effluent Suspended Solids	98
4.3.3	Relationship between Effluent Suspended Solids (ESS) and Effluent Total-P (ETP).....	100
4.3.4	Relationship between Denitrification and Effluent Total-P (ETP).....	103
4.3.5	Relationship between Denitrification and Effluent Ortho-P (EOP)	104
4.3.6	Relationship between Denitrification and Dissolved Oxygen (DO) in the Sludge	106
4.3.7	Relationship between Denitrification and Oxidation Reduction Potential (ORP) in sludge	107
4.3.8	Relationship between Denitrification and pH.....	108
4.3.9	Relationship between Denitrification and Concentration of Alkalinity Recovered	109
4.3.10	Relationship between RAS Ortho-P and Effluent Ortho-P.....	111

4.3.11	Relationship between Denitrification and Soluble Chemical Oxygen Demand (SCOD) in the Sludge.....	112
4.3.12	Relationship between P-release and Soluble Chemical Oxygen Demand (SCOD).....	113
4.4	Conclusions.....	114
CHAPTER 5 : USE OF SLUDGE BLANKET HEIGHT AS A TOOL TO CONTROL DENITRIFICATION IN SECONDARY CLARIFIER.....		115
5.1	Introduction.....	115
5.2	Materials and Methods.....	117
5.2.1	Measurement of Sludge Blanket Height.....	117
5.3	Results and Discussion	118
5.3.1	Relationship between DO and Sludge Blanket Height (SBH) in the Clarifier	118
5.3.2	Relationship between SCOD and Sludge Blanket Height (SBH) in the Clarifier.....	119
5.3.3	Relationship between pH increase in sludge Blanket and Sludge Blanket Height (SBH) in the Clarifier	119
5.3.4	Relationship between Denitrification and Sludge Blanket Height (SBH) in the Clarifier.....	120
5.3.5	Relationship between P-release and Sludge Blanket Height (SBH) in the Clarifier.....	121
5.3.6	Relationship between Sludge Blanket Height (SBH) and Effluent Suspended Solids (ESS).....	122
5.3.7	Relationship between Blanket Height (SBH) and Effluent Total Phosphorus (ETP).....	122
5.4	Conclusions.....	123
CHAPTER 6 : APPLICATION OF FLUX THEORY AND STATE POINT ANALYSIS TODENITRIFICATION CONTROL IN THE SECONDARY CLARIFIER... ..		125
6.1	Introduction.....	125
6.2	Materials and Methods.....	126
6.3	Results and Discussion	127
6.3.1	Solid Flux Curve for CCSD.....	127
6.3.2	Relationship between Solid Flux, Sludge Blanket Height, and Suspended Solid Concentrations.....	129
6.3.3	Relationship between Solid Flux and DO in the sludge	129
6.3.4	Relationship between Solid Flux and SCOD Concentration in the Sludge.....	130
6.3.5	Relationship between Solid Flux and Denitrification in the sludge	131
6.3.6	Relationship between Solid Flux and P-release in the sludge	131
6.3.7	Utilization of Solid Flux Curve to Determine Operational Conditions in the Clarifier	132
6.4	Conclusions.....	136
CHAPTER 7 : CONCLUSIONS AND RECOMMENDATIONS		138

APPENDIX A – RAW DATA COLLECTED FOR CCSD PLANT	142
APPENDIX B – REGRESSION ANALYSIS	173
APPENDIX C – MASS BALANCE ON DENITRIFICATION	177
APPENDIX D – MASS BALANCE ON P-RELEASE	185
APPENDIX E – ALKALINITY RECOVER.....	190
APPENDIX F – SLUDGE BLANKET HEIGHT	197
APPENDIX G – COLUMN SETTLING TEST	200
APPENDIX H – SOLID FLUX	203
APPENDIX I – TWO SAMPLE T-TEST FOR CHAPTER 5	206
APPENDIX J – TWO SAMPLE T-TEST FOR CHAPTER 6	210
REFERENCES	214
VITA	231

LIST OF FIGURES

Figure 2-1	Single Sludge Nitrification System.....	16
Figure 2-2	Two-Sludge Nitrification System	17
Figure 2-3	One Sludge Denitrification System	31
Figure 2-4	Two Sludge Denitrification System.....	33
Figure 2-5	Schematic Diagram Center-Feed Circular Clarifier Components (Modified from Metcalf & Eddy, 1991)	36
Figure 2-6	Secondary Clarifier with its Associated Fluxes.....	44
Figures 2-7a and 2-7b	Interface height-time and Interface settling velocity as Function of Solids Concentrations.....	51
Figure 2-8	Underloaded, Critically loaded, and Overloaded Clarifier Conditions (Modified from Rittmann, 2001)	56
Figure 2-9	OFR and underflow operating lines and location of state point (Modified from Rittmann, 2001).....	58
Figure 2-10	Case 1 (Modified from Keinath, 1985).....	60
Figure 2-11	Case 2 (Modified from Keinath, 1985).....	61
Figure 2-12	Case 3 (Modified from Keinath, 1985).....	62
Figure 3-1	Sampling Points Location in the Secondary Clarifier # 4.....	68
Figure 3-2a	Vertical Profile for Nitrate Concentration in the Secondary Clarifier at points 1 and 3	70
Figure 3-2b	Horizontal Profile for Nitrate Concentration in the Secondary Clarifier at Surface and Bottom.....	71
Figure 3-3a	Vertical Profile for DO Concentration in the Secondary Clarifier	72
Figure 3-3b	Horizontal Profile for DO Concentration in the Secondary Clarifier	72
Figure 3-4a	Vertical Profile for ORP Concentration in the Secondary Clarifier	73
Figure 3-4b	Horizontal Profile for ORP Concentration in the Secondary Clarifier	73
Figures 3-5a and 3-5b	Relationship between DO (a) Nitrate Decrease and (b) O-P	74
Figures 3-6a and 3-6b	Relationship between ORP & (c) Nitrate Decrease (d) Ortho-P.....	74
Figure 3-7a	Vertical Profile for pH in the Secondary Clarifier.....	75
Figure 3-7b	Horizontal Profile for pH in the Secondary Clarifier.....	76
Figure 3-8a	Vertical Profile for TSS in the Secondary Clarifier.....	77
Figure 3-8b	Horizontal Profile for TSS in the Secondary Clarifier.....	77
Figure 3-9a	Vertical Profile for Soluble Chemical oxygen Demand (SCOD) in the Secondary Clarifier	79
Figure 3-9b	Horizontal Profile for Soluble Chemical oxygen Demand (SCOD) in the	

	Secondary Clarifier	79
Figure 3-9b	Horizontal Profile for Soluble Chemical oxygen Demand (SCOD) in the Secondary Clarifier	79
Figures 3-10a and 3-10b	Relationship between Soluble Chemical oxygen Demand (SCOD) and (c) Nitrate Decrease, mg/L, (d) Ortho-P concentration, mg/L	79
Figure 3-11	Relationship of SCOD with TSS and DO at the Clarifier Bottom of Points 1, 2 and 3, respectively	80
Figure 3-12a	Vertical Profile for Temperature in the Secondary Clarifier.....	81
Figure 3-12b	Horizontal Profile for Temperature in the Secondary Clarifier	82
Figures 3-13a and 3-13b	Relationship Between Nitrate Decrease and (a) Cold Temperature (b) Hot Temperature in the Secondary Clarifier	82
Figure 3-14a	Vertical Profile for nitrite Concentration in the Secondary Clarifier.....	83
Figure 3-15	Relationship between Nitrate Decrease and Nitrite Increase at 3 Points...85	
Figure 3-16	Relationship Between pH Increase and Nitrate Decrease at the Bottom of the Clarifier	86
Figure 3-17a	Vertical Profile for TP in the Secondary Clarifier	88
Figure 3-17b	Horizontal Profile for TP in the Secondary Clarifier.....	88
Figure 4-1	Schematic Layout of Typical BNR process.....	95
Figure 4-2a and 4-2b	Correlation between Denitrification and P-release in clarifier using data set1	98
Figure 4-3a and 4-3b	Correlation between Denitrification and Effluent Suspended Solids in clarifier using data set 1	99
Figure 4-4a	Correlation between Effluent Suspended Solids (ESS) and Effluent Total-P (ETP) in clarifier using data set 2	100
Figure 4-5a	Correlation between Denitrification and Effluent Total-P (ETP) in clarifier using data set 1	103
Figure 4-6a and 4-6b	Correlation between Denitrification and Effluent Ortho-P (EOP) in clarifier using data set 1	105
Figure 4-7a and 4-7b	Correlation between Denitrification and Dissolved Oxygen (DO) in clarifier using data set 1	107
Figure 4-8a and 4-8b	Correlation between Denitrification and Oxidation Reduction Potential (ORP) in clarifier using data set 1	107
Figure 4-9a and 4-9b	Correlation between Denitrification and pH in clarifier using data set 1	109
Figure 4-10a and 4-10b	Correlation between Denitrification and Concentration of Alkalinity Recovered in clarifier using data set 1	110
Figure 4-11a and 4-11b	Correlation between RAS Ortho-P and Effluent Ortho-P in clarifier using data set 1	111
Figure 4-12a	Correlation between Denitrification and SCOD in Sludge using data set 1	113
Figure 4-13a	Correlation between P-release and SCOD) in the Sludge using data set 1	114
Figure 5-1	Relationship between DO and SBH in CCSD Clarifier # 4.....	118
Figure 5-2	Relationship between SCOD and SBH in the Clarifier	119
Figure 5-3	Relationship between pH increase in sludge Blanket and SBH	120
Figure 5-4	Relationship between Denitrification and SBH in the Clarifier	121

Figure 5-5	Relationships between P-release and SBH in the Clarifier.....	121
Figure 5-6	Relationship between SBH and Effluent Suspended Solids (ESS)	122
Figure 5-7	Relationship between SBH and Effluent Total Phosphorus (ETP)	123
Figure 6-1	Interface height-time profile as a function of solids concentration for CCSD Sludge	127
Figure 6-2	Solid Flux Curve for CCSD Plant.....	128
Figure 6-3a and 6-3b	Relationship between Solid Flux, Sludge Blanket, and Suspended Solid Concentrations	129
Figure 6-4	Relationship between Solid Flux and DO in the sludge	130
Figure 6-5	Relationship between Solid Flux and Denitrification in the sludge	130
Figure 6-6	Relationship between Solid Flux and Denitrification in the sludge	131
Figure 6-7	Relationship between Solid Flux and P-release in the sludge	131
Figure 6-8	Representative Data of Underload Clarifier Conditions at CCSD.....	133
Figure 6-9	Representative Data of Overload Clarifier Conditions	134
Figure 6-10	Overload and Underload Clarifier Conditions for CCSD Plant.....	135
Figure 6-11	Control Strategy for Overload Condition	136

ACKNOWLEDGEMENTS

I would like to thank the Clark County Sanitation District and the Applied Research Initiative of the University of Nevada Las Vegas for the financial and institutional support. I heartily appreciate my advisor, Dr. Jacimaria Batista, for her relentless support through all aspects of this research. I would also like to thank all the committee members, Dr. David E. James, Dr. Barbara A. Luke, and Dr. J. Abiodun Elegbede, for reviewing my thesis.

I would like to specially thank the CCSD plant managers Bill Shepherd for providing so much information and data on the plant operation. Appreciation goes to Don Schoengold, David Paulsen, and Wanda Flohr at the AWT laboratory and to the analysts at the AWT laboratory, Randy White, Esther Disuanco, Max Sosa, Barry Bowers, Scott Chappell, Billy Clark, and Elizabeth Perez, for analyzing the samples.

I would also like to thank Dr. Richard Unz and Dr. Heinrich Buhr for their inputs on data evaluation and for reviewing the final research report.

I am really grateful to my parents and my loving sister Chanchala, also I would like to thanks all my colleagues, whose love and support made my studies possible.

CHAPTER 1

STATEMENT OF THE PROBLEM

The major objective of secondary clarification is to separate biosolids from liquid. However, processes that would normally take place in bioreactors, such as denitrification, may occur in secondary clarifiers. When denitrification occurs during clarification it may have negative or positive effects on the plant's efficiency in removing nutrients. This is especially significant in biological nutrient removal (BNR) plants where one-sludge systems are used. In these systems, a single activated sludge tank is used to oxidize BOD (biological oxygen demand) and ammonia, and to biologically remove phosphorus. The effluent from one-sludge activated sludge systems, which is sent to the secondary clarifier, contains high levels of nitrate and suspended solids laden with polyphosphate. In the secondary clarifier, conditions may develop that will promote both denitrification (e.g. biological conversion of nitrate to nitrogen gas) and phosphate release from the suspended solids.

Strong denitrification in the clarifier may be detrimental to the plant's efficiency to remove phosphorus. Nitrogen bubbles formed during denitrification will promote rising of the sludge to the surface of the clarifier. This results in increased suspended solids concentration in the clarifier effluent, affecting the overall removal efficiency of the plant with respect to BOD, total suspended solids (TSS), total nitrogen and total phosphorus. On

the other hand, strong denitrification is beneficial in increasing the alkalinity of the wastewater (e.g. increase in pH), lowered during nitrification.

Weak or absent denitrification can be detrimental to a plant's efficiency to remove phosphorus biologically (Bio-P) because high concentrations of nitrate in the return activated sludge (RAS) negatively affect P-release in the anaerobic zone of the Bio-P process. In contrast, moderate denitrification within the clarifier may be beneficial to the performance of BNR systems, because it does not significantly inhibit microbial P-release by microorganisms in the anaerobic stage of the process and also because it allows for recovery of alkalinity.

The occurrence of denitrification within secondary clarifiers and its negative effects on biological phosphorus removal has been reported. However, little is known about the parameters affecting denitrification in the clarifiers and not much research has been performed on potential tools for its control.

In this research an attempt was made to determine the main parameters affecting denitrification in clarifiers in the full-scale wastewater treatment plant, the Clark County Sanitation District (CCSD), in Las Vegas, Nevada. In addition, the concepts of sludge blanket height (SBH), solid flux, and state point analysis was explored as potential tools to control denitrification in clarifiers. The specific objectives of this research were:

(1) To investigate the occurrence and determine the major parameters influencing denitrification within secondary clarifiers at the CCSD, (2) To use the mass balance approach to estimate the extent of clarifier denitrification occurring at CCSD, and (3) To examine whether sludge blanket height, solid flux, and state point analysis can be used as operational tools for clarifier denitrification control.

CHAPTER 2

LITERATURE REVIEW

This literature review cover topics which background is needed to understand the fundamentals involved in this research. It is divided into three main sections:

- 1) Biological Nutrient Removal (BNR) – It covers the fundamentals of biological phosphorus (P) and nitrogen removal with on the influence of nitrate on P-removal. In addition it covers the intentional and unintentional denitrification as well as the principles of nitrification.
- 2) Secondary Clarifiers – It includes the basics of clarifier design and operation.
- 3) Solid Flux and State point – It covers the history and use of the solid flux and state point analysis for designing and analyzing secondary clarifiers performance.

2.1 Biological Nutrient Removal (BNR)

Both nutrients, nitrogen (N) and phosphorus (P) are present in wastewater in organic and inorganic (ammonia, nitrate, nitrite, phosphate) forms. The major sources of nitrogen include industrial waste, human waste, and fertilizers applied to farms. The presence of these nutrients in waterbodies has an adverse effect on the quality of the water. The presence of nitrogen in water is undesirable for several reasons: a) Nitrogen in free ammonia form is toxic to fish and many other aquatic life (Colt & Armstrong,

1979), b) Nitrogen in ammonium or ammonia form are oxygen-consuming compounds, that deplete dissolved oxygen in receiving waters (Barnes & Bliss, 1983; and Sorensen & Jorgensen, 1993) c) Nitrogen in the nitrate and nitrite form, when present in drinking waters are responsible for causing methemoglobinemia (infantile cyanosis), and carcinogenesis (particularly, gastric cancer, EPA, 1993), and d) N and P in any form can be available as a nutrient to aquatic plants and can significantly contribute to eutrophication.

Eutrophication is the nutrient enrichment in an aquatic ecosystem which stimulates algal blooms. This is one of the important reason why N and P should be eliminated from waterbodies. Either N or P can be the limiting nutrient controlling eutrophication because large amounts are required for biomass growth compared to other nutrients like sulfur, potassium, calcium, and magnesium. Phosphorus is often the growth-limiting factor for algae (Horan, 1990). Generally, phosphorus is a limiting nutrient in fresh waterbodies, whereas nitrogen is a limiting nutrient in estuarine and marine waters (Metcalf & Eddy, 1991).

Activated sludge is the most widely used biological process for treating domestic and industrial wastewater. Normally, the activated sludge process is strictly aerobic, consisting of a biological reactor (e.g. aeration basin) and a secondary clarifier. Sludge is recycled from the secondary clarifier to the aeration basin and can be removed from the process through a sludge wasting line. Over the years, modifications were made in this process to accommodate the removal of nutrients such as nitrogen (N) and phosphorus (P) (Randall et al., 1992). These systems are called biological nutrient removal (BNR) systems because they remove nutrients from wastewater by biological means. BNR

systems incorporate anoxic, anaerobic, and aerobic zones with mixed liquor recirculation. The aerobic zone is an essential component of all BNR systems, since nitrification and phosphorus uptake is performed in this zone, while the anaerobic zone is essential to accomplish phosphorus release, and the anoxic zone is required for nitrogen removal by denitrification.

2.1.1 Benefits of Adopting BNR Process

The BNR process for wastewater treatment is more economical than conventional chemical addition processes used to remove nutrients (Chaung et al., 1997). It also provides environmental, and operational benefits. Chemical addition for phosphorus removal is significantly more expensive than biological phosphorus removal (Bowker & Stensel, 1990). Furthermore, any reduction in chemical addition reduces the amount of sludge produced in the system, providing further economic benefit by reducing sludge management and disposal costs. Several methods are available to eliminate P from wastewater that involve chemical, biological, or physical processes. Chemical precipitation using iron and aluminum salts or lime is commonly used in combination with either chemical or biological processes where low levels of effluent phosphorus are required (Murakami et al., 1987). Ultra filtration and reverse osmosis are effective physical methods used for phosphorus removal.

To accomplish complete nitrification, the biological nitrogen removal process is more economical than physiochemical processes such ammonia stripping, breakpoint chlorination, ion exchange, membrane process, and precipitation (Metcalf & Eddy, 1991; Sedlak, 1991; and Sorensen & Jorgensen, 1993). In addition, one half of the alkalinity

destroyed during nitrification can be recovered by denitrification, providing an additional economic benefit. Properly designed and operated BNR processes are more stable and produce good quality effluent in respect to BOD, TSS, and phosphorus removal as compared to conventional activated sludge systems with chemical coagulants for P-removal.

A number of biological processes have been developed to remove the nutrients (N and P). Some of these processes were developed originally for phosphorus removal and later evolved into nutrient removal (N and P). The most commonly used BNR systems include: the A^2/O , the five-stage Bardenpho process, the University of Capetown (UCT), and the VIP process. A complete review of the different BNR system configuration can be found in Mota (2001). The main difference between these processes lies in the location of recycled sludge. In the A^2/O process, the return activated sludge (RAS) containing nitrate is directed to the anaerobic zone from the end of nitrification stage for denitrification. In UTC process, the RAS is diverted to an anoxic zone to remove recycled nitrate by denitrification. The RAS is also diverted to an anoxic zone in the VIP process, while denitrified anoxic mixed liquor is also directed from the end of the anoxic zone back to the anaerobic zone.

Wanner et al. (1992) designed a new arrangement of the biological process to remove nutrients from wastewater. All the arrangements were similar to that A^2/O process, except for the denitrification reactor where oxidized supernatant is mixed with activated sludge separated from the anaerobic reactor.

2.2 Enhanced Biological Phosphorus Removal (EBPR)

EBPR involves design or operational modifications of conventional treatment systems that results in the growth of a biological population that has much higher cellular phosphorus content. The typical phosphorus content in the microbial solids is 1.5 to 2% on a dry weight basis (WPCF, 1985). In EBPR systems, cell P content can reach 5 to 6% during high phosphorus uptake (Tetreault, 1986). Phosphorus removal can be achieved biologically by allowing the wastewater to pass through an anaerobic tank followed by an aerobic tank, with continuous sludge recycling, and finally wasting the sludge.

In EBPR processes, the wastewater is submitted to alternate anaerobic and aerobic conditions. The anaerobic zone is a biological selector for phosphorus accumulating organisms (PAOs). This zone provides a competitive advantage for PAOs, since they can take up substrate in this zone before other non-PAO bacteria can. Thus, the anaerobic zone allows the development or selection of a large population of PAOs in the system. The proliferation of filamentous bacteria that cause poor settling characteristics can be prevented by specific population selection of PAOs in the anaerobic zone (Mino et al., 1994). During this phase, PAOs obtain energy from the breakdown of intracellular PP to promote the uptake of volatile fatty acids (VFAs). VFAs are stored as intracellular polyhydroxyalkanoates (PHAs) that are used as an energy source for phosphorus uptake in the subsequent aerobic zone.

PAOs are capable of taking up more phosphorus in the aeration basin than the amount released in the anaerobic zones. The above mechanism indicates that the level of biological P-removal achieved is directly related to the amount of substrate that can be

fermented by microorganisms in the anaerobic zone and subsequently assimilation and storage as fermentation products (PHA and/or PHB) by PAOs, in anaerobic zone.

Following are advantages and disadvantages of BNR as cited by Bowker & Stensel (1990), Metcalf & Eddy (1991), and Sedlak (1991).

Advantages:

- The amount of sludge produced by biological phosphorus removal processes are comparable to sludge produced by conventional activated sludge systems,
- EBPR can be implemented directly at existing plug-flow activated sludge plants with little or no equipment changes or additions, provided that the plant has sufficient capacity,
- Little or no chemicals or chemical handling equipment is required, except for effluent polishing,
- With some of the processes phosphorus removal can be achieved together with ammonia nitrogen or total nitrogen removal at virtually no additional operating cost, and
- EBPR can utilize existing sludge handling equipment for plants installed with biological phosphorus removal process if phosphorus is not solubilized and returned to the plant during sludge handling

Disadvantages:

- The BOD:TP ratio of the wastewater controls the performance of the phosphorus removal system,
- The process is not easily installed into fixed biological systems,

- Standby chemical feed equipment may be necessary in case of loss of biological phosphorus removal efficiency,
- EBPR requires highly efficient secondary clarifier performance to achieve 1 mg/L total phosphorus (because secondary sludge contains stored poly-phosphate), and
- Recycle streams must be low in phosphorus content.

2.2.1 History of EBPR Systems

In 1955, Greenburg et al. noted that activated sludge could take up phosphorus at levels beyond the normally accepted microbial growth requirements. The first researcher to report the occurrence of biological P-removal from wastewater treatment plant sludge was Srinath (1959). Levin and Shapiro (1965) termed high removal of phosphorus by microorganisms as “luxury uptake”. Besides, Levin and Shapiro (1965), Vacker et al. (1967) and Milbury et al. (1971) also observed high removal of phosphorus at a number of full-scale wastewater treatment plants (WWTP).

Barnard (1974) reported that P-release was occurring at the inlet of the activated sludge tanks of some plants. He also reported that high P-removal could occur biologically in a system where sludge is first subjected to an anaerobic zone to release phosphorus, followed by an aerobic zone. He also reported that high P-removal could occur biologically in a system where sludge is first subjected to an anaerobic zone to release phosphorus, followed by an aerobic zone. This observation provided explanation for the performance of several full-scale plants that experienced high level of P-release. In a later paper, Barnard (1976) suggested the use of a separate anaerobic basin ahead of the aerated basin and the process was termed as the Phoredox process. This process was derived from phosphorus and redox potential to signify the lower reducing environment

required in the anaerobic zone. Barnard also observed that nitrates in the anaerobic zone adversely affected the biological phosphorus removal efficiency.

Simpkins et al. (1978) and Nicholls et al. (1979) in a pilot plant experiment confirmed the negative effect of nitrates on biological phosphorus removal. Fuhs and Chen (1975) observed that strains of *Acinetobacter* from EBPR systems were capable of accumulating polyphosphates (PP), and polyhydroxybutyrate (PHB). In 1983, Brodisch found strains of *Aeromonas punctata* other than *Acinetobacter* capable of P-removing. These are heterotrophic organisms capable of acid fermentation. In the last thirty years much work has been performed on several aspects of bio-P which include microbial storage product polyphosphates (PP), glycogen, polyhydroxyalkanoates (PHAs) that led to the development of several metabolic models for EBPR.

There are currently 4 models that attempt to explain the removal of P from water by bacteria: the Comeau et al. model (1987), Mino et al. model (1987), the Wentzel et al. model (1988), and the Smolder et al. model (1994). The important role of PP, PHA, and glycogen on EBPR systems has been extensively reported by Fuhs and Chen (1975), Comeau et al. (1987), Mino et al. (1987), Wentzel et al. (1988), and Smolder et al. (1994).

PP are linear polymers of orthophosphate molecules joined by phosphoanhydride bonds (Schuler, 1998). PHAs include polyhydroxybutyrate (PHB) and polyhydroxyvalerate (PHV). The PHAs can be degraded by intracellular depolymerases and subsequently metabolized as a carbon and energy source, when the supply of limiting nutrient is restored (Lee and Park, 1998). Nicholls and Osborne (1984) stated that as a result of the fermentation process, short chain fatty acids, such as acetate, are produced.

The disappearance of soluble BOD and the role of fatty acids was confirmed in their study by an increase in PHB storage products during the anaerobic contact period of EBPR systems. Increased PHB concentration in the anaerobic zone of EBPR were also observed by Timmerman (1979). The observation made by Comeau et al. (1987) on PHB and PHV storage suggests that preferred fermentation substrates for phosphorus accumulating organisms (PAOs) are acetate and propionate. Steinbuchel (1991) reported the existence of nearly 300 different bacteria that accumulate various PHAs. Schuler (1998) stated that the most common and studied PHA is PHB.

2.2.2 Factors Affecting EBPR

Deakyne et al. (1984) and Tetreault et al. (1986) reported that P concentration as low as 0.2 mg/l in the effluent of EBPR system. However, achieving such low phosphorus discharge levels is not possible at all plants and for all operating conditions. To achieve the standard of 1 mg/l as total phosphorus, very low effluent soluble phosphorus concentration would be required in the effluent. Low soluble phosphorus in the effluent can be accomplished either by effluent filtration to remove the phosphorus containing total suspended solids (TSS) or by chemical addition to lower the soluble phosphorus.

Bowker and Stensel (1990) observed the following characteristics contributed the most to maximizing biological phosphorus removal: 1) dissolved oxygen concentration equal or greater than 2 mg/l, 2) aeration of secondary clarifier to avoid P-release, and 3) preventing sludge handling streams which contain soluble phosphate, from reentering the plant.

Several factors affect the efficiency of EBPR systems. These are related to wastewater characteristics, system design, and operational methods. The factors affecting the EBPR efficiency include VFA concentration, the presence of nitrates, DO concentration, temperature, pH, solids retention time (SRT), anaerobic and aerobic detention times, and waste sludge handling methods.

2.3 Biological Nitrogen Removal

Nitrogen can be removed from wastewater biologically or by physicochemical processes. Physicochemical processes for nitrogen removal include ammonia stripping, breakpoint chlorination, ion exchange, membrane process, and precipitation. The selected method of removal generally depends on concentration and form of nitrogen compounds in the process influent, effluent quality of wastewater required, effluent standards for other parameters, construction and operational costs for the process, and reliability and flexibility of the process over the actual range of operating temperature.

Above all aforementioned methods, biological removal of nitrogen is the most commonly used because of its high removal efficiency, moderate cost, high process stability and reliability, relatively easy process control, and low land area requirement (Wanielista & Eckenfelder, 1978; Sedlak, 1991; and EPA, 1993). Biological nitrogen removal involves two processes, nitrification and denitrification. In nitrification, ammonia is autotrophically oxidized to nitrate using molecular oxygen as an electron acceptor. In the denitrification process, nitrate is used as an electron acceptor and is heterotrophically reduced to nitrogen gas. Biological nitrification and denitrification are the most economical processes for elimination of nitrogen from domestic and industrial

wastewater. The design and economics of biological nitrogen removal systems are governed by their kinetics. Indeed, the rate with which nitrification and denitrification proceed depends on the microbial population, composition and strength of the wastewater, and on a wide variety of chemical and physical parameters (Sedlak, 1991; and Sorensen & Jorgensen, 1993).

Domestic wastewaters have more or less uniform quality; therefore the design parameters are well established. On the other hand, industrial wastewater composition varies in quality from case to case and design parameters have to be developed for each case.

2.3.1 Biological Nitrification

Nitrification is a biological oxidation of ammonia to nitrate with nitrite as an intermediate. For nitrification to occur, two conditions must be fulfilled in a treatment plant: a) solids retention time (SRT) should be sufficiently high to prevent the washout of the slow growing nitrifying microorganisms, and b) the contact time between the bacterial mass and ammonia must be long enough to ensure its oxidation. The microorganisms involved in nitrification are strictly aerobic autotrophic bacteria (nitrifiers). This means the energy for cell growth is derived from oxidation of nitrogen compounds). In contrast, to the heterotrophic bacteria, nitrifiers use inorganic carbon (carbon dioxide) rather than organic carbon for synthesis of new cells.

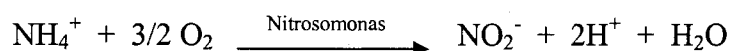
The principal genera of bacteria involved in the nitrification process are *Nitrosomonas* and *Nitrobacter*; however, *Nitrosopira*, *Nitrosolobus*, and *Nitrosoumbrio* are also involved in biological nitrification (Rittmann, 2001). Winogradsky (1890) was

the first to observe the nitrifying bacteria, *Nitrosomonas* and *Nitrobacter*, which oxidized ammonia sequentially to nitrite and then to nitrate respectively.

In 1970, Painter found other genera of bacteria capable of obtaining energy from the oxidation of ammonia including, *Nitrosococcus*, *Nitrospira*, *Nitrosocystis* and *Nitrosoglea*, and nitrite, *Nitrocystis*. Eylar and Schmidt (1959), Painter (1970), and Randall et al. (1992) observed that some heterotrophic bacteria are also capable of forming nitrite or nitrate. Focht and Chang (1975) found that heterotrophic nitrification is possible with various genera of bacteria, fungi, and actinomycetes. However, nitrification rates by heterotrophic bacteria are generally 10^4 - 10^5 times lower than autotrophic nitrification rates (Niel et al., 1993).

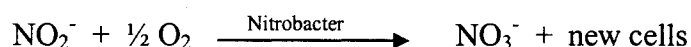
Nitrification is a two-step process. In the first step ammonium is converted to nitrite and in the second step, nitrite is converted to nitrate. The conversion process is as follows:

First Step:



Nitrosomonas is the most commonly recognized genus of bacteria to carry out the first step.

Second Step:



Nitrobacter is the most common genus of nitrite oxidizers

The empirical equation for the overall nitrification reaction including synthesis and oxidation is as follows (Rittmann, 2001):



The above equation illustrates the stoichiometry of the nitrification reaction. Oxygen is required to oxidize ammonia-nitrogen, and 4.33 mg of O₂ is required for each mg of NO₃-N generated. Alkalinity is also consumed in the reaction to both neutralize the acid produced (i.e. ammonia-nitrogen is a base and nitrate-nitrogen is an acid) and as required for the synthesis of new biomass. The alkalinity requirement calculated from the above equation is 7.05 mg of alkalinity as CaCO₃ for each mg of NO₃-N produced.

2.3.1.1 Classification of Nitrogen Removal Process

To accomplish nitrification in wastewater either (a) Single stage or One sludge system, or (b) Separate stage or Two sludge systems are available.

Schematic layouts of single and two sludge nitrification process with activated sludge are shown in Figures 2-1 and 2-2, respectively.

2.3.1.1.1 Single or One Sludge Nitrification System

Nitrification can be accomplished in any of the suspended-growth activated sludge process. The most commonly used processes are conventional plug flow, complete mix, extended aeration and various modifications of the oxidation ditch.

The process configuration in which heterotrophs and nitrifiers coexist in a single mixed liquor that simultaneously oxidizes ammonium and organic BOD is termed the one-sludge nitrification process. This system is also called a single stage nitrification because it consists of one reactor stage. One sludge nitrification consists of one reactor (e.g. aeration basin) and one secondary clarifier.

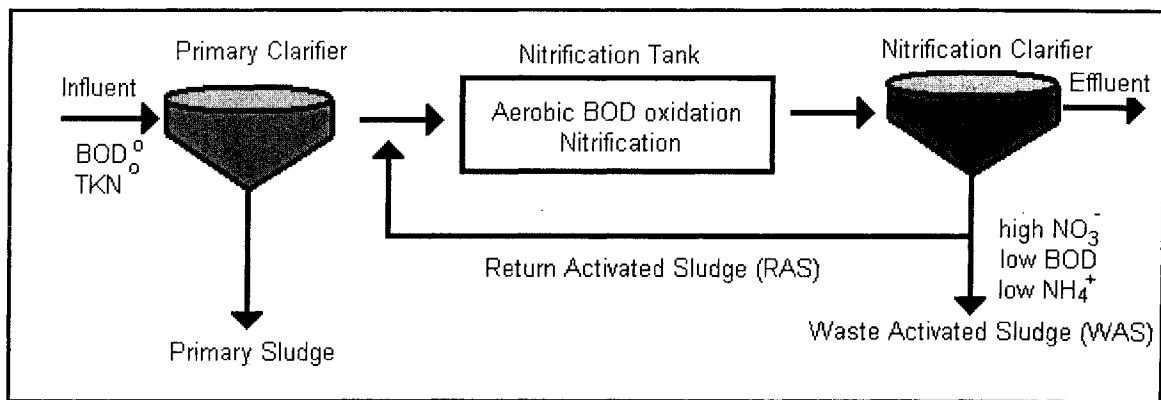


Figure 2-1 Single Sludge Nitrification System

The advantages of using a single sludge system include the following: combined treatment of carbon and ammonia in a single stage; low effluent ammonia is possible; and inventory control of mixed liquor sample due to high BOD₅/TKN ratio. On the other hand, there are some disadvantages of using this system which include, no protection against toxicants, only moderate stability of operation, stability of the operation linked to operation of secondary clarifier for biomass return, and large reactor required in cold weather.

2.3.1.1.2 Two or Separate Sludge Nitrification System

Nitrification in a two-sludge process allows greater process flexibility and reliability. Two sludge is an attempt to reduce the competition between heterotrophs and nitrifiers by operating each process (carbonaceous oxidation and nitrification) independently in separate stages. In each stage, a different microorganism community (heterotrophs and nitrifiers) exists, which differ from an ecological point of view. In this system, toxic effects may be reduced because biodegradable organic matter, which may be toxic to nitrifiers is removed in the first stage, which is essentially free of nitrifiers (Metcalf & Eddy, 1991). The selection and operation of the nitrification process is affected by the degree of organic carbon removed in the first oxidation stage.

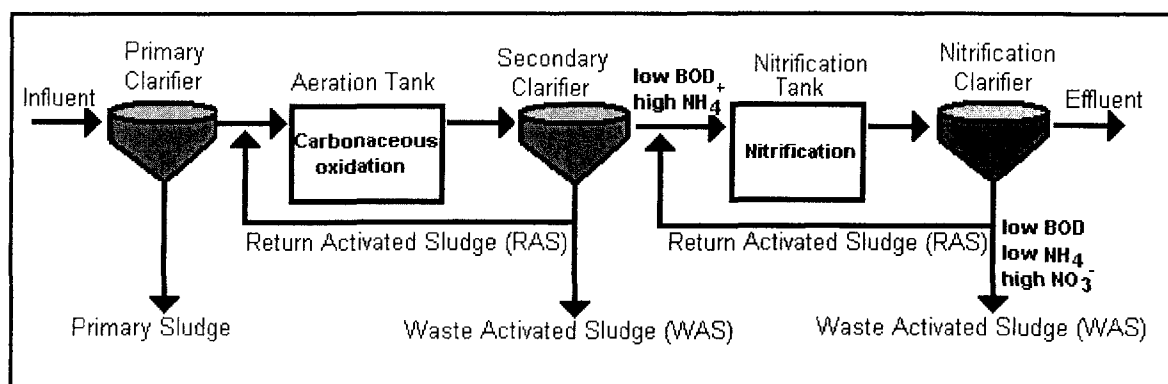


Figure 2-2 Two-Sludge Nitrification System

The advantages of using two sludge systems include good protection against most toxicants, stable operation, and lower effluent ammonia concentration. On the other hand, there are some disadvantages of using this system which include, sludge inventory requires careful control when BOD₅/TKN ratio is low, stability of the operation depends

on secondary clarifier biomass return, and greater number of unit processes required than for the single sludge nitrification process.

2.3.1.2 Factors Affecting the Nitrification Process

Several factors such as ammonia and nitrite concentration, DO, pH, temperature, SRT, BOD/TKN ratio can affect biological nitrification. Ammonia and nitrite concentration, and DO concentration will affect the maximum growth rate of nitrifiers. Huang (1973) observed that ammonia oxidation was possible in a film reactor mixed culture with ammonia concentration 2.5 to 110.0 mg-NH₄-N /L. Praksam et al. (1974) noted that oxidation was possible with ammonia concentration of 600 mg-NH₄-N /L, while Anthonisen et al. (1976) observed that at ammonia concentration of 800 mg-NH₄-N /L only 10.1% of oxidation was possible. Pokallus (1963), Painter (1970), and Prakasam et al. (1974) observed the inhibition of ammonia oxidation by nitrite concentration of 500, 4200, and 1200 mg-NO₃-N /L, respectively.

DO concentrations of less than 2 mg/l have been found to inhibit nitrification rates (Haug & McCarty, 1972; Metcalf & Eddy, 1973; Forster, 1974; Beccari et al., 1992). However, Downing and Knowles (1966) observed that DO concentrations less than 3 mg/l have been found to inhibit the rate of nitrification as well. The fractions of nitrifiers present in single sludge nitrification processes are related to BOD₅/TKN ratio (Tchobanoglous & Burton, 1991). Temperature has direct significant effect on the nitrification rate constant. Nitrification rates were found not to be influenced by temperature above 30⁰C, while inhibition was observed below 15⁰C (Borchardt, 1966; Downing 1968; Wild et al., 1971; and Sutton et al., 1974). pH values between 6 to 8.5 have been found not to influence nitrification rates, but pH values below 6 and above 8

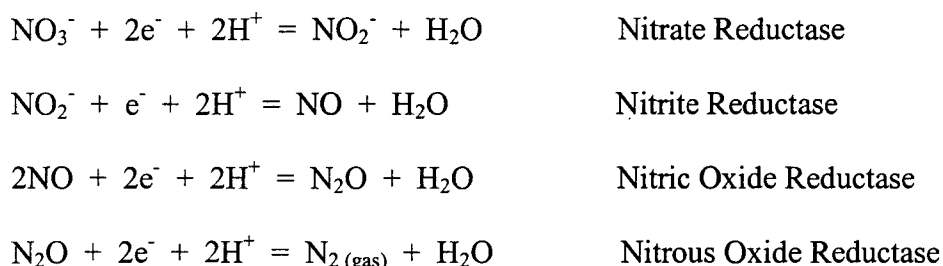
showed some inhibition on nitrification rate (Barrieth, 1933; Lees, 1954; Prakasam and Loehr, 1972; Metcalf & Eddy, 1973; Hall, 1974; and Sorensen & Jorgensen, 1992). To avoid washout of nitrifiers, SRT values must be always greater than the reciprocal of the nitrifiers' net specific growth rate (Sorensen & Jorgensen, 1993).

2.3.2 Biological Denitrification

Denitrification, the conversion of nitrate to nitrogen gas by heterotrophic bacteria is an important step in biological nutrient removal (BNR) systems. For denitrification to occur, denitrifiers use biodegradable organic carbon as an electron donor and nitrate as an electron acceptor. Therefore, the rate of denitrification in the system is dependent on the amount and nature of organic carbon in the wastewater (Ekama et al., 1997). In the mid 1800's, interest in the denitrification reaction increased because of the need to understand the loss of nitrogen from fertilized soils. Gayon and Dupetit (1982) introduced the term denitrification to explain gas production during anaerobic activity with nitrate using bacteria from sewage.

Denitrification is a biological conversion of nitrate-nitrogen to the more reduced form such as nitrogen gas (N_2), nitric oxide (NO) and nitrous oxide (N_2O) under anoxic (without oxygen) conditions. In the past, denitrification was considered a completely anaerobic process. However, the principal biochemical pathways of denitrification are not anaerobic but rather modification of aerobic pathways; therefore the term "anoxic" is considered more appropriate instead of anaerobic to describe this system (EPA, 1975). Conversion of nitrate-nitrogen proceeds in a stepwise manner, where first the conversion of nitrate to nitrite occurs, followed by nitric oxide, nitrous oxide, and nitrogen gas.

The reactions for nitrate reduction and there associated enzymes catalyzing are as follows (Rittmann, 2001):



Denitrification can be accomplished by several genera of denitrifying bacteria (denitrifiers). Denitrifiers are facultative aerobes. When oxygen becomes limiting they can shift to nitrate or nitrite as an alternate electron acceptor. Due to their wide diversity they are found in soils, surface waters, ground waters, and wastewater treatment plants. In 1981, Payne listed the following genera of bacteria responsible for denitrification: *Achromobacter*, *Acinetobacter*, *Agrobacterium*, *Alcaligenes*, *Arthrobacter*, *Bacillus*, *Chromobacterium*, *Corynebacterium*, *Flavobacterium*, *Hypomicrobium*, *Moraxella*, *Neisseria*, *Paracoccus*, *Propionibacterium*, *Pseudomonas*, *Rhizobium*, *Rhodopseudomonas*, *Spirillum*, and *Vibrio*. In addition, Gayle et al. (1989) listed two denitrifiers, *Halobacterium* and *Methanomonas*.

Robertson et al (1988), in a classic experiment, reported a unique heterotrophic organism (*Thiophaea pantotropha*) capable of simultaneous nitrification and denitrification under aerobic conditions, using acetate as carbon source. The methods used to identify the denitrifiers include chromatographic techniques, MPN technique, and

measurements of the enzymatic activity plates (Lenhard, 1969; Payne, 1973; Tood and Nuner, 1973).

The treatment units that receive the influent wastewater after primary clarification have low COD/N ratio, since a large amount of organic matter is removed in the primary clarifier, resulting in organic carbon deficiencies for complete denitrification (Aravinthan et al., 1999). Montieth et al. (1979) suggested that when the COD/N ratio is below 3:1, external carbon source or hydrogen may be added to encourage the denitrification capacity of the system.

External carbon sources that have been used include methanol (McCarty, 1969; Issacs et al., 1994; and Lemmer et al., 1997), ethanol (Bringmann et al., 1959; McCarty, 1969; and Issacs et al., 1994), glucose (Wuhrmann, 1960; Christenson et al., 1967; Balakrishnan, 1968; Balakrishnan & Eckenfelder, 1969; Mccarty, 1969; Ide et al, 1972; and Clayfied, 1974), acetone (Mccarty, 1969) and various organic acids. Another option that can be considered to promote denitrification is the use of an internal carbon source produced from sludge hydrolysate, acid fermentation of the primary sludge, cell material, and hydrogen donors. The use of an internal carbon source is advantageous over an external carbon source because the internal carbon source is cost-effective and results in the production of less sludge (Ekama et al., 1997).

Several types of external carbon sources have been used to support denitrification and some have been found to be more effective than others. Koch and Siegrist (1997) conducted a study for extended denitrification by using methanol in tertiary filtration. The results showed that 1 kg-N/m³.d of denitrification rate was achieved at a temperature range of 12-15⁰C, while nitrite accumulation was observed at temperatures varying from

20-22⁰C. In another study, Tam et al. (1992), found that high sodium acetate concentration (150 mg/l) promoted complete denitrification, while complete denitrification was observed in shorter time by the addition of the same concentration of methanol. Glucose was found to be least effective substrate for denitrification.

Hasselblad and Hallin (1998) investigated denitrification capacity by intermittent addition of ethanol as an external carbon source to a pre-denitrifying system in a pilot plant study. Intermittent addition of ethanol for five weeks did not change the level of nitrate reduction in the system. In addition, it negatively affected the system's denitrification capacity. Gerber et al. (1986) observed that citrate followed by glucose, methanol, ethanol, and 2,3 butanediol, in that order, resulted in the lowest denitrification rate, while acetate, butyrate, and lactate resulted in the highest denitrification rate. Engeler et al. (1998) observed higher denitrification rates with acetate and propionate than with methanol addition.

The use of internal carbon sources to promote denitrification has been reported by several researchers as well. Hang et al. (1999) performed a study to preserve influent organic matter in the sludge required for denitrification. In this study, they observed a large amount of organic matter absorbed onto the mixed liquor suspended solids (55 mg SCOD/g MLSS). Denitrification efficiency increased up to 63%, and 8.72 mg SCOD was consumed to reduce 1 mg nitrate.

Aravinthan et al. (1999) performed a study using the product of sludge hydrolysis as a source of organic carbon for denitrification. Alkaline autoclaved, acid autoclaved, and solubilization methods were used to hydrolyze the sludge. Nearly the same

denitrification rates (185-200 mg N/g MLSSCOD/d) were observed for both alkaline and acid autoclaved sludge hydrolysate.

Acidification of primary sludge, the second phase in the anaerobic digestion process, was used to obtain an organic carbon source for denitrification in a full-scale wastewater treatment plant (Teichgraber, 2000). The results suggest that acidification of primary sludge can be used as a carbon source for denitrification, but it leads to technical (clogging, odor, etc.) and safety (risk of explosion, poisoning, and/or asphyxiation) problems in covered tanks.

Engeler et al. (1998) used the product of primary sludge fermentation as an organic carbon source for denitrification. Denitrification rates were (6 g NO₃-N/COD.hr), higher than the rate observed when using acetate and propionate (3.8 and 1.7 g NO₃-N/COD.hr, respectively). Kuroda et al. (1997) performed a study on simultaneous COD removal and denitrification using hydrogen as the electron donor in batch experiments. High denitrification rates and COD removal were observed.

Barnard (1974), Tchobanoglous and Burton (1991), and Sakakibara et al. (1994) used hydrogen as an electron donor to eliminate nitrogen from the wastewater. The results indicate that nearly complete denitrification occurred.

2.3.2.1 Denitrification in Secondary Clarifiers

The major objective of clarification is to separate solids from liquid. However, processes that would normally take place in bioreactors, such as denitrification, may occur in clarifiers. When denitrification occurs during clarification it may have negative or positive effects on the plant's efficiency in removing nutrients. Denitrification in the clarifier can contribute substantially to nitrogen removal in activated sludge systems

(Siegrist & Gujer., 1994). It can also result in the production of alkalinity, which can partially offset the alkalinity consumed during nitrification and it recovers oxygen utilized in nitrification, thus reducing the energy required during nitrification (Ekama et al., 1997; Henze et al., 1993).

Strong denitrification in the clarifier may be detrimental to the plant's efficiency to remove phosphorus. Nitrogen bubbles formed during strong denitrification will promote rising of the sludge to the surface of the clarifier and breaking up of the flocs into smaller parts, some of which will partially settle again while others will escape with the clarifier effluent (Henze et al., 1993). This results in increased suspended solids concentration in the clarifier effluent, affecting the overall removal efficiency of the plant with respect to BOD, COD, total suspended solids (TSS), total nitrogen and total phosphorus (Siegrist and Guger, 1994; Ekama et al., 1997; and Parker et al., 2000). This problem is typically observed in activated sludge plants with nitrification (Cole et al., 1974) and in some cases in plants with partial denitrification (Christensen et al., 1978). On the other hand, strong denitrification is beneficial in increasing the alkalinity of the wastewater (e.g. increase in pH), lowered during nitrification.

Weak or absent denitrification can be detrimental to a plant's efficiency to remove phosphorus biologically (Bio-P) because high concentrations of nitrate in the RAS negatively affect P-release in the anaerobic zone of the Bio-P process. Furthermore, weak denitrification will not generate sufficient alkalinity needed to increase the pH of the wastewater lowered by nitrification.

In contrast, moderate denitrification within the clarifier may be beneficial to the performance of BNR systems, because it does not significantly inhibit P-release by

microorganisms in the anaerobic stage. In addition, moderate denitrification in the clarifier partially recovers alkalinity and oxygen utilized in nitrification (Ekama et al., 1997; Ying-Feng et al., 2001).

2.3.2.2 Effects of Nitrates on Biological P-removal

Wastewater treatment plants (WWTP) for combined biological nutrient removal (phosphorus and nitrogen) generally include anaerobic/anoxic/aerobic unit processes. The anaerobic zone is provided for phosphorus release, while denitrification occurs in the anoxic zone, and nitrification as well as phosphorus uptake take place in the aerobic zone. In general, oxygen is the electron acceptor for phosphorus uptake and nitrate is an electron acceptor for the denitrification process. Generally, it is widely accepted that the presence of nitrates in the anaerobic zone inhibits phosphorus release, affecting the overall plant's efficiency to remove phosphorus (Csiti, 1991). The release of phosphorus in the BNR system mainly depends on the amount and the nature of organic matter present in the wastewater, to allow facultative anaerobic bacteria to produce readily biodegradable volatile fatty acids for use by the phosphorus-accumulating microorganism (PAOs) (Ghekiere et al., 1991).

PAOs are heterotrophic microorganisms responsible for excess P-accumulation (Bernardes & Klapwijk, 1996). The facultative anaerobic bacteria are responsible for the conversion of available BOD into volatile fatty acids (VFAs) by fermentation. The presence of nitrates in the anaerobic zone will not allow the fermentation acids to accumulate, preventing the formation of appropriate anaerobic conditions needed for phosphorus release and subsequent phosphorus uptake in the aerobic zone (Ghekiere et al., 1991). In addition, denitrifying bacteria compete with phosphorus accumulating

organisms (PAOs) for simple carbon substrate and consume all readily biodegradable short chain organic acids, leaving nothing for PAOs (Ghekiere et al., 1991). Unfortunately, nitrates are introduced into the anaerobic zone from recycling sludge, due to incomplete denitrification (Ekama et al., 1997). Barnard (1982) suggested that nitrate levels below 5 mg-N/l should be maintained in the RAS for successful and consistent removal of phosphorus.

Several researchers (Kuba et al., 1993 Kuba et al., 1996a; Kuba et al., 1996b; Kuba et al., 1997) have reported that from a microbiological point of view, nitrate entering in the anaerobic zone will be utilized by denitrifying phosphorus bacteria (DPB) as an electron acceptor instead of oxygen. DPB have similar potential to remove phosphorus as conventional PAOs (Kuba et al., 1993). However, the exact metabolism process of phosphorus release by DPB as well as PAOs in simultaneous presence of COD and nitrate is not yet clearly understood (Kuba et al., 1997). Kuba et al. (1996) observed that use of DPB is advantageous because (a) less energy is required for aeration, (b) less COD is utilized, and (c) less sludge is produced in the overall phosphorus (P) and nitrogen (N) removal process.

Paepcke (1983) performed a study to determine the performance and operational aspects of BPR plants in South Africa. The results obtained from his study show that excessive nitrate and dissolved oxygen concentrations entering the anaerobic zone are the major factors adversely affecting P-removal. Hascoet and Florentz (1985) observed that in the anaerobic zone, both substrate (COD) concentration and nitrate concentrations influenced P-release. They also observed that continuous addition of nitrates to the anaerobic zone modified the entire microbial population because P-release was not

immediately observed after stopping nitrate addition to the feed. In a study by Iwema and Meunier (1985), to confirm experimentally a competition between DPB and PAOs for a simple organic substrate, they observed that P-release efficiency decreased with increasing nitrate concentrations. Furthermore, after the addition of acetic acid to the activated sludge, it was observed that P-release increased with increasing acetic acid concentration, even in the presence of nitrate.

Vlekke et al. (1988) studied EBPR with oxygen and nitrate as electron acceptors in a sequencing biological reactor (SBR). After comparison between P-uptake rates using oxygen or nitrate as electron acceptors, they suggested that nitrate is less efficient than oxygen for P-uptake. Ghekiere et al. (1991) conducted an investigation on the effects of nitrates and carbon compounds on EBPR, using activated sludge from a pilot plant. The results show that nitrates inhibited P-release, due to the competition between fermentation and denitrification for available substrates in the wastewater. On the other hand, they also observed that nitrate did not inhibit P-release in the presence of acetate.

In another study performed to evaluate the effects of nitrate on the P-release in EBPR system, Kuba et al. (1994) noted that in the presence of DPB, P-release was strongly inhibited by nitrate addition, while nitrate did not show any effect on P-release in the absence of DPB. Meinhold et al. (1999) conducted a study to investigate the influence of nitrite on EBPR. The results indicated that nitrite in high concentrations (above 8 mg $\text{NO}_2\text{-N/l}$) totally inhibits anoxic phosphorus uptake.

Kuba et al. (1993) performed a study on EBPR in anaerobic/aerobic and anaerobic/anoxic sequencing batch reactors (SBR) process. They observed that the amount of phosphorus taken up per mole of electrons transferred was 20-30% lower with

nitrate ($0.19 \text{ mol-P/mol-e}^-$) as an electron acceptor than with oxygen ($0.23 \text{ mol-P/mol-e}^-$) as an electron acceptor. Jerpersen and Henze (1993) found that one group of PAOs is capable of utilizing both oxygen and nitrate as an electron acceptor. Kuba et al. (1996a) conducted a study to investigate the feasibility of simultaneous phosphorus and nitrogen removal by integration of denitrifying dephosphatation in a two sludge system. They observed that DPB removes phosphorus under these conditions with: minimal COD (50% less than PAOs), minimal oxygen consumption (30% less than PAOs), and minimal surplus sludge production (50% less than PAOs).

Kuba et al. (1996b) studied a metabolic model for BPR under denitrifying conditions. The simulation results show that the metabolic model for EBPR can be used successfully by DPB during the denitrifying dephosphatation process. They observed that nearly 40% lower energy production efficiency was achieved with nitrate compared to oxygen. Kuba et al. (1997) investigated the occurrence and the contribution of DPB to phosphorus removal in full-scale wastewater treatment plants (WWTP). The results obtained from this study show that denitrifying dephosphatation was occurring in a full-scale WWTP, and approximately 50% of the phosphorus removal occurred via denitrifying activities.

Another group of microorganism present in the EBPR system is the glycogen-accumulating organisms (GAOs), which can take up organic substrate in the anaerobic phase without P-release (Mino et al., 1998). Glycogen is accumulated as carbon storage by microorganism, which may be utilized during carbon. Cech and Hartmen (1990) observed this group of microorganism in a glycogen-fed reactor and named this group G-

bacteria. They observed the breakdown of the EBPR system due to outgrowth of “G-bacteria” when acetate and glycogen was added as carbon source.

Later on, Cech and Hartman (1990), and Satoh et al. (1994) explained the breakdown of the EBPR system by the fact that when the influent wastewater contains glucose, GAOs dominate the anaerobic/aerobic process. During this process, they do not accumulate PP under aerobic conditions and are capable of taking up glucose without releasing phosphate under anaerobic conditions. The presence of GAOs has been observed in both lab-scale (Mino et al., 1998) and full-scale systems (Cech & Hartman, 1990; and 1998; Filipe, 1999).

In the literature, several reasons for GAOs proliferation has been mentioned including the presence of glucose in wastewater (Cech & Hartman, 1990), improper seeding and long SRT and HRT (Fukase et al., 1985). Grady and Filipe (2000) suggested that proliferation of GAOs at the expense of PAOs can lead to decrease in the capability for P-removal. Mino et al. (1998) observed that PAOs and GAOs have similar metabolic pathways but these pathways are regulated by different mechanisms. It was also observed that the major difference between PAOs and GAOs is the energy source. PAOs generate energy efficiently by degrading poly-P, whereas GAOs ferment glycogen to PHA and CO₂ to generate an energy source. A metabolic model was proposed by Mino et al. (1998) for supporting the breakdown of the EBPR system by GAOs. In 1999, Filipe developed metabolic models for the anaerobic metabolism of both PAOs and GAOs.

2.3.2.3 Classification of Denitrification System

Classification is usually based on whether denitrification is achieved (i) in combined carbon oxidation, nitrification/denitrification systems using an internal or endogenous carbon source of organic carbon or (ii) in separate reactors using external source of organic carbon (Metcalf & Eddy, 1991). Combined systems are termed “one or single sludge system” and separate system are often termed “separate or two sludge systems”.

2.3.2.3.1 One or Single Sludge Denitrification System

One-sludge denitrification involves using the influent BOD from wastewater to drive denitrification. In this system mixed liquor contains a mixture of heterotrophic and autotrophic microorganisms. The heterotrophs grow and oxidize carbonaceous organic matter in both the aerobic and anaerobic zones. They utilize molecular oxygen as the electron acceptor in the aerobic zone and nitrate in the anaerobic zone. On the other hand, the autotrophs grow only in the aerobic zone using molecular oxygen and inorganic carbon while oxidizing ammonia. The influent ammonia passes through the anoxic zone to the aerobic zone where it is converted to nitrate. A schematic diagram of the one-sludge system is shown in Figure 2-3.

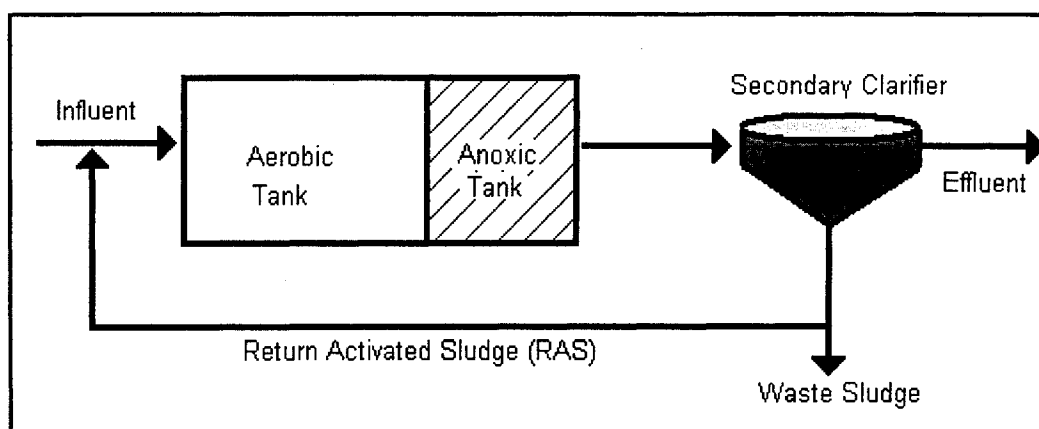


Figure 2-3 One Sludge Denitrification System

Denitrification rates achieved in this process are generally lower compared to that of the two-sludge system (Sedlak, 1991). Generally, these processes are capable of removing 60 to 80% influent total nitrogen (Tchobanoglous & Burton, 1991), yet removals ranging from 85 to 95% also have been observed (Soap & Detergent Association, 1988).

2.3.2.3.2 Two or Separate Sludge Denitrification System

Figure 2-4 shows the typical layout of the two-sludge denitrification system. The process is called two or separate-sludge systems because two separate biological processes are involved to remove nitrate-nitrogen from the effluent of upstream biological nitrification process. Either a separate stage nitrification or combined carbon oxidation and nitrification systems may be used upstream of the two sludge denitrification system. When separate nitrification is used the process is referred as “three stage sludge system” because three biological processes are operating in series.

The first stage removes BOD, the effluent from the first stage is nitrified in the second stage, and the third stage removes the nitrate-nitrogen from the effluent of the

second stage denitrification. When a combined carbon oxidation and nitrification system is used with separate sludge denitrification the process is referred as “two sludge system” because two biological processes are operating in series. In the first stage, carbon oxidation and nitrification occurs, while the second stage removes nitrate-nitrogen from the effluent of the first stage denitrification system. Therefore, in these systems denitrification is accomplished in a separate unit process following BOD removal and nitrification.

The addition of an external carbon source is necessary for denitrification to occur because carbonaceous BOD removal and nitrification remove large amounts of the readily available carbonaceous matter from the wastewater (Sedlak, 1991). However, addition of an external carbon source must be carefully controlled to avoid adversely affecting the plant effluent BOD through overdosing. Typically, two different process options are used for two-sludge denitrification: 1) suspended growth and 2) attached growth (rotating biological contactor (RBC), and fluidized bed reactor) (Sedlak, 1991; Metcalf & Eddy, 1991; and Sorensen & Jorgensen, 1993).

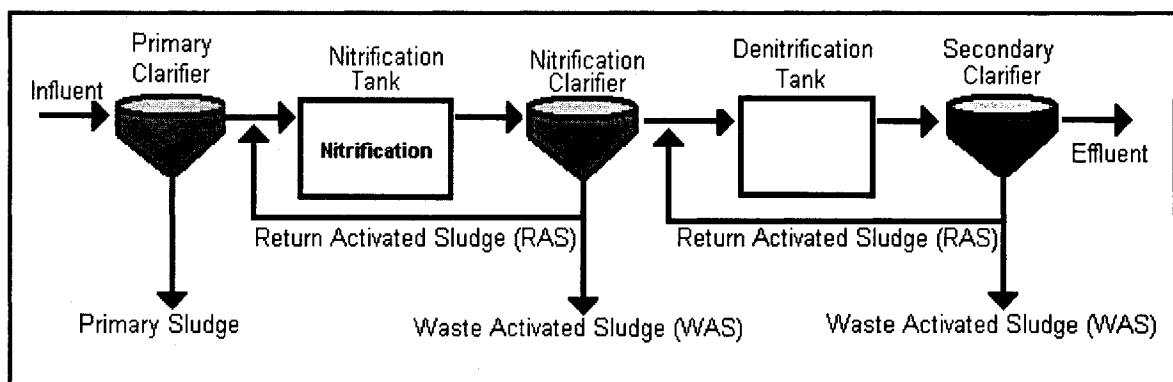


Figure 2-4 Two Sludge Denitrification System

2.3.2.4 Factors Affecting the Denitrification Process

Environmental factors such as temperature, DO, carbon concentration, nitrate concentration and pH, have a significant effect on the kinetic rates of denitrifiers' growth and nitrate removal.

Temperatures below 5°C and above 35°C have been found to significantly affect the removal of nitrate and microbial growth (Ide et al., 1972). Temperature within the range of 5 to 30°C did not inhibit the rate of denitrification (Mechala et al., 1970; Henze et al., 1977; Harremoes & Rimer, 1977; Stensel, 1971; Dawson & Murphy, 1972; Bernard, 1975; Parker et al., 1975; and Henze & Harremoes, 1977).

DO is a critical parameter in denitrifying systems because its presence will suppress the enzyme system needed for denitrification (Randall et al., 1993). Nelson and Knowles (1978) found that DO above 0.13 mg/l inhibited the denitrification rates. Sherman and MacRae (1957), Wheatland et al. (1959), Dawson and Murphy (1972), Terai and Mori (1975), Focht and Chang (1975), and Pochanu and Keller (1999) observed that DO above 0.2 mg/l inhibited the rate of denitrification. Drews and Greef (1973) noted that DO above 0.3 mg/l has an influence on the rate of denitrification. DO above 0.5 mg/l (Ludzack and Ettinger, 1962; Pasveer, 1965; and Schuster, 1970) and DO above 1.5 mg/l (Rittmann and Langeland, 1985) have been found to affect the denitrification rate.

Nitrate and carbon concentration will affect the maximum growth rate of the organisms responsible for denitrification. pH values above 8 and below 6 depress denitrification rate (Wiljer & Delwiche, 1954; Nommik, 1956; Bremner & Shaw, 1958;

Hermann 1962; McCarty, 1969; Hamm, 1970; Stensel, 1971; Dawson & Murphy, 1972; and- Sorensen & Hjulser, 1992). Ide et al. (1972) observed denitrification within a pH range of 6.0 to 10.0. Denitrification was observed within the pH range of 5.0 to 8.5 (Clayfield, 1974; and Kiff, 1972).

2.4 Secondary Clarifiers

Treated wastewater is ultimately returned to receiving water bodies or to land. Low effluent quality can cause serious problem such as eutrophication, and toxicity to aquatic life. Therefore, effluent requirements have been made more stringent. When wastewater treatment plants have to achieve stringent effluent standards, the secondary clarifier often becomes the focus of attention for improvements (Ekama et al., 1997).

Secondary clarifier or secondary settling tank is one of the most important and commonly used unit operations in wastewater treatment. The secondary clarifier contributes to one-fourth of the total capital investment for treatment plant (Prabhata & Tyagi, 1995). The performance of wastewater treatment plants based on the activated sludge process essentially depends on the behavior of the secondary clarifier (Lage, 1994; Uffe, 1994).

The main functions that the secondary clarifier provides include, clarification, solid thickening, and solids storage. If it fails to perform any one of the above functions, suspended solids (SS) will be carried over the effluent weir and escape with the effluent (Narayanan & Ooten, 2000). In the case of an activated sludge system where only biological oxygen demand (BOD) and SS are removed, the largest fraction of the BOD in the clarifier is associated with biological solids. Therefore, failure in clarifier performance implies increased SS concentration and BOD of the effluent, thus impacting

effluent quality (Harandy & Schroeder, 1995). In plants where the removal of phosphorus is desired, excellent performance of the secondary clarifier is essential to minimize the escape of phosphorus within the effluent SS (Sperling & Froes, 1999). Furthermore, in plants where nitrogen removal is introduced the settling capacity of the sludge often deteriorates (Jenkins et al., 1993). Therefore, it is clear that in the design of activated sludge process, special attention should be given to the performance of secondary clarifiers.

2.4.1 Secondary Clarifier Components

Figure 2-5 illustrates the typical components of a center-feed circular clarifier. It consists of wet well, skimmer, scraper, return sludge pipe, waste sludge pipe, scum trough, influent pipe, and bridge.

- **Wet Well:** It is nearly 25 to 50% of total diameter of the clarifier (Ekama et al., 1997). It is used to direct the flow towards the tank bottom, to reduce turbulence, and to allow good flocculation.
- **Skimmer:** The skimmer travels around the clarifier and pushes the scum, grease and other floating materials into a scum trough.
- **Scum Trough:** It receives all floating materials from skimmer and discharges into scum discharge pipe for removal.
- **Scraper:** Scrapers are located along trussed arms that slowly rotate and physically push the thickened sludge blanket towards a central sludge storage tank, from where the underflow is pumped for wasting and recycle. Under-designed or

faulty scrapers will result in an excessively thick sludge blanket because sludge moving capacity is inadequate.

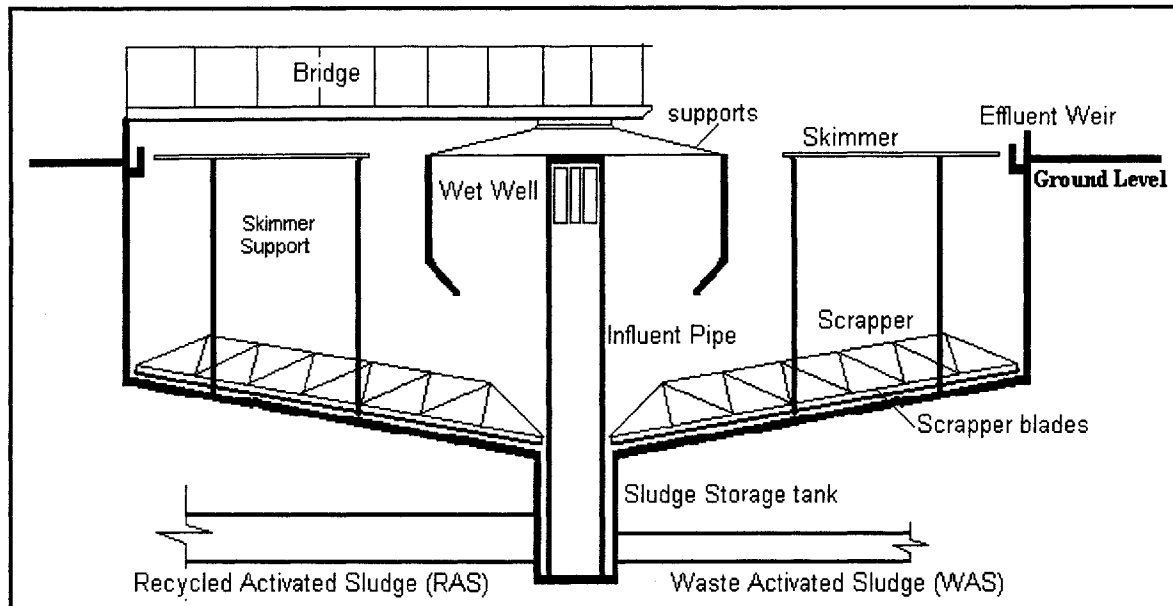


Figure 2-5 Schematic Diagram Center-Feed Circular Clarifier Components (Modified from Metcalf & Eddy, 1991)

Although, there are several clarifier configurations, each clarifier configuration must include the following four essential components (Ekama et al., 1997, Rittmann, 2001):

- 1) an inlet zone , for energy dissipation and for good flocculation
- 2) a quiescent settling zone, for solids separation and thickening
- 3) an outlet zone, for prevention from escape of solids through effluent
- 4) a sludge collection and removal system, for thickened sludge at the bottom of the clarifier.

2.4.2 Clarifier Design Factors

The following factors have been cited (Metcalf & Eddy, 1991; Ekama et al., 1997; and Randall et al., 1998) as being important in the design of secondary clarifiers and increasing their performance: 1) clarifier configuration, 2) settling sludge characteristics for proper plant operation, 3) surface and solids loading, 4) side water depth (SWD), 5) flow control, and 6) structural factors (inlet and outlet design, intermediate or perforated baffles).

2.4.2.1 Clarifier Configuration

The most commonly used clarifier configurations are circular and rectangular. Square clarifiers are also used, but are not as effective in retaining separated solids as are circular and rectangular clarifiers (Metcalf & Eddy, 1991). Ekama et al. (1997) suggests that the radius of the circular clarifier should not exceed 5 times the SWD of the clarifier. Further they recommend that circular clarifiers be commonly constructed with diameter ranging from approximately 10m to 40 m.

Generally, it is recommended that the length of rectangular clarifiers do not exceed 10 to 15 times their depth (Metcalf & Eddy, 1991). It is generally considered that since design producer are equally applicable to circular and rectangle clarifiers, land area required for a rectangle clarifier is smaller than for a circular clarifier, because of their higher clarifier surface area to land area ratio (Ekama et al., 1997). Wilson (1984, 1991) suggested that rectangular clarifiers will be the best choice for large plants on tight sites. However, some consultants recommend circular clarifiers are mostly preferable and asserted to be superior for any size and type plant (Parker, 1991a & b).

2.4.2.2 Sludge Settling Characteristics

Secondary clarifiers should be designed properly with respect to two functions: (1) separation of the mixed liquor suspended solids (MLSS) and (2) thickening of the return sludge. Both of these functions will be affected by clarifier depth; therefore special consideration should be given in selecting the clarifier depth so that sufficient volume is available to perform both functions (Metcalf & Eddy, 1991). The area required for clarification is based on the overflow rate (OFR) of the clarifier, whereas the area required for the thickening of the MLSS is based on the limiting solid flux transported to the bottom of the clarifier (Yoshioka et al., 1957; Dick & Ewing, 1967; Keinath et al., 1977). The larger of two areas required for clarification and thickening will be selected for clarifier construction.

The settling, thickening and flocculation characteristic of the activated sludge are affected by conditions in the biological reactor. For instance, if the sludge is under-aerated, settleability and thickenability of the sludge is decreased, which ultimately leads to the bulking of the sludge in the clarifier (Ekama et al. 1997). Sludge settleability and reactor concentration govern the thickening function of the sludge within the clarifier. If clarifiers serve all the above functions except settleability, then it fails thickening the sludge (Ekama et al. 1997).

2.4.2.3 Surface and Solid Loading Criteria

In clarifier design loading criterion is considered to be an important design parameter. The Water Pollution Control Federation (WPCF, 1985) published values for OFR and solids loading, based on wastewater flowrates. These values can be used to design the clarifier without performing settling tests. If the design criteria are exceeded, a

large amount of solids may be lost in the effluent, therefore OFR for clarifier design should be based on peak flow conditions (Metcalf & Eddy, 1991; Wilson 1996). In clarifiers, the solids loading rate can be determined by dividing the mass rate of applied total solids by the clarifier surface area. Effluent quality will deteriorate if the solids-loading is increased beyond characteristic design values for the suspension (WPCF, 1985).

2.4.2.4 Side Water Depth (SWD)

Liquid depth plays an important role on the effectiveness of SS removal and in the concentration of the return sludge. Liquid depth in a circular clarifier is measured at the sidewalls, whereas for rectangular clarifier it is measured at the effluent end walls. A recent trend is to design deeper clarifiers, particularly in the plants that have low-density activated sludge (Metcalf & Eddy, 1991).

In 1992, Merrill et al. found that deeper circular clarifier produced low effluent suspended solids. The advantages of designing deeper clarifiers include reductions in negative interferences between the clear water zone near the weirs and the sludge blanket (Rittmann, 2001), and providing greater flexibility of operation and larger margin of safety when changes in the activated sludge process occur (Metcalf & Eddy, 1991). SWDs ranging from 5 to 6 m are more commonly used for clarifier design (WPCF, 1985; Rittmann, 2001).

2.4.2.5 Flow Control

Any variation in the flow between multiple process units can lead to clarifier underloading or overloading of the individual units affecting the overall performance of the plant (Metcalf & Eddy, 1991). WPCF (1985) and Ekama et al. (1997) suggest that

flow can be maintained and distributed in the clarifier by geometric symmetry in piping, feed gate or inlet port control, hydraulic distribution using hydraulic symmetry, and flow measurements and flow control valves.

2.4.2.6 Structural Factors

The behavior and the performance of a secondary clarifier is affected by structural factors, such as inlet and outlet location, intermediate baffles, etc (Harandy & Schroeder, 1995; and Lewyata, 1996), density currents (Vitasovic et al., 1997), and sludge characteristics such as settling, thickening, flocculation and foaming (Ekama et al., 1997; Deininger et al., 1998). The effect of the inlet and outlet locations on clarifier performance is strongly related to the flow pattern through the clarifier. Inlet-outlet location and simultaneous draw-off at multiple locations can increase the vertical component of the fluid velocity near inlet-outlet points, influencing the density currents (Harandy & Schroeder, 1995). Depending on the predominant flow pattern (bottom or surface density currents), the sludge inlet-outlet locations can be used to improve the flow patterns through clarifiers (Stamou, 1997).

Another parameter which has influence on the behavior and performance of a clarifier is density currents. The occurrence and causes of density currents in clarifiers were first identified by Camp (1946). Later on, Larsen (1977), Stukenberg et al. (1983), Crosby (1984), Bender et al. (1987), Semon (1987), and Moursi et al. (1995) observed the occurrence of density currents in the clarifier. Anderson (1996) documented the formation and prevention of density currents in secondary clarifiers. Moursi and McCorquodale (1995) stated that density currents may be the result of concentration effects, temperature variation, and release of gas bubbles. Camp (1946) and Bender et al.

(1987) stated that the formation of uniformly distributed flow pattern in full-scale activated sludge secondary clarifiers may be impossible. The possible reason for this is that activated sludge has the inherent tendency to form density currents within the secondary clarifier. The density currents within the clarifier affect hydraulic efficiency of a secondary clarifier, but still there is no general agreement on how the removal efficiency of a clarifier is affected by density currents (McCorquodale, 1976, & 1987).

Several approaches for controlling the impact of density currents on the clarifier performance have been put forward, which include a) shifting the effluent weir away from the upturn of the density currents or away from the mounding of solids caused by turbulence of density currents (Anderson, 1945), b) properly designed inlet-outlet structures (Anderson, 1945; Bender et al., 1987), c) using intermediate baffles or porous walls to break up the density currents within the clarifier (Crosby, 1984; Kreb et al., 1995), and d) diverting currents away from the effluent weir (Anderson, 1945; Stukenberg et al., 1983).

2.4.3 Clarifier Design Approaches

Although, secondary clarifiers are important units in the activated sludge processes, they are designed based on operational experience or empirically using traditional design parameters such as overflow rate (OFR), solids loading, and solids retention time (Krebs et al., 1995; Prabhata & Tyagi, 1996; Stamou, 1997). The concept of OFR was first introduced by Hazen (1904) for designing secondary clarifiers. Coe and Clevenger (1916) originally conceived the solid flux theory, which was later developed

by Kynch (1952), Yoshioka et al. (1957), Dick and Ewing (1967), Keinath et al. (1977), and Keinath (1990) for designing secondary clarifiers.

Designers used high factors of safety for the above aforementioned design parameters to compensate for uncertainties in the hydrodynamics of clarifiers (Well & Laliberte, 1998) and to ensure that the resulting constructions achieve the required SS removal efficiency (Stamou, 1997). Both concepts, OFR and solids flux assume uniform (ideal) flow pattern, while the interaction between sedimenting particles and the flow is not accounted in the design. In 1982, Dick showed that several secondary clarifiers do not follow uniform (ideal) flow behavior because SS removal in a clarifier is often not a function of OFR. This was also observed by Tray and Heinke (1983), DeVantier and Larock (1987), and Wells (1990). Narayanan and Ooten (2000) stated that solid flux and OFR approaches are well suited for studying the effect of real limitations, but not for hydraulic limitations.

However, the clarifier design can be made more realistic to real world clarifiers using mathematical models (MM). These models can be used to predict SS concentrations and removal efficiency of the solids in the clarifier. MM represent the physical, chemical, and biological processes of real engineered systems. The simplest MM is referred as “black box” (Ekama et al., 1997; and Vitasovic et al., 1997).

There exist a complex MM for secondary clarifiers referred as “glass box” (Ekama et al., 1997; and Vitasovic et al., 1997) that represents all the important processes in the clarifier and reveals the role of natural laws in determining the clarifier performance. The complex MM uses differential equations of continuity, momentum, energy, mass transport, and biological reactions subjected to realistic conditions.

Kao (1977), DeVantier and Larock (1987), Takacs et al. (1991), Krebs (1991), Zhou et al. (1992), Zhou and McCorquodale (1992a, b, c), Zhou et al. (1994), Finnson (1994), Dupont & Dahl 1995, Xu (1996), and Hasselblad & Xu (1998) used several numerical and analytical models that include prediction of density currents in a clarifier. These models simulate the formation of density currents qualitatively and quantitatively still the success of these models is limited. Bryant (1972), Tracy and Keinath, (1973), Lessard and Beck (1993) proposed a model to predict the sludge height in clarifiers based on application of limiting solid flux theory.

2.4.4 Solid Flux Theory

Solid flux theory is a commonly used concept for designing secondary clarifiers or thickeners in activated sludge processes (Kynch, 1952; Yoshioka, 1957; Keinath, 1985; and Ekama et al., 1997). The design parameters used in this concept are sludge return rate and solids mass loading, both of which are more or less empirical and result in plant capacity designs varying over a wide range. Figure 2-6 shows a schematic layout of a typical secondary clarifier with its associated fluxes. The various variables shown in Figure 2-6 are defined in Table 2.1.

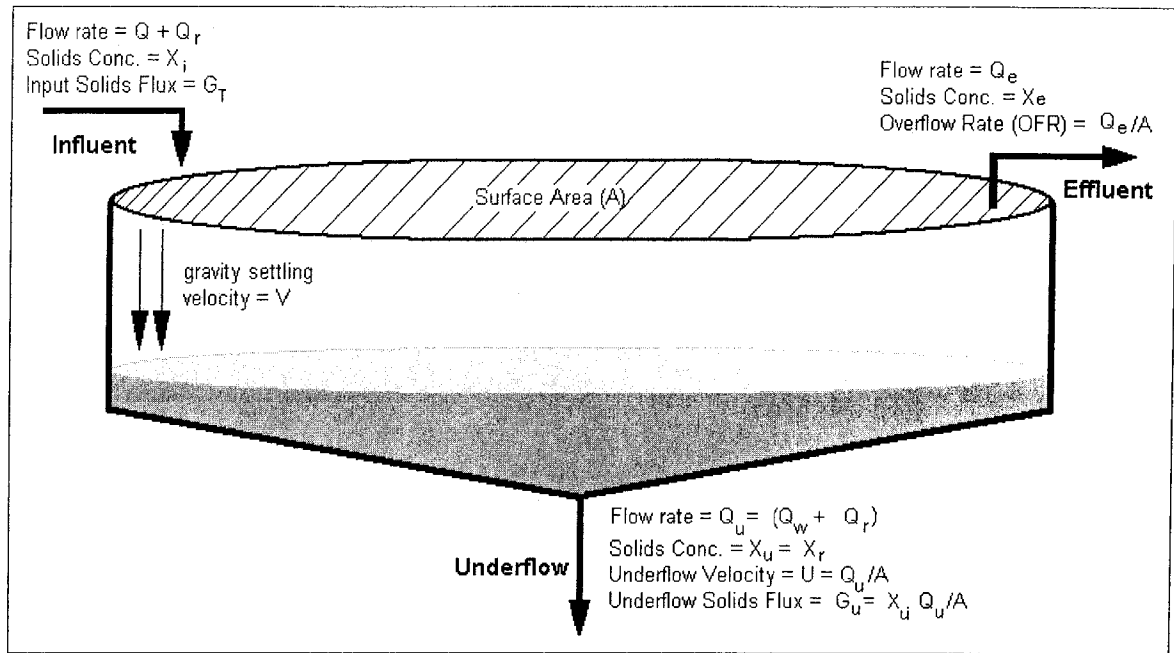


Figure 2-6 Secondary Clarifier with its Associated Fluxes

Solid flux is defined as the mass of solids per unit time passing through a unit area perpendicular to the direction of flow (Rittmann, 2001). In secondary clarifier, flux (G) is the product of the solids concentration (X) (mass/volume) times velocity (V) (length/time) as shown in equation 2.1.

$$G = X * V \quad (2.1)$$

Table 2-1 Defined and Derived Variables for Figure 6

Q	= Inflow, (MGD)
Q_e	= Effluent flow, (MGD)
Q_u	= Underflow rate, (MGD) = $(Q^r + Q^w)$
Q_r	= Return flow, (MGD)
Q_w	= Sludge wasted, (MGD)
X_i	= Influent solids concentration, (mg/L)
X_e	= Effluent solids concentrations, (mg/L)
X_u	= Underflow solids concentration. (mg/L)
V	= Solids settling velocity, (m/s)
U	= Underflow Velocity = $U = Q_u/A$ (m/s)
A	= surface area of the clarifier, (m ²)
G_T	= Total input flux, (kg/m ² .d)
G_u	= Underflow solid flux, (kg/m ² .d)
OFR	= Overflow rate, Q_e/A , (m/s)

Other Parameters	
G_a	= Applied flux due to inflow, (kg/m ² .d)
G_s	= Settling solid flux, (kg/m ² .d)
G_b	= Bulk solid flux, (kg/m ² .d)

In secondary clarifiers, the total solid flux (G_T) is the sum of the solid flux due to gravity setting (G_s) and the solid flux due to bulk downward (G_b) movement of liquid caused by the withdrawal of underflow sludge.

The gravity settling flux can be represented by equation 1.2.

$$G_s = X_i V \quad (2.2)$$

The flux due to gravity settling depends on the solids concentration (X_i) and on the settling velocity at that concentration (V). The settling velocity of the solids is more or less independent of concentration, so at low solids concentrations (<1000 mg/l), the movement of the solids due to gravity is small (Metcalf & Eddy, 1991). Therefore, if the velocity remains the same and solids concentration increases, the total flux due to gravity settling starts increasing with the solids concentration. The total flux due to gravity becomes very low at high solids concentration because settling velocity approaches zero (Metcalf & Eddy, 2002).

The bulk flux is the product of the solids concentrations in the thickening zone and the downward velocity caused by the withdrawal of the underflow sludge (equation 2.3)

$$G_b = X_i U \quad (2.3)$$

Therefore the total solid flux is calculated as:

$$G_T = G_s + G_b = X_i V + X_i U \quad (2.4)$$

2.4.4.1 History and Development of Solid Flux Theory

Coe and Clevenger (1916) introduced the concept of flux to the operations of thickener in the mining industry, which states that in a layer of settling sludge, horizontal zones having different suspended solids concentrations would have varying capacities to transport solids to the bottom of the clarifier. They noted that if a layer in a suspension

has a lower solids-handling capacity than the overlying layer it will not be able to discharge solids as fast as they are received and will consequently increase in thickness. Accordingly, if a layer is able to transmit solids at a higher rate than they are received from the overlying area, its thickness will remain very thin. Thus, a zone having the limiting solids-handling capacity will govern the overall solids-handling capacity of the thickeners. When the thickener is overloaded the zone with lowest solids-handling capacity will ultimately reach the liquid surface. This finding constitutes the basis for determining the area required for the thickening function of a secondary clarifier. They suggested that sufficient clarifier area should be provided for thickening to assure that solids are applied at a rate less than the solids-handling capacity of the limiting layer. To identify this limiting layer they performed a series of batch settling test at various sludge concentrations.

Kynch (1952) developed the theoretical basis for settling, which Coe and Clevenger failed to identify or to develop. The concept was based on the assumption that “at any point in dispersion, the velocity of fall of a particle depends on the local concentration of particles”. For a batch settling test, Kynch (1952) developed a continuity equation for solids entering and leaving an infinitely thin element at the surface layer of the given solids concentration. He showed that continually decreasing slope of the suspension liquid interface-versus-time curve in batch settling tests represent the successive intersection of slower subsiding, more concentrated layers, with the interface. Kynch’s analysis was completely theoretical and he did not discuss the applicability of his work to real systems. Albertson (1963) and Scott (1966) found that the Kynch analysis cannot be applied to the compression zone of a thickener. However,

Kynch's analysis is considered as the fundamental basis for present procedures for determining the area required for thickening in clarifiers. Dick and Ewing (1967) suggested that Kynch's thickening analysis would be used as an ideal model to which the behavior of actual suspension might be compared.

Talmadge and Fitch (1955) further expanded the Kynch's (1952) method to develop design procedure for thickener. However, this procedure was based on the results of only one batch settling test. In 1967, Vesilind found that design procedure developed by Talmadge and Fitch (1955) had very limited application in the design of full-scale thickeners. Later on, Yoshioka et al. (1957) extended Kynch's analysis into the compression zone by developing a graphical method for analyzing clarifiers using the results obtained from several batch-settling tests. The method can be used to calculate settling areas from two standpoints. One was based on the batchwise thickening operation and other on the mass settling velocity. Thickening area required from both the standpoints was proved to coincide with each other.

In 1964, Hassett modified Yoshioka et al. (1957) method to calculate limiting flux, which can be used to determine the surface area required for the clarifier. To facilitate the design and operation of secondary clarifier, Daigger and Roper (1985) and Keinath (1990) developed different operational diagrams based on the solid flux theory. Daigger and Roper (1985) used the return activated sludge (RAS) concentration, while Keinath (1990) used MLSS concentration and recycle ratio (R) as a master parameters. However these procedures did not include all operational parameters affecting clarifier performance.

2.4.4.2 Application of Solid Flux Theory

The solid flux theory is commonly used for analyzing clarifier design and performance. It is used to determine solids loading rates (SLR) as a function of sludge settling characteristics and sludge return rate. However, the determination of SLR requires knowledge of the sludge thickening characteristics. Thus, the solid flux method is more applicable to the evaluation and expanding existing plants, for which the sludge characteristics are already known (Sperling & Froes, 1997). Design parameters such as true yield, maximum specific rate of substrate utilization, maximum specific growth rate can be found in Kang (1987) and WEF (1998) and can be used to design new treatment system where data is not available.

To apply the solid flux curve or concept to real clarifiers, some simple recommendations should be followed because the procedure used to calculate a solid flux curve is tedious (Ekama et al. 1997):

- 1) Clarifiers should be designed based on 80% to 90% of the calculated maximum flux curve at any point.
- 2) The underflow velocity line must be below the safe flux curve at any point.

Ekama et al. (1997) comments that although the flux theory is well tested, it has some drawbacks including: a) intensive work is required to obtain the setting flux curve, and b) its applicability to a full-scale design and operation has not been definitively demonstrated. Parker et al. (2000) further adds that the critical solids loading predicted by the solid flux theory may not be practically achieved. That is, a sludge blanket may form at solids loading rates other than predicted.

2.4.4.3 Methods for Calculating Solid Flux

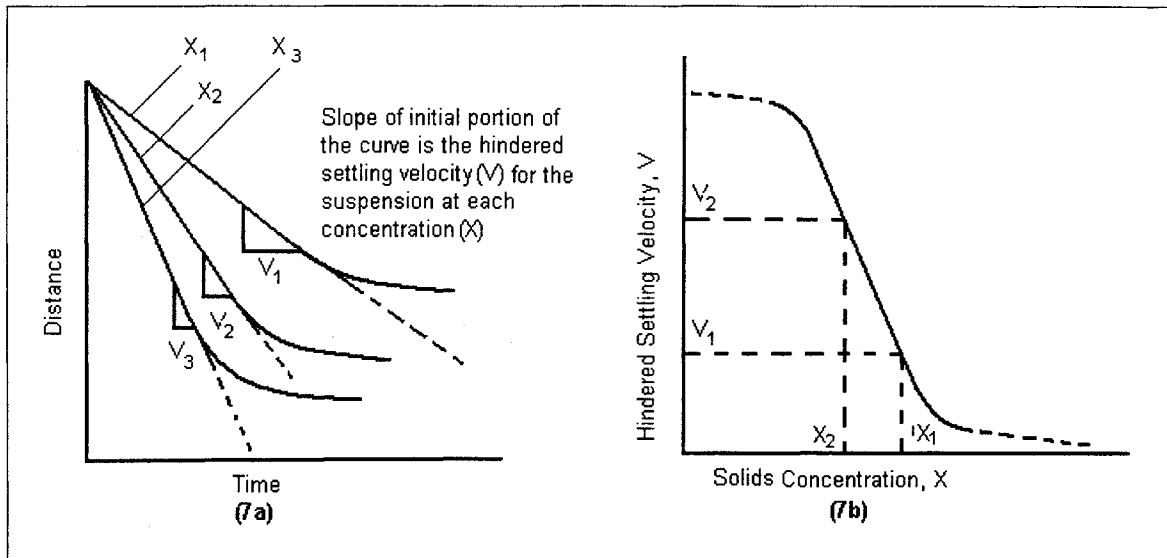
Solid flux can be calculated using graphical and mathematical techniques. Both techniques used to calculate limiting flux (G_L) give more or less the same values (Pitman, 1980).

2.4.4.3.1 Graphical Method

A graphical procedure to determine solid flux was developed by Yoshioka et al. (1957). The graphical procedure involves the use of the solids flux curve and the underflow operating line. This method is used to calculate the clarifier area required for thickening. It determines the limiting solids-handling capacity of clarifiers and it predicts the underflow solids concentration. The graphical method can be described as follows:

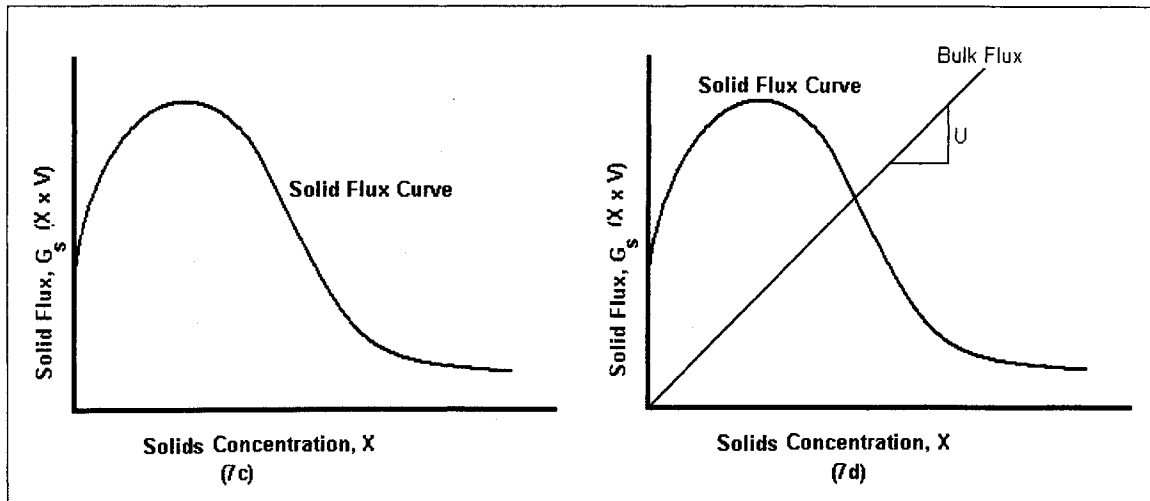
A) Development of the Solids Settling Flux Curve

Column settling tests are performed to collect settling flux data. The tests are conducted in a series of columns to which well mixed activated sludge with a range of concentrations is added. The sludge is allowed to settle and the height between the clear water zone and the top of the sludge blanket is noted as a function of time. Plots are generated of the height of the clear zone versus time for each sludge concentration (Figure 2-7a). The hindered settling velocity is then determined using the linear portion of each curve (Figure 2-7a).



Figures 2-7a and 2-7b Interface height-time and Interface settling velocity as a Function of Solids Concentration

The velocity obtained from the set of curves (Figure 2-7a) and corresponding solids concentration data are plotted as hindered settling velocity (V) versus solids concentration (X) on the y and x axis, respectively (Figure 2-7b). The obtained curve is used to obtain V - X data pairs that are used to calculate the gravity settling flux (G_s). Each value of G_s represents the gravity settling flux per unit area of clarifier that would be expected to occur at the corresponding activated sludge concentration (MLSS). G_s values obtained from Figure 2-7b are used to develop a solid flux curve (solid flux versus solids concentration) as shown in Figure 2-7c.

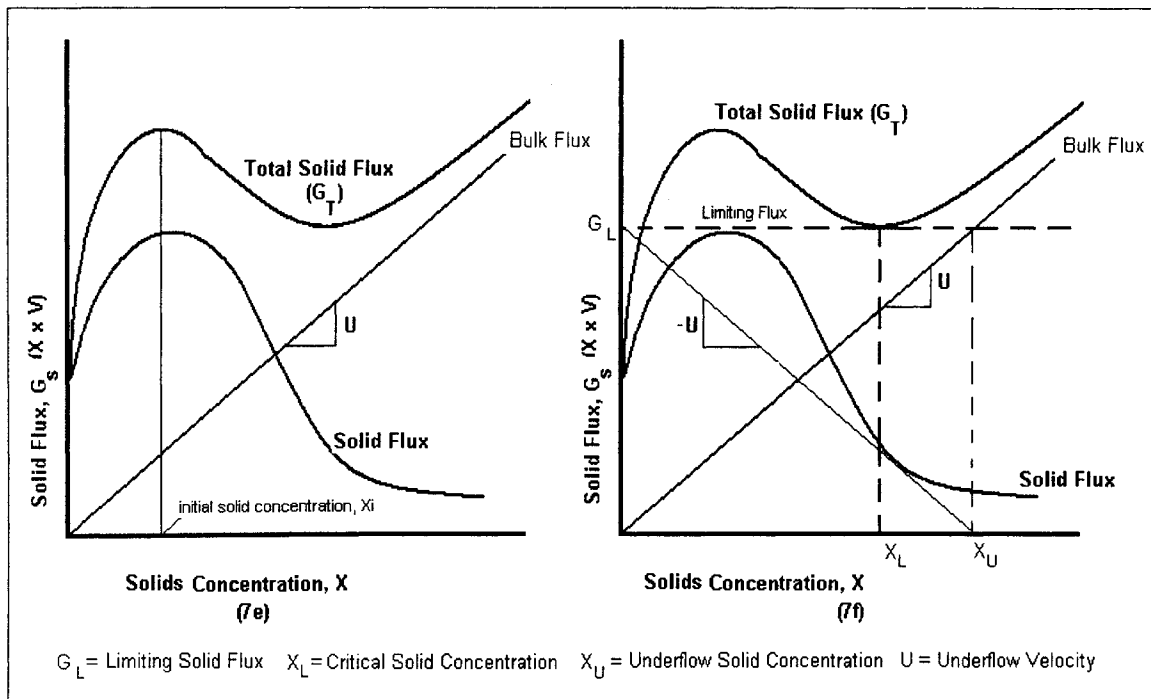


Figures 2-7c and 2-7d Modified from Metcalf and Eddy (1991)

B) Utilization of Settling Flux Curve for Clarifier Design

A straight line passing through the origin with a slope equal to the clarifier underflow velocity, representing the bulk flux, is drawn and combined with the above developed solid flux curve (Figure 2-7d). Next, the total flux curve is superimposed on the above developed solid flux curve. This curve is the sum of the bulk flux and solid settling flux curves (Figure 2-7e). If a horizontal line is drawn tangent to the lower point on the total flux curve, its intercepts the vertical axis at the limiting solid flux (G_L) that can be processed in the clarifier.

The corresponding critical underflow concentration is obtained by drawing a vertical line from the tangent point at the solid flux curve at G_L to the x-axis. This can be done because the gravity settling flux (G_s) is negligible at the bottom of the clarifier and the solids are removed by the bulk flux (Figure 2-7f).



Figures 2-7e and 2-7f Modified from Pitman (1980)

The required clarifier area can be calculated using the limiting solid-flux (G_L) value as:

$$A = (Q + Q_u) * X_i / G_L \quad (2.5)$$

2.4.4.3.2 Mathematical Method

A mathematical method for clarifier design was initially developed by Kynch (1952) and later by Talmadge & Fitch (1955). They developed a design procedure for thickeners based on the results of only one batch settling experiment. To determine the limiting flux condition based on experimentally derived constants, a direct mathematical

method was developed by Vesilind (1968) and later was expanded by Dick and Young (1972).

Dick and Young (1972) obtained a good correlation between underflow velocity (U) and solids concentration (X), and derived equations for calculating the limiting flux using traditional optimization techniques. In 1992, Hartel and Popel developed the dynamic models of the activated sludge process based on the solid flux theory. Koen et al. (1996) developed a new model to determine the surface area of the clarifier using flux theory and its behavior was compared to that of a full-scale clarifier. The simulation results indicated that model was representative of full-scale behavior, except when severe overloads occurred.

2.4.4.4 Clarifier Conditions

Ekama et al. (1997) observed that for any fluctuation in flows, sludge concentrations and settling properties, the clarifier will go either in thickening underload or in clarification/thickening overload. It is instructive to consider how these changes affect the operational state of the plant and how a plant operator should respond.

Underload Clarifier Condition:

Figure 2-8 illustrates underload conditions in a clarifier. A clarifier is said to be underloaded when the sludge settling velocity is greater than the hydraulic loading rate. In this case, the underflow velocity line lies below the settling flux curve (Keinath, 1981; and Ekama et al., 1997). Operating under this condition does not present a particular problem. From Figure 2-8 it can be seen, however, that X_u (the underflow sludge concentration) is less under underloaded condition. Thus, underloading could impact the downstream sludge handling system since Q_w would need to be increased to maintain a

solids balance in the activated sludge basin mainly if the underloaded condition was significant and maintained for an extended period.

Critically Loaded Clarifier Condition:

A clarifier is said to be critically loaded, when the underflow line is within the settling flux curve and is tangent to the settling flux curve as depicted in Figure 2-8.

Overloaded Clarifier Condition:

The overload condition in a clarifier is also depicted in Figure 2-8. According to Keinath (1981):

- 1) The clarifier is said to be in clarification overload when the hydraulic loading rate exceeds the sludge settling velocity, and
- 2) The clarifier is said to be in thickening overload when the applied solid flux exceeds the limiting solid flux.

The overloaded condition means that a greater mass of solids is entering the clarifier than can be transported by the bulk and settling fluxes. In this case, the limiting flux is exceeded and results in an increase in sludge blanket height in the clarifier. This may lead to clarifier failure if the sludge blanket rises too high, resulting in solids being carried over the weir. The system can be brought to critical load or underloaded condition by increasing the slope of the underflow operating line until it is tangent to or under the flux curve, respectively. This yields a new operating underflow concentration (X_u') and limiting flux (G_L'). In this case, operator action can be determined by taking the slope of new underflow operating line and applying the relationship $U = Q_u/A$.

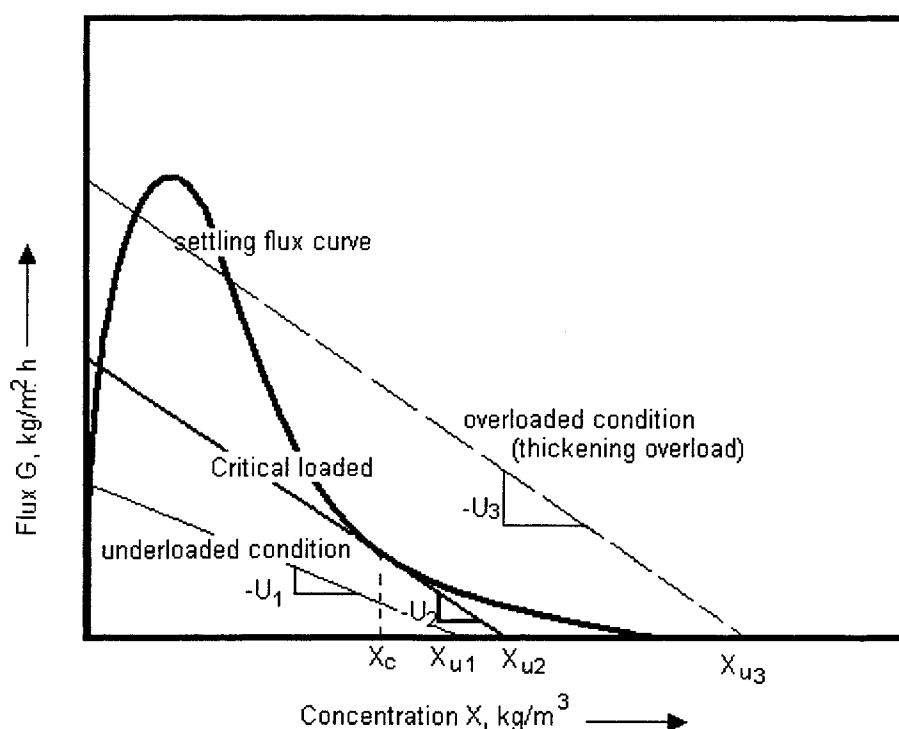


Figure 2-8 Underloaded, Critically loaded, and Overloaded Clarifier Conditions (Modified from Rittmann, 2001)

2.4.5 State Point Analysis

The state point is a tool that can be used to identify the loading conditions (e.g. overloaded, underloaded, or critically loaded) in the clarifier of an activated sludge system. State point analysis allows for the coupling between the operation of the secondary clarifier and the aeration basin (Rittmann, 2001). Therefore, state point analysis can be used as a tool to optimize the design and operation of activated sludge systems and in the development of appropriate solids inventory control strategies.

The application of state point analysis requires the knowledge of the settling characteristics of the mixed liquor as defined by the mixed liquor settling flux curve. The settling flux curve of given mixed liquor is a curve that shows the relationship between

the solids concentration (X_i , mass/volume) and the initial settling velocity (V , length/time). The settling velocity is also a function of the concentration, X_i .

In state point analysis, recycle and effluent flow rates are considered independent variables and mixed liquor suspended solids (MLSS) are controlled by bioprocess considerations that are independent of the secondary clarifier (Rittmann, 2001). Therefore, the state point concept is used to couple the aeration basin to the secondary clarifier.

Graphically, the state point is defined by the intersection (point C) of two operating lines one representing the overflow rate of the clarifier and the other representing the underflow rate (Figure 2-9). The overflow rate (OFR) operating line is a line passing through the origin with slope equal to the OFR. The OFR is defined as flow into the basin divided by its total surface area. The underflow operating line (AB) is a line having a slope of $-U$ (underflow velocity) and passing through some known value of either X_U (point B) or total flux due to feed and recycle flows (point A).

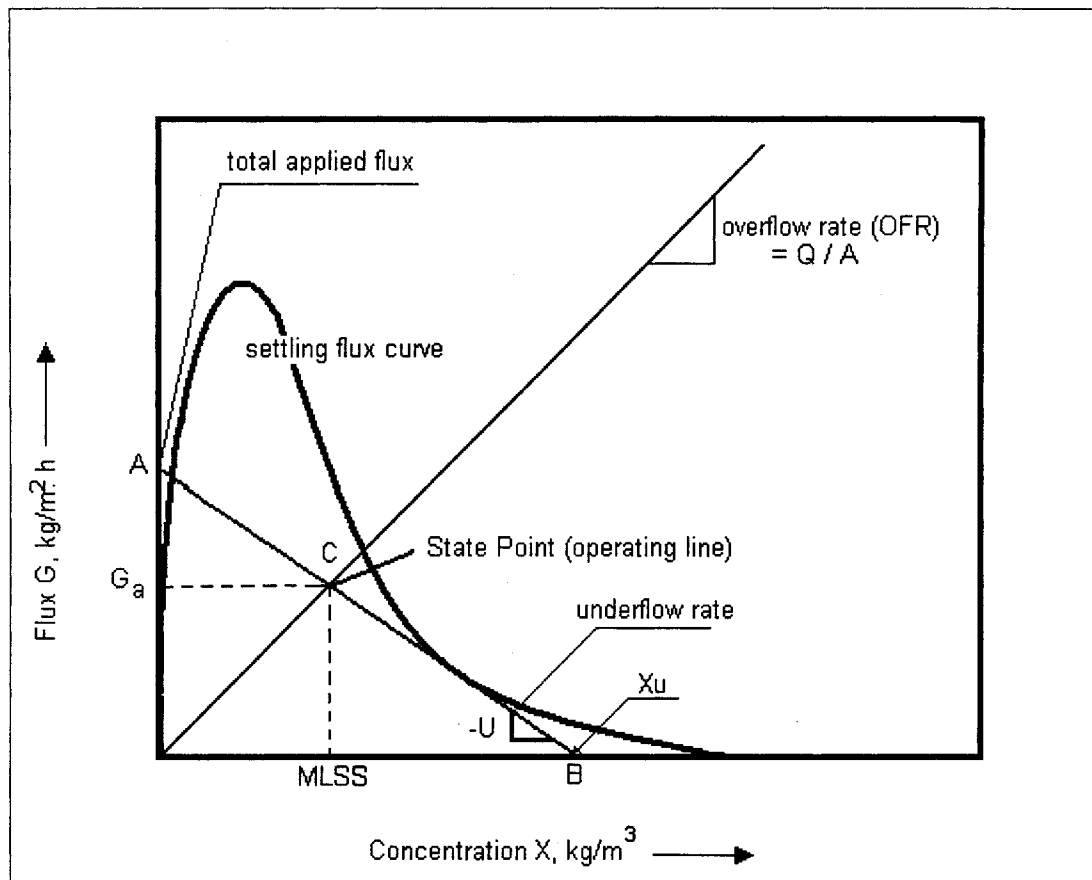


Figure 2-9 OFR and underflow operating lines and location of state point (Modified from Rittmann, 2001)

In Figure 2-9, a vertical line through the state point (point C) intersecting the X-axis represents the mixed liquor suspended solids (MLSS) concentrations. A horizontal line through point C intersecting the y-axis represents the flux due to the flow rate (Q).

2.4.5.1 Importance of State Point Analysis

The location of the state point is of critical consideration for the following reasons (Keinath, 1985):

- 1) In activated sludge systems, the parameters (OFR, X_i), which define the location of the state point, are controlled by external factors other than the clarifier operation. The OFR rate is controlled by the influent flow rate, while X_i is

controlled by the influent substrate loading and the solids retention time (SRT) in the aeration tank. Therefore, the operation of the secondary clarifier by itself cannot change the location of the state point, since the location point is externally imposed.

- 2) The position of the state point in the relation to the solids settling curve is an indicator of the clarifier operational state. Secondary clarifiers operate either in underloaded, critically loaded, or overloaded conditions. These conditions can be identified by the position of the state point and the underflow line with respect to the settling flux curve. Depending on the position of the state point three different cases are discussed below.

Case 1: (Figure 2-10)

When the state point is below the settling flux curve and

- a) if the underflow operating line lies below the settling flux curve, the clarifier is underloaded,
- b) if the underflow operating line lies on the settling flux curve, the clarifier is critically loaded, and
- c) if the underflow operating line lies above the settling flux curve, the clarifier is overloaded

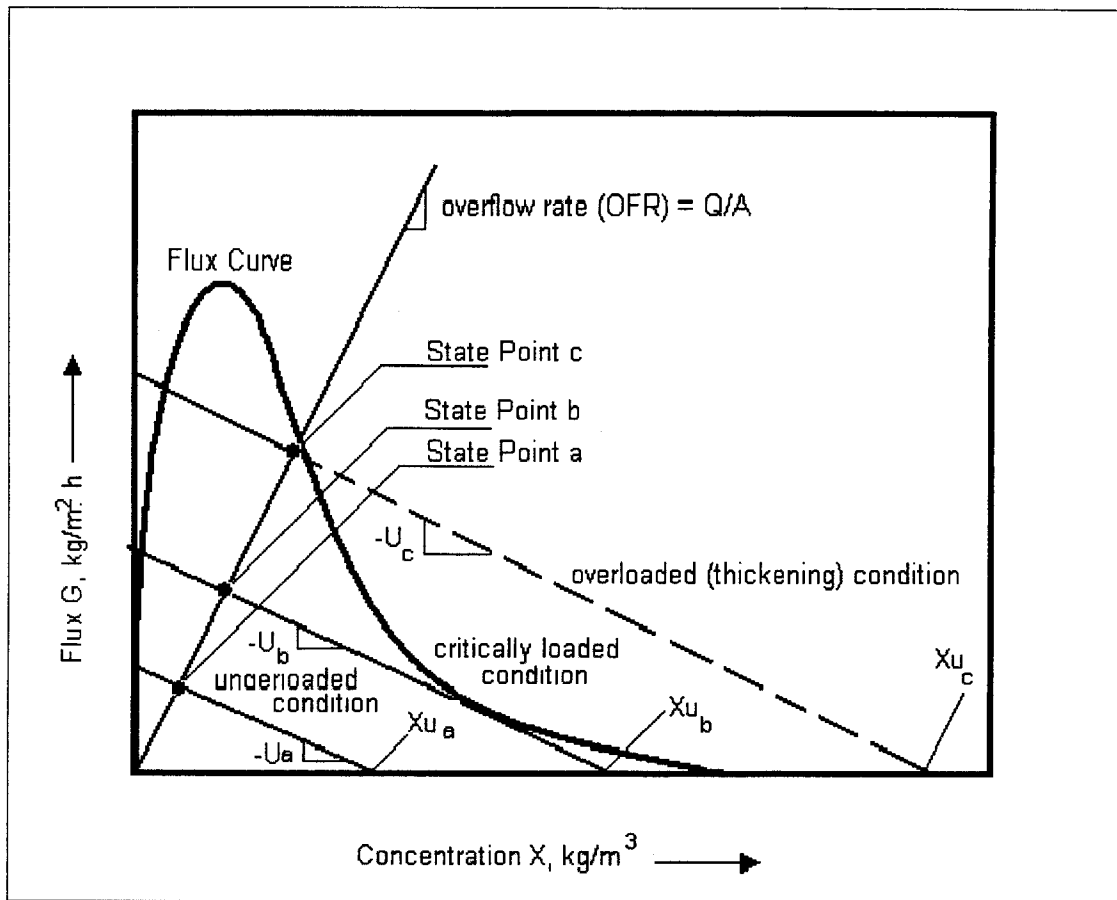


Figure 2-10 Case 1 (Modified from Keinath, 1985)

Case 2: (Figure 2-11)

When the state point is on the settling flux curve, and

- a) if the underflow operating line lies below the settling flux curve, the clarifier is critically loaded, and
- b) if the underflow operating line lies above the settling flux curve, the clarifier is overloaded

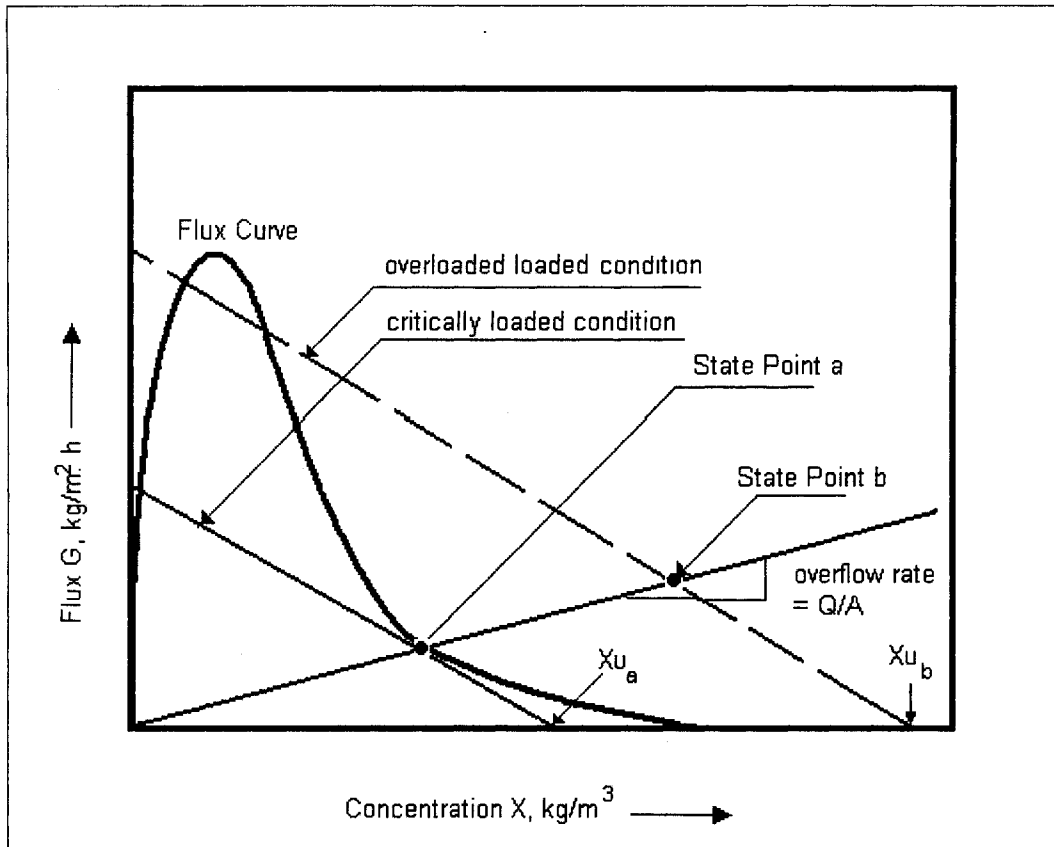


Figure 2-11 Case 2 (Modified from Keinath, 1985)

Case 3: (Figure 2-12)

When the state point is above the settling flux curve, the input flux is greater than downward flux for the input solids concentration and the underflow operating line is above the settling flux curve, the clarifier experiences both clarification and thickening overload.

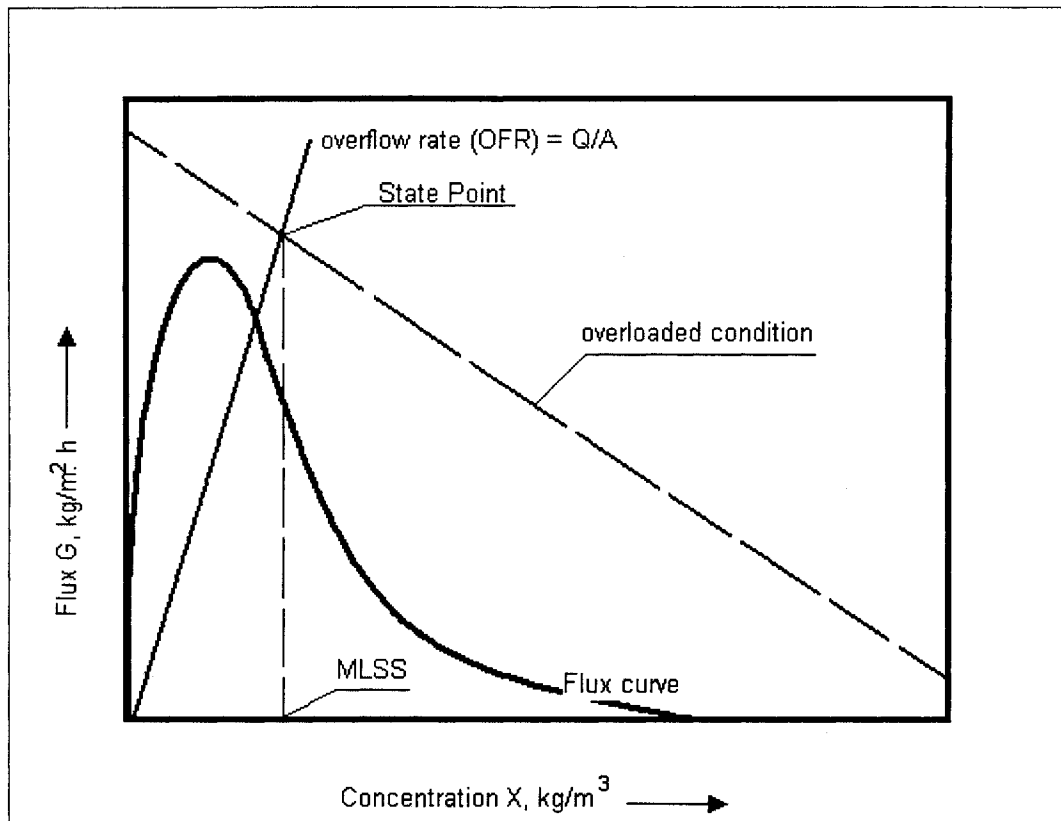


Figure 2-12 Case 3 (Modified from Keinath, 1985)

2.4.5.2 Clarifier Operations Control Strategies

Keinath (1985) has suggested some remedies to avoid the overloaded conditions in the clarifier for the above aforementioned cases which include:

- a) In case 1, by increasing the recycle rate, critically loaded and overloaded conditions can be changed to an underloaded condition,
- b) In case 2, an overloaded condition can be changed to an underloaded condition also by increasing the recycle rate.

In cases 1 and 2, since the recycle operating line lies below the settling flux curve, the critically loaded and overloaded conditions can be altered to the underloaded condition just by adjusting the recycle rate.

In case 3, since the state point and recycle operating line lies above the settling flux curve, adjusting the recycle rate itself cannot alter overloaded condition. In addition, input solids concentration has to be decreased to achieve the underloaded condition. The input solids concentration can be decreased either by steep feeding or by decreasing the SRT of the system.

2.4.5.3 Consequences to Plant Performance

In an overloaded clarifier, the sludge blanket starts rising and ultimately the solids are lost through the clarifier weir affecting the performance of the plant. Therefore, it is necessary to operate the clarifier either in underloaded or critically loaded condition. An overloaded condition can be altered to the underloaded condition by adjusting the underflow recycle rate, using the state point as a pivot point for the recycle rate operating line. In addition, the state point can be vertically shifted upward or downward by increasing or decreasing the flow to the plant respectively. However, if no control precautions are taken to bring the clarifier to underloaded condition, the system itself responds to this condition. The system starts transferring solids from the aeration basin to the clarifier, which results in a decrease in MLSS concentration and rise in upward movement of the sludge blanket in the clarifier to accommodate the transferred solids (Keinath,1985).

CHAPTER 3

CHARACTERIZATION OF DENITRIFICATION IN SECONDARY CLARIFIERS IN THE CCSD WASTEWATER TREATMENT PLANT

3.1 Introduction

In order to avoid eutrophication of receiving waterbodies, wastewater effluent requirements for nutrient removal have been made more stringent in recent years (EPA, 1993; and Keller et al., 1997). In addition, low effluent quality causes other serious problems, such as toxicity to aquatic life (Colt & Armstrong, 1979; and White, 1995), depletion of dissolved oxygen in receiving waters (Barnes & Bliss, 1983; and Sorensen & Jorgensen, 1993), diseases like methemoglobinemia (infantile cyanosis), and carcinogenesis, particularly, gastric cancer (EPA, 1993). When wastewater treatment plants have to achieve high levels of nutrient removal, the secondary clarifier often becomes the focus of attention for improvements (Ekama et al., 1997).

The main functions of the secondary clarifier are clarification, solid thickening, and solids storage. If the clarifier fails to perform any one of the above functions, suspended solids (SS) will be carried over the effluent weir and escape with the effluent (Narayanan & Ooten, 2000). An increased suspended solids concentration in the clarifier effluent affects the overall removal efficiency of the plant with respect to BOD, COD, total suspended solids (TSS), total nitrogen and phosphorus (Siegrist & Guger, 1994;

Ekama et al., 1997; and Parker et al., 2000). This problem is typically observed in activated sludge plants with nitrification (Cole et al., 1974) and in some cases in plants with partial denitrification (Christensen et al., 1978).

Although, the major objective of clarification is to separate solids from liquid, the processes that would normally take place in bioreactors, such as denitrification, may occur in clarifiers. Denitrification occurring during clarification may be beneficial or detrimental to the operation of BNR systems, depending on its intensity. Therefore, characterization of denitrification within the clarifier provides the insight into the influence of denitrification on the overall performance of BNR systems. Several parameters are known to influence denitrification in the clarifier, which affect efficiency to remove nutrients. Parameters which play an important role in the amount of denitrification within the clarifier include availability of carbon source (e.g. soluble COD), influent nitrate concentration (SS), dissolved oxygen (DO) concentration, temperature, pH, and sludge concentration. The primary objective of this study was to investigate the occurrence and to determine the parameters influencing denitrification within the secondary clarifier of a full-scale wastewater treatment plant.

The present study was performed in a full-scale BNR wastewater treatment plant, the Clark County Sanitation District (CCSD), in Las Vegas, Nevada. The CCSD plant treats approximately 88 MGD of domestic wastewater. This plant has eight identical aeration basins, each compartmentalized into anoxic/anaerobic/aerobic sections with total detention time of 4 hours and its dedicated secondary clarifier with detention time of 3.5 hours. The study was performed in one of the 8 aeration basins and its dedicated clarifier, which treat on average 10 MGD of wastewater (aeration basin and clarifier # 4).

The BNR system in this plant works well; nearly 95% of N-removal and 97% of P-removal is achieved. However, the system suffers some instability and sporadic phosphorus-excursion. The CCSD plant discharges its effluent into the Las Vegas Wash, which flows into Lake Mead. Lake Mead is a national recreational area and the primary source of drinking water for much of the southwestern United States. Hence, the CCSD operates the plant under strict regulation for nutrient (N and P) removal in order to avoid eutrophication of the lake.

3.2 Materials and Methods

In order to characterize denitrification in the secondary clarifier, nine sampling points were established on an axial plane (Figure 3-1). The clarifier is 140 feet in diameter with 14 feet side water depth. To perform characterization, the clarifier diameter was divided into two platforms, A and B. Assuming similar conditions exist throughout the clarifier, the axial characterization profile was performed on platform A. The axial plane was divided into three locations, to define 9 sampling points, C_{1-S} , C_{2-S} , and C_{3-S} at the surface; C_{1-10} , C_{2-10} , and C_{3-10} , at 10 feet depth, and C_{1-10} , C_{2-10} , and C_{3-10} , at the bottom.

Samples were collected twice a week for an 8-month period within a basin and a clarifier (referred herein as # 4). Two sets of each, filtered and unfiltered grab samples, were collected for this study. Samples were vacuum filtered through a 0.145 μm membrane filter immediately after collection, placed on ice, and transported to laboratory for analysis. Filtered samples were analyzed for nitrate (NO_3^-), nitrite (NO_2^-), ortho-

phosphate (OP), and soluble COD. Unfiltered samples were analyzed for total suspended solids (TSS), total phosphorus (TP), and sludge volume index (SVI).

The CCSD advanced Water Treatment (AWT) laboratory analyzed samples for nitrate (NO_3^-), nitrite (NO_2^-), ortho-phosphate (OP), and total-P. Nitrate (NO_3^-) and nitrite (NO_2^-) were determined using Standard Methods with a BRAN LUBBE/Technicon TRAACS 800 flow analyzer. Ortho-P was analyzed using an ALPKEM FS3000 flow injection analyzer. Total phosphorus analyses were performed by digesting the unfiltered samples with persulfate in an autoclave at 121°C for 30 minutes. Ortho-P in the digested samples was analyzed by either ALPKEM FS3000 flow injection analyzer or by the spectrophotometric ascorbic acid method. Soluble COD and TSS were measured at the UNLV Environmental Engineering Laboratory. Soluble COD was measured using HACH high range COD vials. TSS was determined gravimetrically using standard methods (APHA, 1990).

On-site measurements of temperature, conductivity, oxidation-reduction potential (ORP), pH, and DO were performed in each location using a Hydrolab H20-G multiprobe. The probe was calibrated weekly as per manufacturer instructions.

The raw data collected are shown in Appendix A. To determine the influence of the several measured parameters on denitrification and P-release, three statistical evaluations were performed using multiple regression analysis with the software Minitab. All the sampling data were used to perform the statistical analysis. The first and third regression analyses were performed to evaluate which parameters influenced denitrification and OP-release, respectively, the most. The second regression was performed to evaluate whether known products of denitrification (e.g. nitrite and pH

increase) correlate well with the decrease in nitrate concentrations within the clarifier. In addition, profiles of all measured parameters were drawn to illustrate trends within the clarifier. The data used to construct the profiles were chosen randomly from the large data set collected. This was done to avoid overcrowded graphs. However, the trends shown in the profiles are representative of the entire data set. All plots built in this chapter are for same sampling dates chosen.

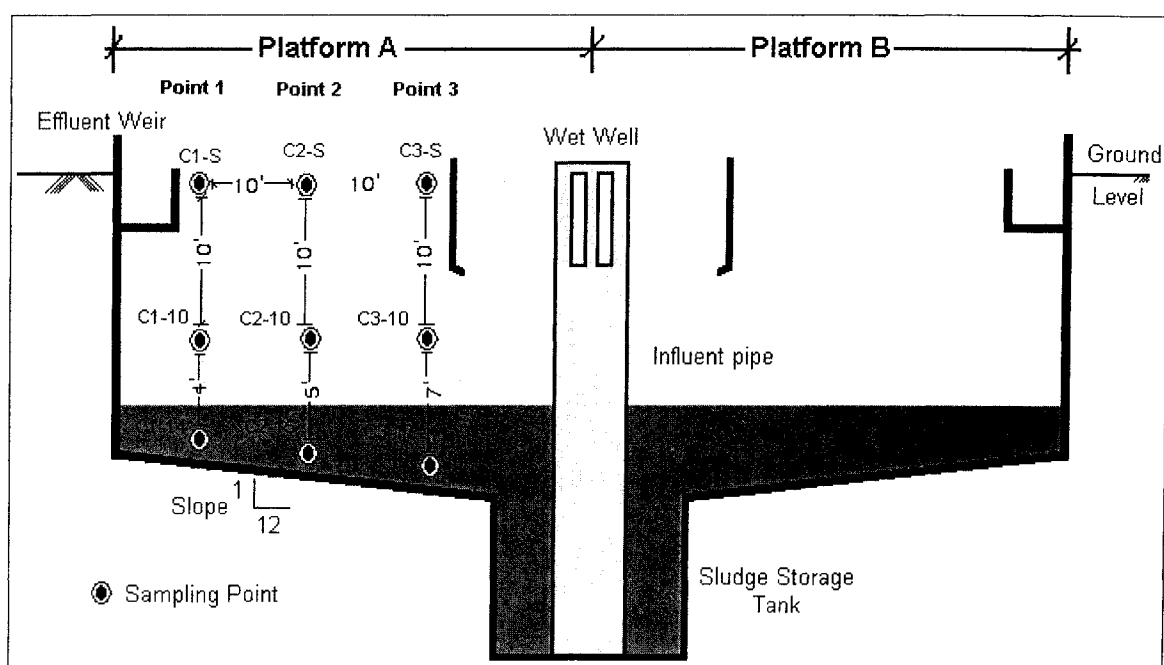


Figure 3-1 Sampling Points Location in the Secondary Clarifier # 4

3.3 Results and Discussions

3.3.1 Regression Analysis # 1

The first regression analysis, using nitrate concentration as the response variable and the other measurements as influencing parameters (DO, SCOD, pH, temperature, and

ORP), for all three vertical sampling points (1, 2, & 3), yielded regression coefficient (R^2) values of 0.8914, 0.9143, and 0.939, respectively (Appendix B, Table 1). The p-values obtained from this simulation for point 1 (close to the effluent weir) indicate that the decrease in nitrate concentrations within the clarifier was greatly influenced first by SCOD concentrations ($p = 0.000$) then by DO concentrations ($p = 0.008$) and TSS concentrations ($p = 0.056$). pH values ($p = 0.6714$), temperature ($p = 0.1496$), and ORP ($p = 0.225$) in this order were found to have little effect on the decrease of nitrate concentrations. For points 2 and 3, p-values indicate that the nitrate decrease was strongly influenced by first DO ($p = 0.000$ and $p = 0.001$, respectively) concentrations and by SCOD ($p = 0.007$ and $p = 0.003$, respectively). SS concentrations ($p = 0.092$ and $p = 0.090$, respectively), pH ($p = 0.830$ and $p = 0.888$, respectively), temperature ($p = 0.650$ and $p = 0.1478$, respectively), and ORP ($p = 0.287$ and $p = 0.216$, respectively) had little effect on nitrate concentration decrease. Thus, DO and SCOD, for all three points considered, were found to be the variables that influence clarifier denitrification the most at CCSD. The DO and SCOD concentrations were found to have nearly the same influence.

3.3.2 Nitrate Profiles

Nitrate concentrations in the influent to the clarifier averaged 13.90 mg/L, while nitrate concentration in the RAS varied from 0.02 and 14.81 mg/L. A distinctive decrease in nitrate concentration (between 0.02 - 9 mg/L) along the vertical axis from the surface to the bottom of the clarifier was observed (Figure 3-2a). Along the vertical axis, closer to the wet well (point 3), the decrease in nitrate concentrations was more abrupt

than that at points closer to the effluent weir (points 1 & 2). Along the horizontal axis, nitrate concentration did not vary much at the clarifier surface (averaging 14 mg/L). However, it did vary at the bottom of the clarifier from 3.53 to 0.146 mg/L, with lower values towards the center well (Figure 3-2b). In general, a decrease in nitrate concentration was observed vertically within the clarifier with largest decrease observed at point 3, closer to the wet well. Horizontally, nitrate concentrations did not vary much, except at the sampling points located at the clarifier's bottom.

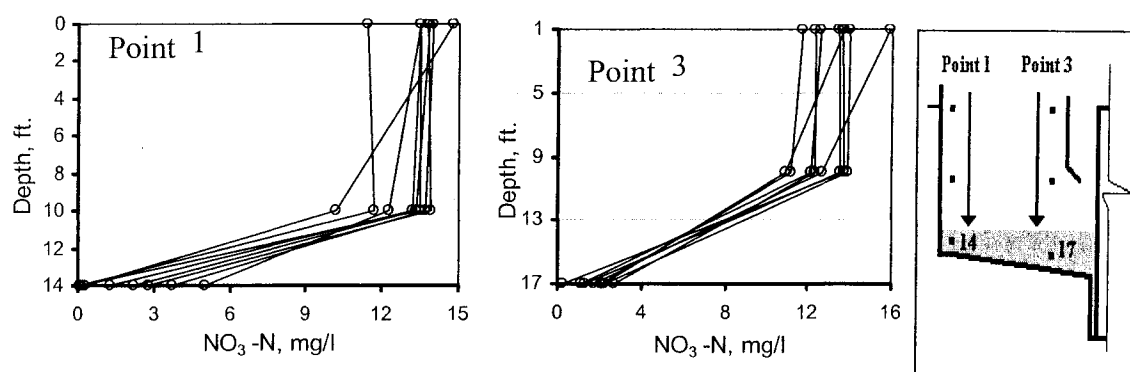


Figure 3-2a Vertical Profile for Nitrate Concentration in the Secondary Clarifier at points 1 and 3

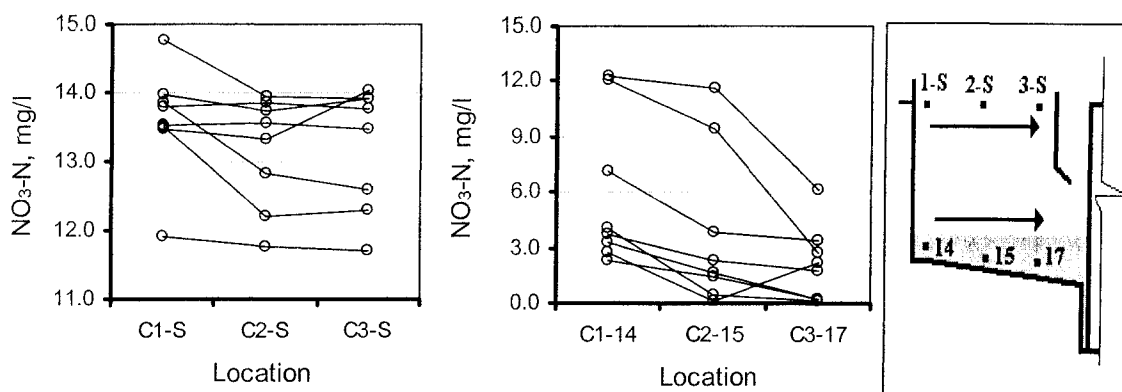


Figure 3-2b Horizontal Profile for Nitrate Concentration in the Secondary Clarifier

3.3.3 Dissolved Oxygen (DO) and Oxidation Reduction Potential Profiles

Dissolved oxygen (DO) profiles along the vertical and the horizontal sampling points are presented in Figures 3-3a and 3-3b. DO concentrations along the vertical profile indicate a gradual decrease from the surface to the bottom of the clarifier, varying from 0.06 to 0.3 mg/L. Along the horizontal axis at the clarifier surface, DO concentration did not vary much (averaging 0.14 mg/L); However, variation occurred at the bottom of the clarifier from 0.06 to 0.21 mg/L. These DO measurements were within the range of DO levels reported in the literature (< 0.2 mg/L) as the limit for denitrification to occur (Rittmann & Langeland, 1985; and Pochanu & Keller, 1999). DO concentrations in the clarifier did not exceed 0.3 mg/L anytime during the experiment. These low DO concentrations coupled with low nitrate concentrations at the bottom of the clarifier suggest that denitrification may be occurring within the clarifier. The p -values ($p = 0.008$, $p = 0.000$, and $p = 0.001$ for points 1, 2, and 3, respectively) obtained in the first regression analysis show that low DO has significantly promoted nitrate

decrease within the clarifier, confirming the above interpretation.

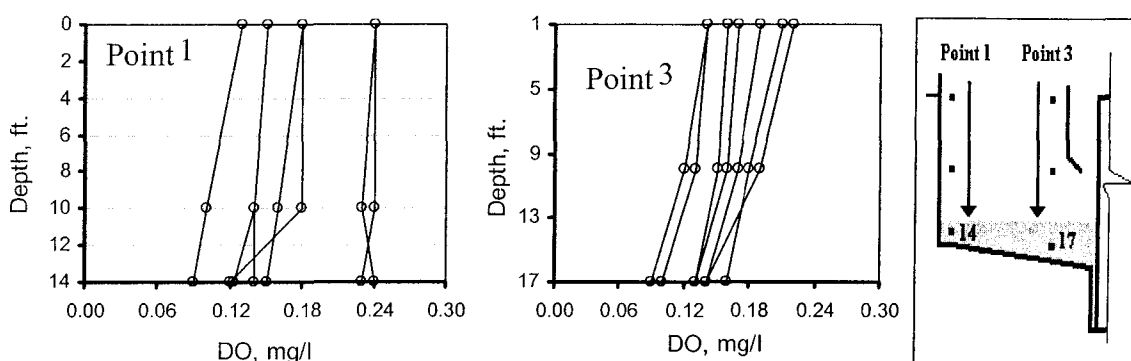


Figure 3-3a Vertical Profile for DO Concentration in the Secondary Clarifier

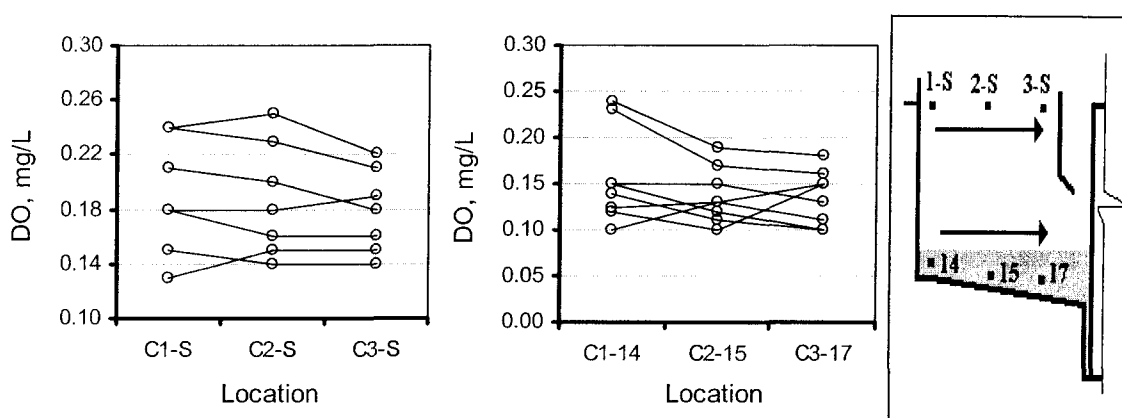


Figure 3-3b Horizontal Profile for DO Concentration in the Secondary Clarifier

Figures 3-4a and 3-4b depict ORP profile along the vertical and the radial sampling points. ORP along the vertical profile varies significantly from 123 to 31 mV indicating more reducing conditions at the bottom of the clarifier than at the top. Along the horizontal profile, ORP varied slightly (124 to 130 mV, 69 to 85 mV, and 41 to 49 mV at the surface, at 10 feet depth, and at the bottom of the clarifier, respectively).

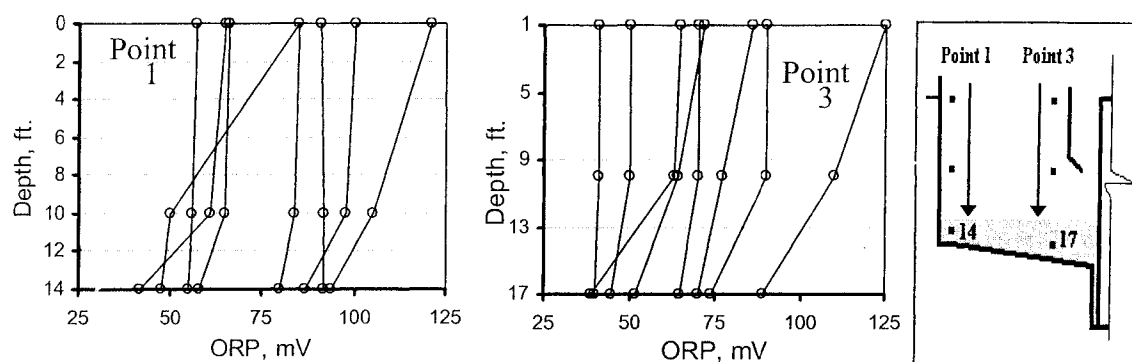


Figure 3-4a Vertical Profile for ORP Concentration in the Secondary Clarifier

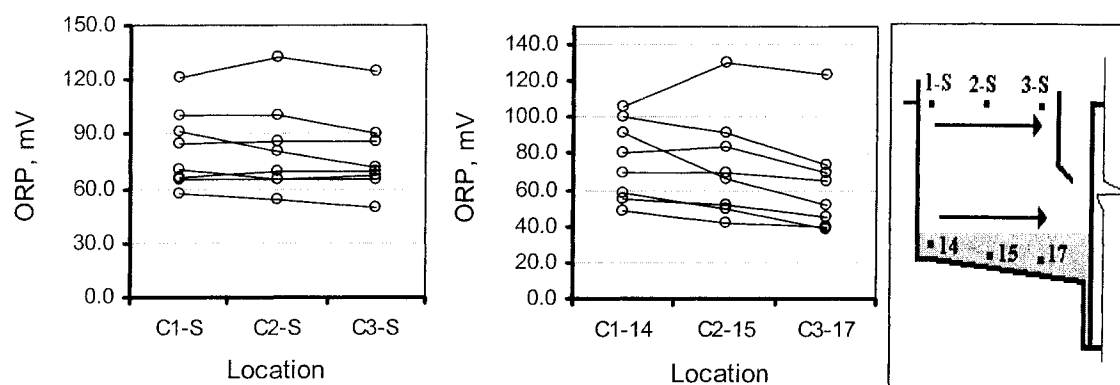
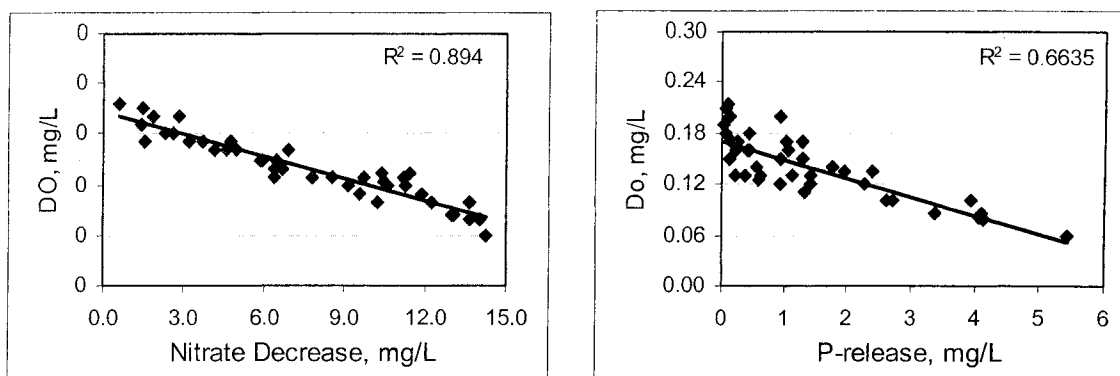


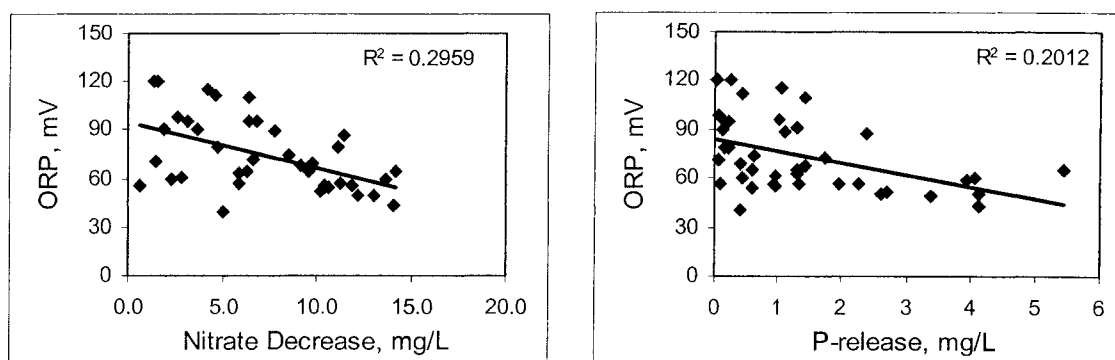
Figure 3-4b Horizontal Profile for ORP Concentration in the Secondary Clarifier

Linear regression analysis between DO and nitrate decrease showed strong relationship with a $R^2=0.894$ (Figure 3-5a), whereas a moderate relationship was obtained with a $R^2=0.6635$ between DO and ortho-P (Figure 3-5b). These relationships indicate that whenever the DO in the clarifier was low, high nitrate decrease and OP release were observed, suggesting that DO influences denitrification and P-release within the clarifier.



Figures 3-5a and 3-5b Relationship between DO (a) Nitrate Decrease and (b) Ortho-P

The correlation between nitrate decrease and ortho-P increase with ORP ($R^2=0.2959$ & $R^2=0.2012$, respectively) was found to be weak (Figures 3-6a & 3-6b). This result suggests that denitrification and p-release in the clarifier are less influenced by the ORP than by the DO measurement. This interpretation is in agreement with the p-values obtained in the first regression analysis (Appendix B, Table 1).



Figures 3-6a and 3-6b Relationship between ORP and (c) Nitrate Decrease (d) Ortho-P

3.3.4 pH Profiles

The vertical and the horizontal profiles for pH are presented in Figures 3-7a and

3-7b. There is an increase in pH values (from 6.58 to 7.15) along the vertical profile from the surface to the bottom of the clarifier (Figure 3-7a). No variation in pH values (6.6 to 6.59, 6.87 to 6.92, and 7.08 to 7.14 at the surface, at 10 feet depth, and in the bottom of the clarifier, respectively) was observed along the horizontal profile (Figure 3-7b). Stensel (1971), Dawson & Murphy (1972), and Sorensen & Hjuler (1992) reported that the optimal pH range for denitrification to occur is 6 to 8. The pH values observed throughout the experiment were always within the above-mentioned range, suggesting that the pH values were favorable to denitrification. The results of the multiple regression analysis ($p = 0.623$, $p = 0.0830$, and $p = 0.888$ for points 1, 2, and 3, respectively) indicate that for the pH range investigated, nitrate reduction was not affected by pH.

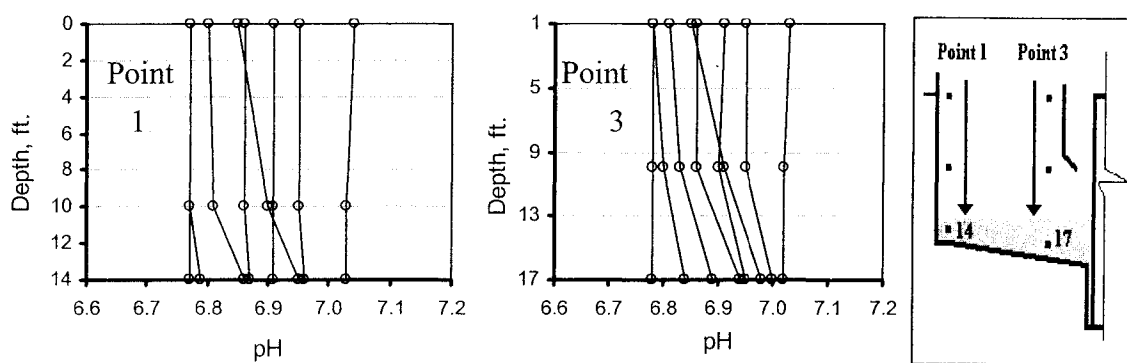


Figure 3-7a Vertical Profile for pH in the Secondary Clarifier

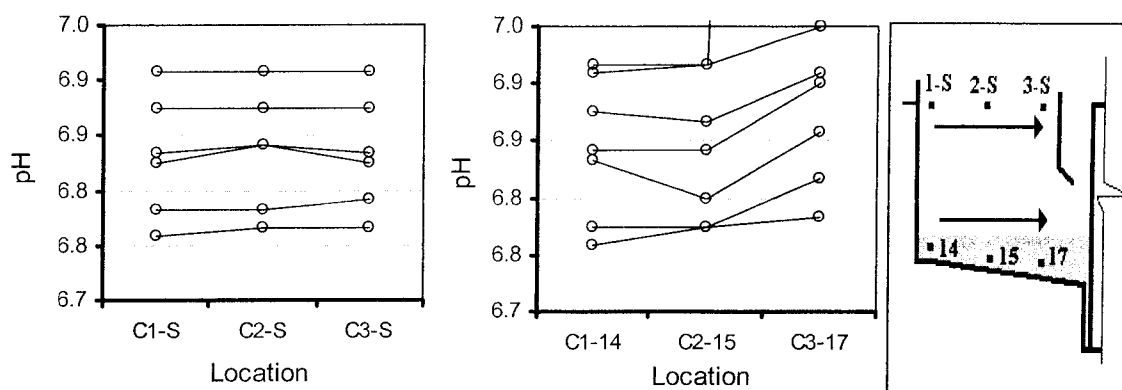


Figure 3-7b Horizontal Profile for pH in the Secondary Clarifier

3.3.5 Total Suspended Solids (TSS) Profiles

Total suspended solids profiles along the vertical and the radial sampling points are shown in Figures 3-8a and 3-8b, respectively. There is a significant increase (from 4 to 12,800 mg/L) in TSS concentration along the vertical profile in the clarifier from the surface to the bottom, as expected. TSS concentration did not vary significantly along the horizontal profile at the clarifier surface, except at the bottom of the clarifier where SS concentrations varied from 3,320 to 12,800 mg/L, with higher values closer to the wet well. The sludge at the bottom of the clarifier has higher solids concentration closer to the wet well (averaging 8,240 mg/L) as compared to points 1 and 2 (averaging, 3,680 and 5,990 mg/L, respectively). This observation is supported by the p-values ($p = 0.056$, $p = 0.092$, and $p = 0.090$ for points 1, 2, and 3, respectively) obtained in first regression analysis (Appendix B, Table 1). These p-values indicate that SS concentration has only slight influence on nitrate decrease.

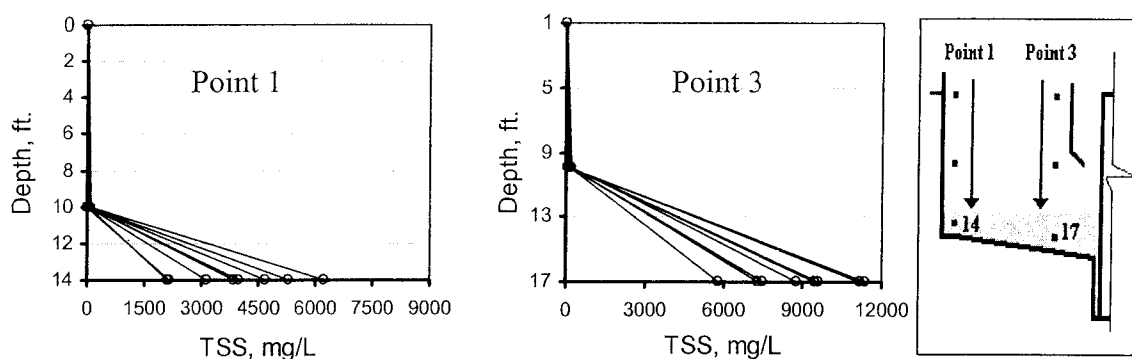


Figure 3-8a Vertical Profile for TSS in the Secondary Clarifier

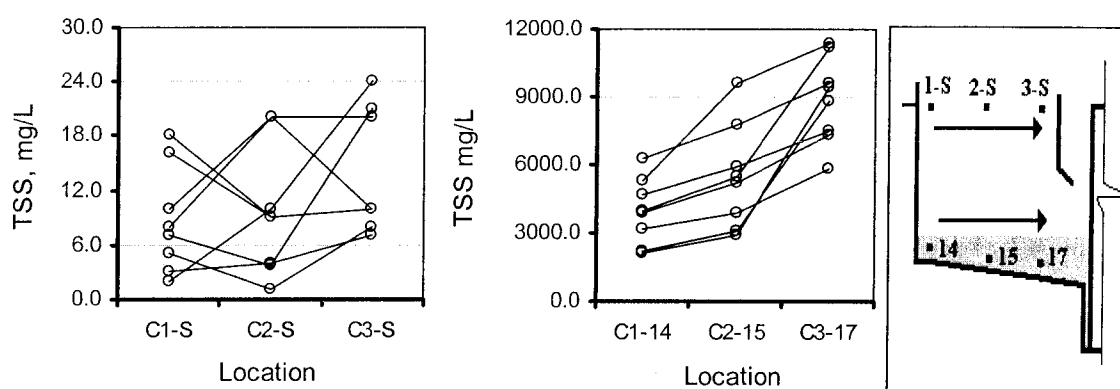


Figure 3-8b Horizontal Profile for TSS in the Secondary Clarifier

3.3.6 Soluble Chemical Oxygen Demand (SCOD)

SCOD increased along the vertical profile from the surface to the bottom of the clarifier (Figure 3-9a). The SCOD values along the vertical profile varied from 12 to 31 mg/L, 34 to 68 mg/L, and 56 to 144 mg/L at the surface, at 10 feet depth, and in the bottom of the clarifier, respectively. The SCOD along the horizontal profile averaged between 68 to 109 mg/L (Figure 3-9b). Effluent soluble COD varies between 12 to 35 mg/L. Thus, SCOD along the vertical profile varied significantly, while there was slight

variation along the horizontal profile. These increases in SCOD at the bottom of the clarifier are due to low DO and high SS values. Under anaerobic conditions, suspended solids will ferment forming soluble COD that can be used for both denitrification and P-release. Koch et al. (1999), Koch & Siegrist (1997) and Siegrist & Guger (1994) have also reported that fermentation of sludge in the clarifier provides carbon source for denitrification.

The above interpretation is supported by the good R^2 values yielded for the correlation between SCOD and TSS ($R^2 = 0.6355$, $R^2 = 0.7167$, and $R^2 = 0.7856$ for points 1, 2 and 3, respectively), and for the correlation between SCOD and DO ($R^2 = 0.6116$, $R^2 = 0.6104$, and $R^2 = 0.801$ for points 1, 2 and 3, respectively) (Figure 3-11). Thus, at CCSD, fermentation of the secondary sludge is the main source of biodegradable carbon that will support denitrification and phosphorus release in the clarifier. This conclusion is supported by the strong relationship obtained between SCOD and nitrate decrease with $R^2 = 0.6217$ (Figure 3-10a), and between SCOD and ortho-p concentration with $R^2 = 0.67141$ (Figure 3-10b) in the clarifier. In addition, p-values ($p = 0.000$, $p = 0.007$, and $p = 0.003$ for points 1, 2, and 3, respectively) obtained from the first regression analysis were also in agreement with the above interpretation.

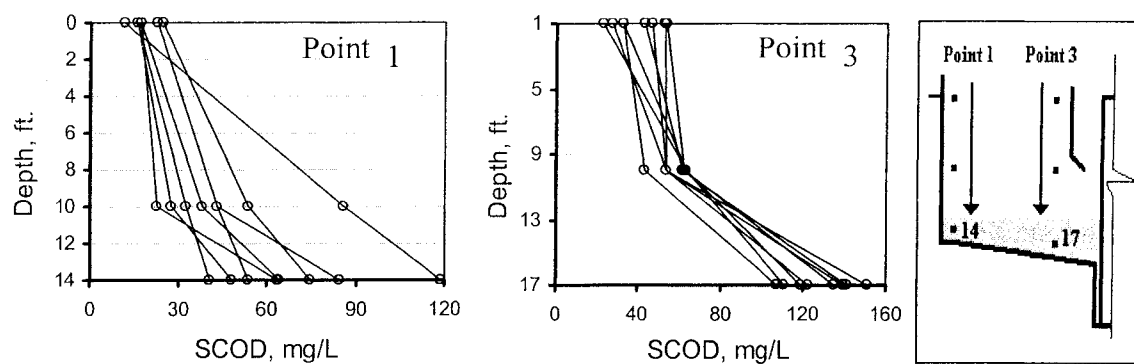


Figure 3-9a Vertical Profile for Soluble Chemical oxygen Demand (SCOD) in the Secondary Clarifier

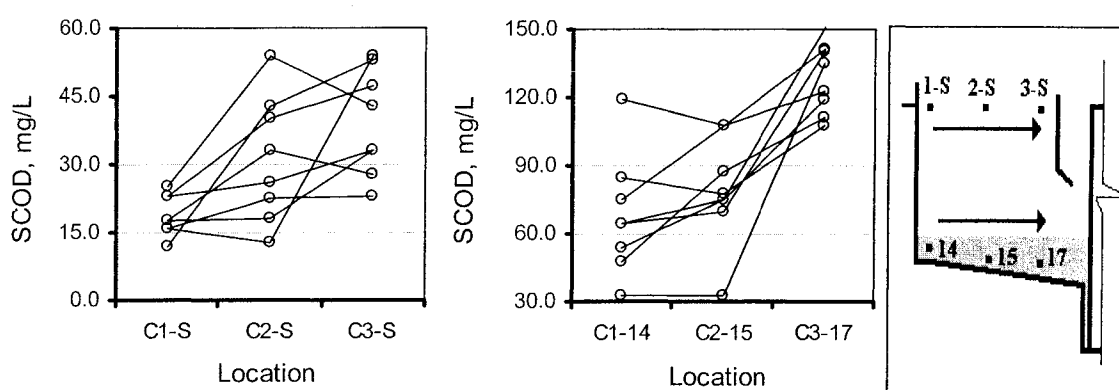
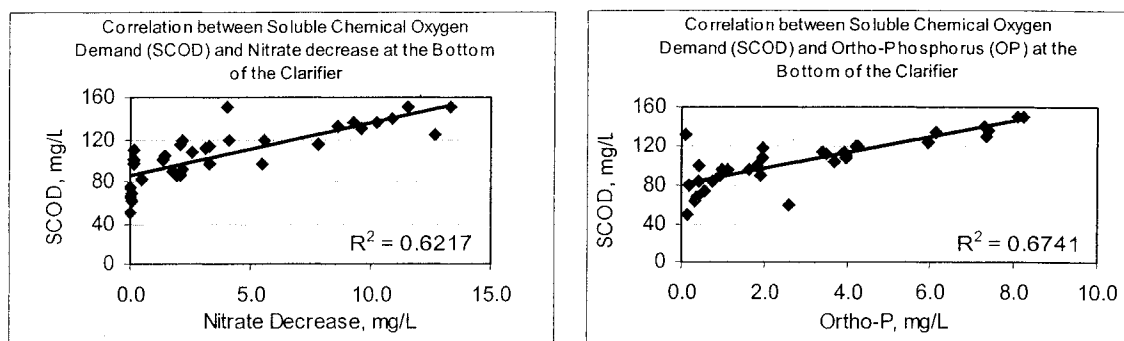


Figure 3-9b Horizontal Profile for Soluble Chemical oxygen Demand (SCOD) in the Secondary Clarifier



Figures 3-10a and 3-10 b Relationship between Soluble Chemical oxygen Demand (SCOD) and (c) Nitrate Decrease, mg/L, (d) Ortho-P concentration, mg/L

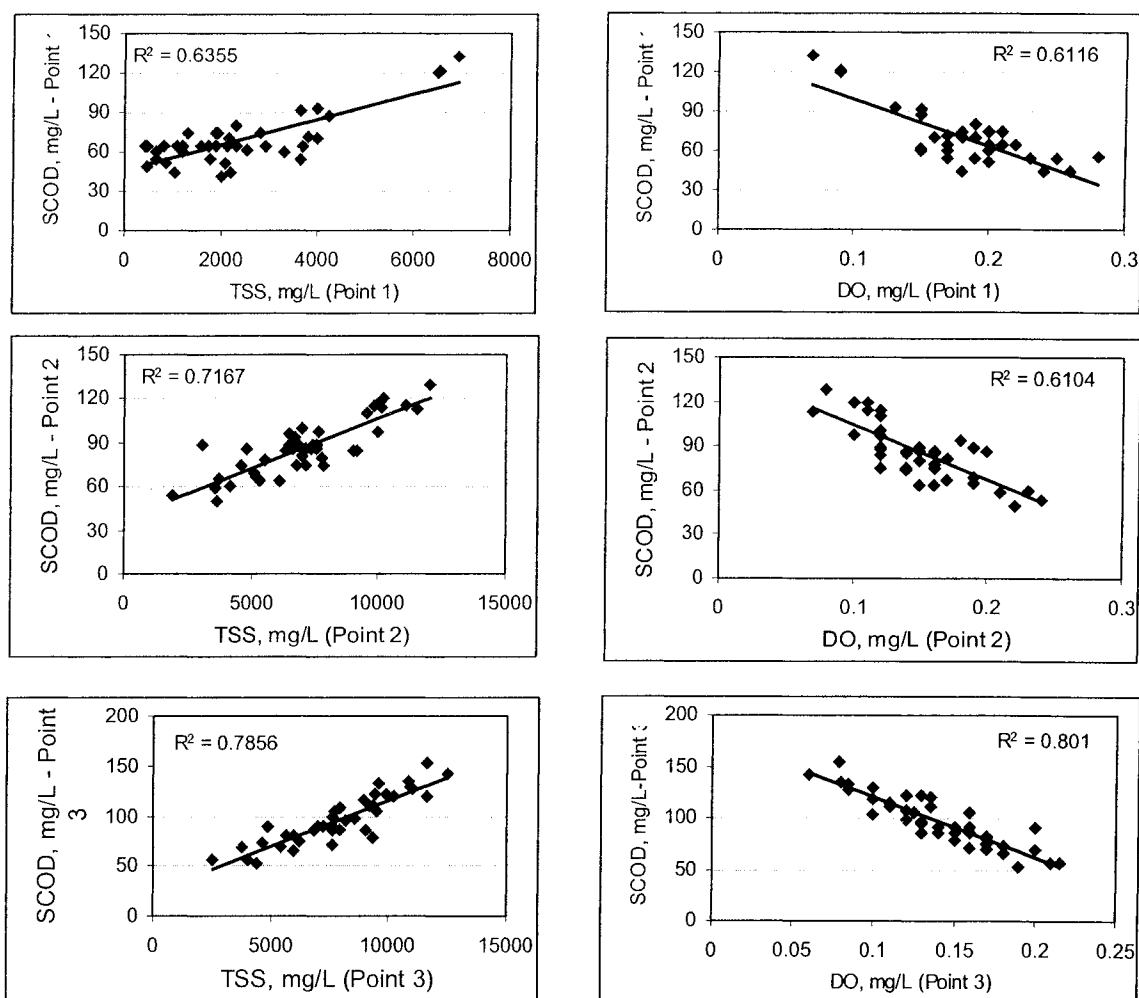


Figure 3-11 Relationship of SCOD with TSS and DO at the Clarifier Bottom of Points 1, 2 and 3, respectively

3.3.7 Temperature

Figures 3-12a and 3-12b display the vertical and the horizontal profiles for temperature in the clarifier. All sampling points measured for the specific sampling dates showed no variation in temperature throughout the clarifier. However, seasonal variation (21.3°C to 28°C from October 2001 to May 2002) was observed. The influence of seasonal temperature variation on nitrate decrease was analyzed. The data was divided

into two categories, moderate temperature (21 to 24°C) and hot temperature (24 to 28°C). The results obtained from linear regression ($R^2=0.19149$ & $R^2 = 0.23$ for moderate and hot temperature, respectively) indicate that temperature had little effect on nitrate decrease within the clarifier (Figures 3-13a & 3-13b). The p-values ($p = 0.1496$, $p = 0.650$, and $p = 0.1478$ for points 1, 2, and 3, respectively) obtained in the first regression analysis also support the above interpretation (Appendix B, Table 1). This interpretation is in agreement with observations made by Dawson & Murphy (1973), Murphy & Sulton (1974), and EPA (1975), that temperature above 20°C has little or no effect on denitrification rates.

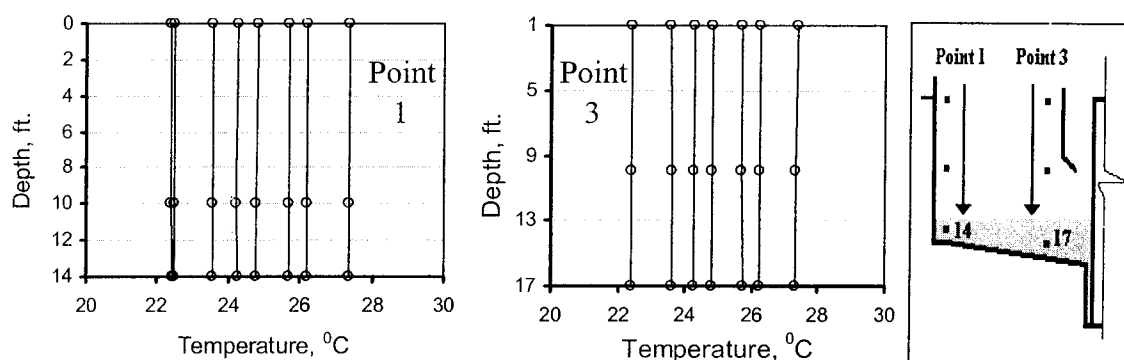


Figure 3-12a Vertical Profile for Temperature in the Secondary Clarifier

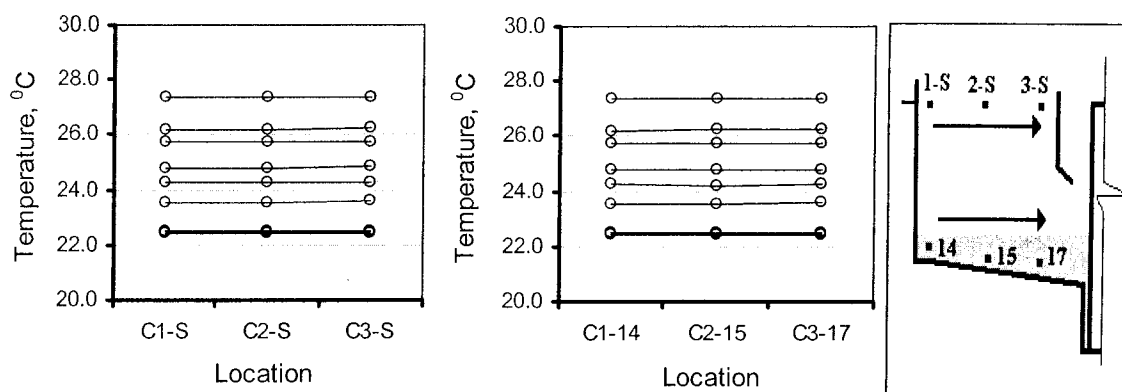
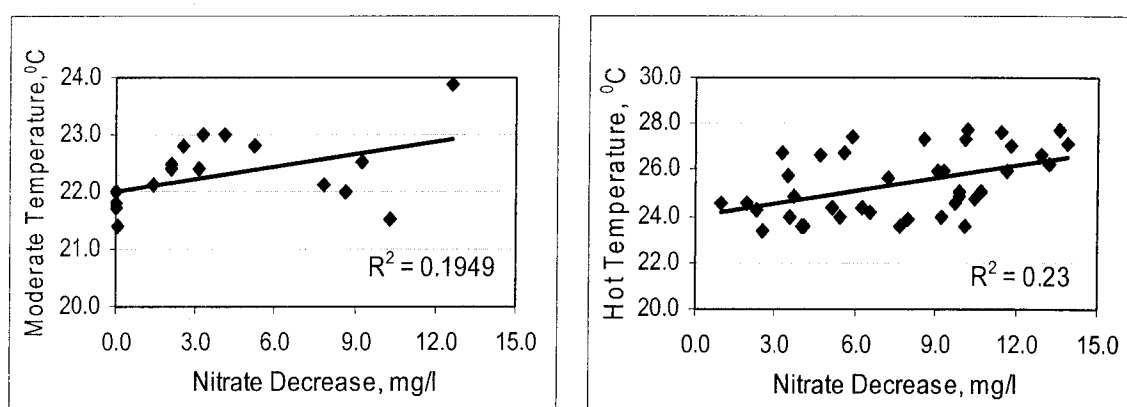


Figure 3-12b Horizontal Profile for Temperature in the Secondary Clarifier



Figures 3-13a and 3-13b Relationship Between Nitrate Decrease and (a) Cold Temperature (b) Hot Temperature in the Secondary Clarifier

3.3.8 Regression Analysis # 2

The objective of regression analysis # 2 was to determine whether there was a relationship between decrease in nitrate concentration and the increase in nitrite concentration and pH values in the clarifier. The results obtained for all three sampling points (1, 2, and 3) showed R^2 values of 0.8914, 0.9143, and 0.939, respectively and P-values all smaller than 0.005 (Appendix B, Table 2). The low p-values obtained from

this simulation for all points strongly suggest that nitrite increase and pH increase within the clarifier are the result of denitrification.

In addition to the second regression analysis, individual profiles of each factors used in this regression were constructed separately to analyze results of denitrification.

3.3.9 Nitrite Profiles

In contrast to nitrate concentrations, nitrite concentrations increased along the vertical axis (0.001 to 10.1 mg/L) from the surface to the bottom of the clarifier (Figure 3-14a). Along the horizontal axis, nitrite concentration did not vary much at the surface, but it varied from 3.68 to 6.86 mg/L at the bottom of the clarifier (Figure 3-14b).

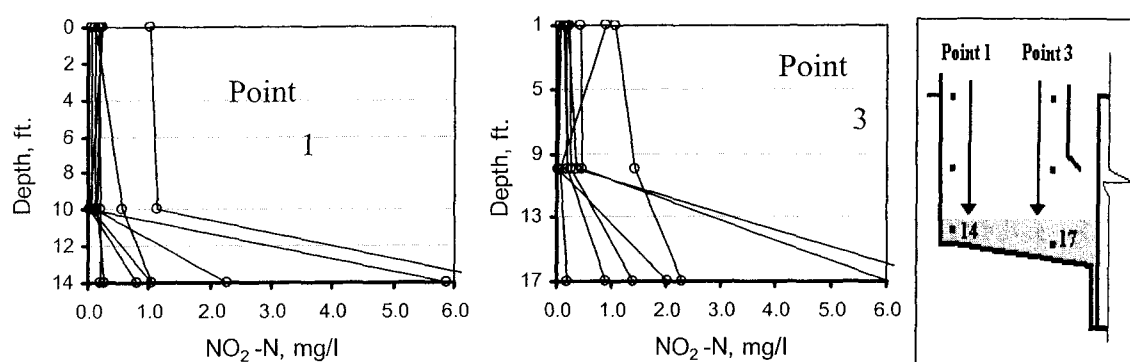


Figure 3-14a Vertical Profile for nitrite Concentration in the Secondary Clarifier

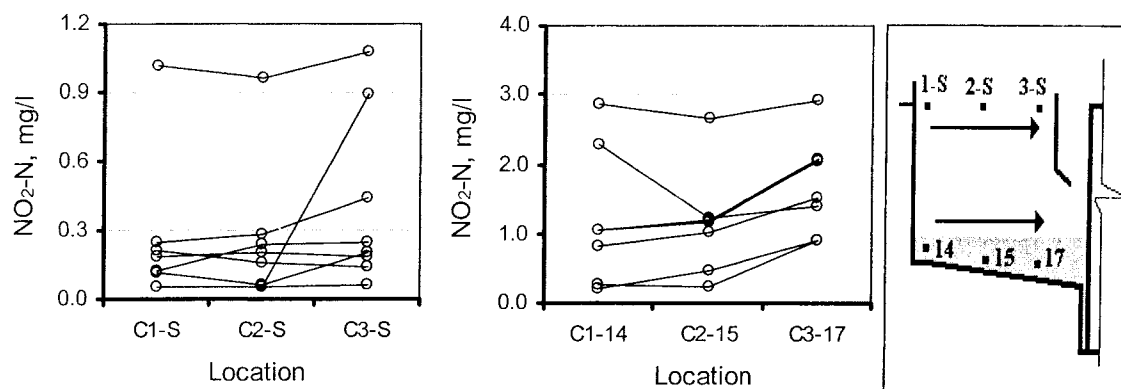


Figure 3-14b Horizontal Profile for nitrite Concentration in the Secondary Clarifier

Linear regression analysis on the nitrite increase along the vertical axis and nitrate decrease along the same axis yielded R^2 values of 0.8221, 0.7516, and 0.6235 along points 1, 2, and 3, respectively (Figure 3-15). Simultaneous nitrate decrease and nitrite increase suggest that denitrification had occurred at the bottom of the clarifier, which is also confirmed by p-values ($p = 0.000$, $p = 0.005$, and $p = 0.002$ for points 1, 2, and 3, respectively) obtained in the second multiple regression analysis (Appendix B, Table 2).

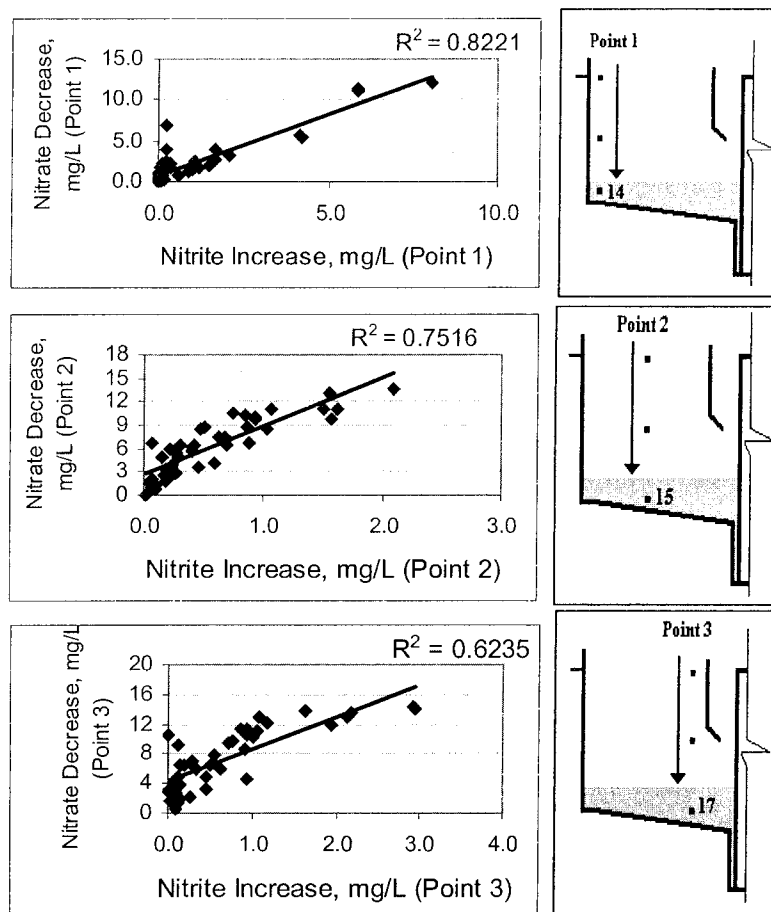


Figure 3-15 Relationship between Nitrate Decrease and Nitrite Increase at all 3 Points

3.3.10 pH Increase

The increase in pH in the clarifier was calculated using RAS and influent pH values. The increase was then related to corresponding decrease in nitrate at the bottom of the clarifier. The relationship obtained between the pH increase and nitrate decrease yielded a strong R^2 value of 0.77, indicating that this increase in pH may be the result of denitrification occurring within the clarifier (Figure 3-16). The p-value ($p = 0.000$, $p = 0.065$, and $p = 0.000$ for points 1, 2, and 3, respectively) obtained in second regression

points to similar conclusions.

In addition, the pH values at the bottom of the clarifier were consistently higher than the influent pH values, indicating denitrification occurred at the bottom of the clarifier. The pH increase at the bottom of the clarifier coupled with corresponding nitrate decrease and low DO concentrations, indicate denitrification is occurring within the CCSD clarifier.

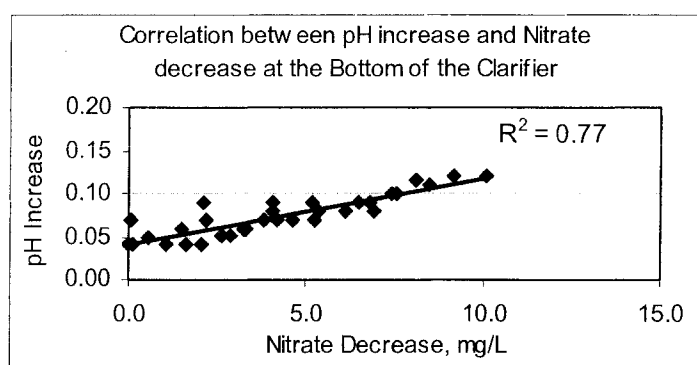


Figure 3-16 Relationship Between pH Increase and Nitrate Decrease at the Bottom of the Clarifier

3.3.11 Regression Analysis # 3

The third regression analysis, using OP concentration as the response variable and the other measurements as influencing parameters (DO, SCOD, pH, temperature, and ORP), for all three vertical sampling points (1, 2, & 3), yielded R^2 values of 0.796, 0.823, and 0.833, respectively (Appendix B, Table 3). The p-values obtained from this simulation for points 1, 2 and 3, p-values indicate that the nitrate decrease was strongly influenced by SCOD ($p = 0.005$, $p = 0.005$ and $p = 0.001$, respectively) concentrations,

and DO ($p = 0.009$ and $p = 0.004$, and $p = 0.002$ respectively). SS concentrations ($p = 0.651$, $p = 0.183$, and $p = 0.226$, respectively), pH ($p = 0.475$, $p = 0.569$ and $p = 0.227$, respectively), temperature ($p = 0.868$, $p = 0.515$ and $p = 0.393$, respectively), and ORP ($p = 0.333$, $p = 0.599$ and $p = 0.759$, respectively) had little or no effect on OP concentration increase. The p -values for DO concentration and SCOD concentration had, nearly the same values for all three points.

In addition to multiple regression analysis, vertical and horizontal profiles of total-P and ortho-P were constructed to analyze trends within the clarifier.

3.3.12 Total Phosphate (TP) and Ortho-Phosphate (OP) Profiles

Total phosphate (TP) concentration profile along the vertical and the horizontal sampling points are shown in Figures 3-17a and 3-17b, respectively. As expected, there is a significant increase in TP concentration (from 0.1 to 145.8 mg/L) along the vertical profile from the surface to the bottom of the clarifier. This increase is the result of high SS concentration at the bottom of the clarifier. TP concentration along the horizontal profile did not vary much at the clarifier surface, but it did vary (22.5 to 145.8 mg/L) at the bottom of the clarifier depending on SS concentration. Most of the time, TP concentrations in the clarifier effluent were below the CCSD NPDES requirement (0.27 mg/L), except for a few sampling dates.

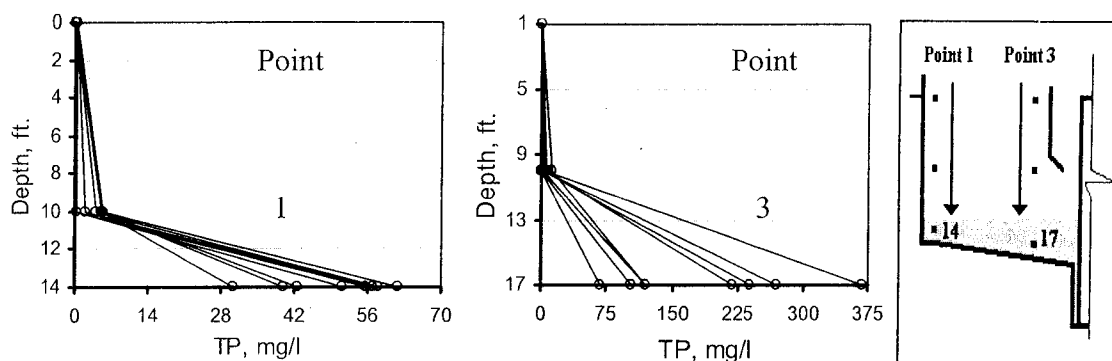


Figure 3-17a Vertical Profile for TP in the Secondary Clarifier

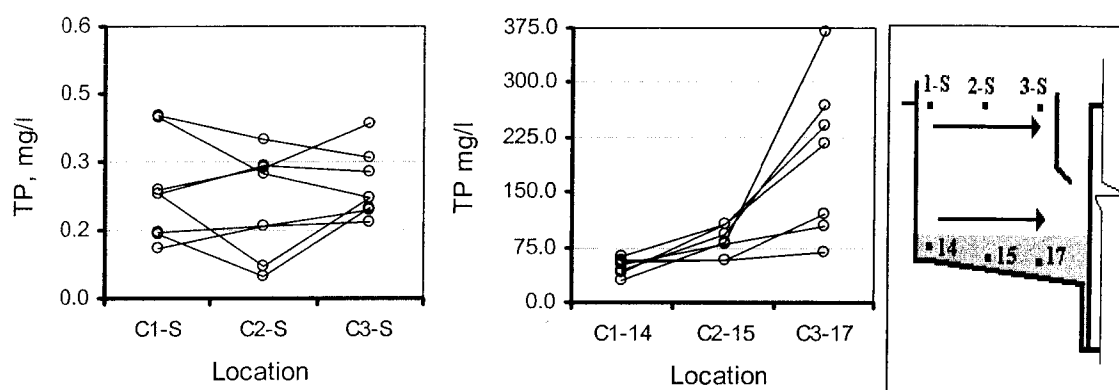


Figure 3-17b Horizontal Profile for TP in the Secondary Clarifier

The vertical and the horizontal profiles for ortho-phosphate (OP) concentrations are shown in Figures 3-18a and 3-18b, respectively. OP concentrations along the vertical profile varied from 0.01 to 5.43mg/L. Along the horizontal profile, OP concentration varied from 1.09 to 5.43 mg/L. Thus, there is a significant increase in OP concentration along the vertical profile, while there is slight variation along the horizontal profile. OP shows a similar trend of TP along the vertical profile, i.e. increase in OP concentration from the surface to the bottom of the clarifier. This increase in OP concentration at the

bottom of the clarifier suggests that there is OP release taking place at the bottom. Low DO (Figure 3-3a) and availability of SCOD at the bottom (Figure 3-9a) favor secondary P-release in the clarifier.

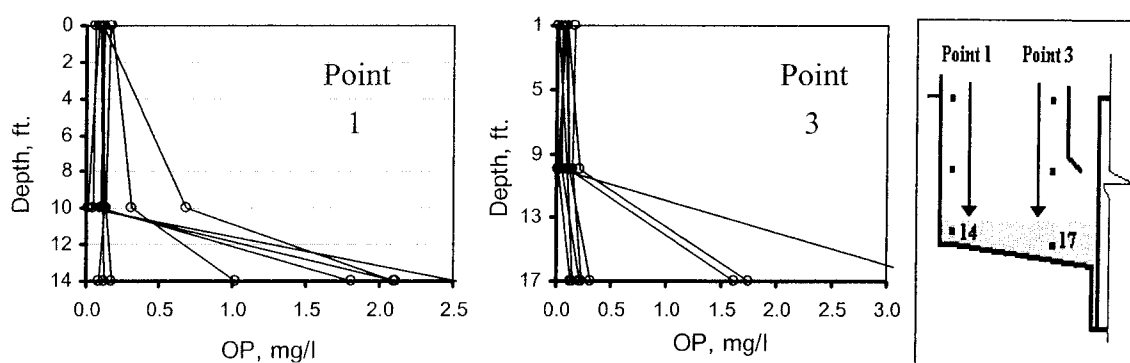


Figure 3-18a Vertical Profile for OP in the Secondary Clarifier

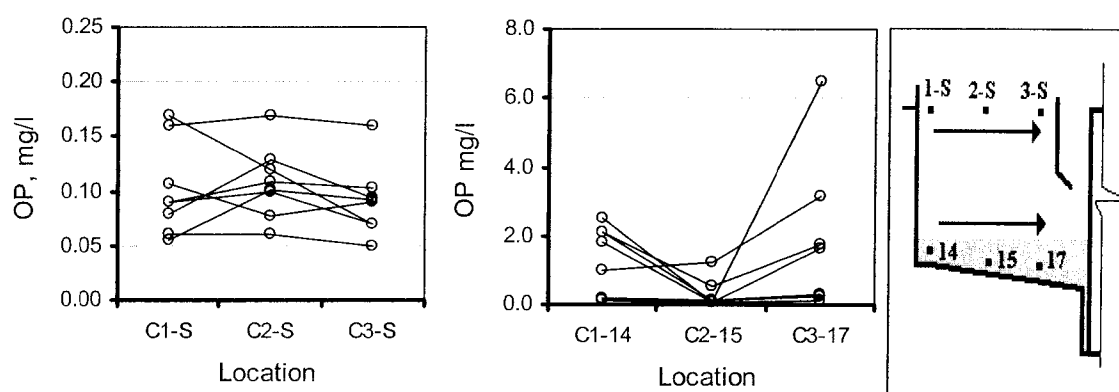


Figure 3-18b Horizontal Profile for OP in the Secondary Clarifier

3.4 Conclusions

The results obtained from statistical analysis and from individual profiles show that denitrification as well as phosphorus release had occurred within the CCSD clarifier.

Statistically significant evidence was found that both denitrification and p-release are strongly influenced by low DO and soluble COD levels within the clarifier.

The low DO levels found at the studied clarifier are within the reported DO range needed to promote denitrification. The soluble COD in the clarifier was found to increase along the vertical axis with higher values found in the bottom of the clarifier where the SS concentrations are higher. For all sampling points suspended solids concentrations were found to correlate well with soluble COD concentrations. Thus, fermentation and solids lysis under low DO conditions generated the needed soluble COD that support both denitrification and P-release; Both phenomena require low DO environment and a carbon source (e.g. soluble COD) to occur.

For all points sampled, pH, temperature, and ORP were found to have of very little effect on denitrification and P-release. Strong evidence was found that the observed reduction in nitrate levels correlates very well with the increase in pH and nitrite concentration.

CHAPTER 4

MASS BALANCE EVALUATIONS OF DENITRIFICATION, P-RELEASE, AND ALKALINITY RECOVERY IN THE CCSD TREATMENT PLANT

4.1 Introduction

In biological nutrient removal (BNR) systems designed for nitrification but not for denitrification the returned activated sludge (RAS) contains high levels of nitrate, which may adversely impact phosphorus removal, when added directly to the anaerobic tank (Rittmann, 2001). This adverse effect occurs because denitrifying bacteria compete with the phosphate accumulating organisms (PAOs) for the volatile fatty acids (VFAs), which PAOs use to form polyhydroxyalkanoates (PHAs) (Ghekiere et al., 1991). In addition, a continuous supply of high nitrate concentration to the anaerobic tank modifies the entire microbial population, decreasing the P-removal efficiency of the system (Hascoet & Florentz, 1985). Hence, control of nitrate level entering the anaerobic tank is a key consideration in the design of BNR processes.

Although, the major objective of clarification is to separate solids from liquid, nitrate in the RAS can be controlled or minimized by allowing the sludge to denitrify under endogenous conditions in the secondary clarifier (Ekama et al., 1997). However, such a practice is detrimental to the biological P-removal. Strong denitrification in the

clarifier is detrimental to the plant's efficiency to remove phosphorus. Nitrogen bubbles formed during strong denitrification will raise the sludge to the surface of the clarifier (Henze et al., 1993). This results in increased suspended solids concentration containing polyphosphate and consequent higher total phosphorus concentration in the clarifier effluent affecting the overall plant's efficiency to remove phosphorus (Siegrist & Guger, 1994; Ekama et al., 1997; Alexis et al., 1999; Parker et al., 2000). On the other hand, strong denitrification will positively contribute to increasing the alkalinity of the wastewater (e.g. pH), lowered during nitrification.

Conversely, weak or absence of denitrification could result in high concentrations of nitrates in the RAS, negatively affecting P-release in the anaerobic zone of the Bio-P process (Choi et al., 1998). Moderate denitrification within the clarifier, however, may overcome both problems, created by strong and weak denitrification. Unlike strong denitrification, it may not significantly inhibit P-release by PAOs in the anaerobic stage. Opposite to weak denitrification, moderate denitrification in the clarifier partially recovers alkalinity and oxygen utilized in nitrification (Nicholas et al., 1996; Ekama et al., 1997; Ying-Feng et al., 2001).

Denitrification in the clarifier can be influenced by various parameters, including substrate concentration (e.g. soluble COD), influent nitrate concentration, temperature, dissolved oxygen concentration (DO), oxidation-reduction potential (ORP), and pH. The availability of readily biodegradable organics and the decay of active biomass (e.g. endogenous respiration) supply the energy source for denitrification and P-release in the secondary clarifier (Siegrist et al., 1995; Ekama et al., 1997). Another parameter that influences denitrification is temperature.

Denitrification can occur at low rates with temperature as low as 5⁰C. EPA (1973), Dawson and Murphy (1973), Murphy & Sutton (1974), and Sorensen & Jorgensen (1993) found that denitrification rates are constant above 20⁰C temperature. However, Henze et al. (1993) observed that temperature above 20⁰C in the sludge blanket encourages faster denitrification, causing sludge flotation.

Low DO concentration (below 0.2 mg/L) in the secondary clarifier can encourage denitrification (Marais & Ekama. 1976; Pochanu & Keller. 1999) and P-release (Randall et al., 1992), since anaerobiosis promotes both denitrification and phosphorus release. To prevent phosphorus release and denitrification in the secondary clarifier, enough DO should be present in the aeration basin effluent (Randall et al., 1992). In contrast, Rittmann & Langeland (1985) reported that denitrification occurring at high DO concentrations of 0.3 to 0.8 mg/L, 0.5 mg/L, and 0.3 to 1.5 mg/L in channel oxidation ditch, activated sludge and semi batch activated sludge, respectively. Low ORP values may also influence denitrification and P-release because they suggest anaerobic conditions, which are indicative of reducing environment in which fermentation, may occur. However, there has been disagreement as to whether phosphorus release is caused either directly by low DO concentrations or by lowered ORP at zero DO (Schon et al., 1993).

Another parameter that influences denitrification is pH. Denitrification rate is not influenced by pH values within the range of 6 to 8; however, any pH values below 6 and above 8 can inhibit denitrification (Nicholas, 1996). Dawson and Murphy (1972) found an optimal denitrification rate at a pH of 7.0, while denitrification rate was half at pH values 6.0 and 8.0. In addition, they also found that there was a linear decrease in

denitrification rate from pH 8.0 to 9.5 and from 7.0 to 4.0. Nommik (1956) and Bremner & Shaw (1958) noted that neutral to alkaline pH values (7.0 to 8.0) conditions favored denitrification.

Denitrification and P-release occur at the same time within the clarifier because both processes require anaerobic conditions and the presence of sufficient VFAs (Osborn & Nicholls, 1984; and Iwema & Meunier, 1985). Therefore, parameters that influence denitrification in the clarifier may have influence on P-release.

The primary objective of this study was to examine parameters affecting the denitrification rate and P-release within the clarifier in a full-scale treatment plant that was not designed for denitrification by using the mass balance approach.

4.2 Materials and Methods

Materials and methods used in this chapter are the same as those described in Chapter 3. In addition, mass balances were performed on the clarifier to calculate denitrification, P-release, and alkalinity recovered within the clarifier. In this chapter all data collected was used to built relationships between several measured and calculated parameters.

4.2.1 Mass Balance Calculations

a) Nitrate Removal and P-Release

To calculate denitrification (nitrate removal) and P-release in the secondary clarifier, a mass balance was performed for nitrate and for phosphorus around the secondary clarifier, using three large and distinct data sets (data set 1 collected from Oct-2001 to May-2002, data set 2 collected from Sep-1999 to April-2001 (Mota, 2001), and

data set 3 collected from Oct-1999 to April-2002 by CCSD lab). These data sets were used to determine whether the observations reposted in chapter 3 regarding clarifier denitrification could also be confirmed in past data from the plant. Figure 4-1 shows a schematic of the mass balance approach used to evaluate nitrate removal and P-release within the secondary clarifier of basin # 4 at the CCSD plant.

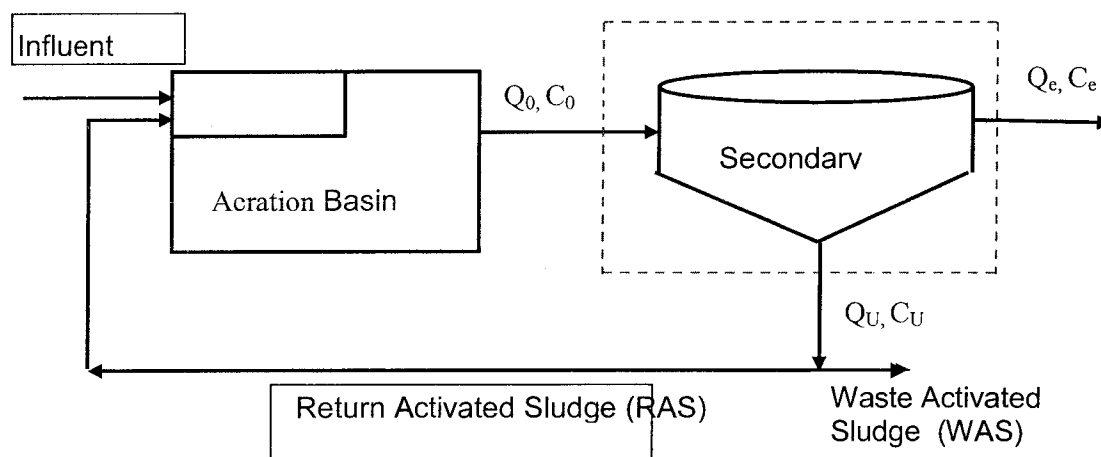


Figure 4-1 Schematic Layout of Typical BNR process

Where:

C_0 = Influent concentration of nitrate/phosphorus to clarifier, mg/L

Q_0 = Inflow to secondary clarifier, MGD

C_e = Effluent nitrate/phosphorus concentration, mg/L

Q_e = Clarifier outflow from secondary clarifier, MGD

C_U = Clarifier underflow nitrate/phosphorus concentration in the clarifier, mg/L

Q_U = Clarifier underflow (RAS flow (Q_{RAS}) + Sludge wasted (Q_{WAS})), MGD

Denitrification and P-release calculated are expressed in kg of nitrate removed and phosphorus release per day (kg/d).

$$\text{Nitrate removal, kg/d} = (C_0 * Q_0 - (C_e * Q_e + C_U * Q_U))$$

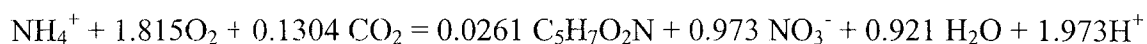
$$\text{P-release, kg/d} = ((C_e * Q_e + C_U * Q_U) - C_0 * Q_0)$$

The calculated denitrification and P-release rates for all three data sets are presented in Appendix C (Table 1, 2, & 3 for data sets 1, 2 & 3, respectively) and Appendix D (Table 1 & 2 for data sets 1& 2, respectively), respectively.

b) Alkalinity Recovered in Secondary Clarifier (mg/L)

To calculate the concentration of alkalinity recovered by denitrification in the clarifier, a mass balance of alkalinity was performed for all three data sets. The results obtained from this mass balance are shown in Appendix E. The concentration of alkalinity recovered in the clarifier is an important parameter to the operating of BNR systems because it returns alkalinity back to effluent water- alkalinity is lost during the nitrification process.

Alkalinity data for sets 1 and 3 were not available. The theoretical alkalinity lost to the liquid during nitrification can be calculated by the following equation (Rittmann, 2001):



The above equation shows that for each mole of ammonia oxidized, 1.973 moles of hydrogen are formed, resulting in lower pH.

4.3 Results and Discussion

Calculated denitrification and P-release within the clarifier were related to various parameters measured to determine the influence of each parameter on denitrification and P-release.

4.3.1 Relationship between Denitrification and P-release in the Clarifier

To evaluate the relationship between denitrification and P-release within the secondary clarifier, both denitrification and P-release were plotted by sampling date sequence (Figure 4-2a). Linear regression analysis of denitrification and P-release on yielded a R^2 value of 0.6156, indicating fair correlation (Figure 4-2b). Denitrification and P-release follow similar trends. As denitrification increased, P-release also increased. The results obtained indicate that high P-release was observed along the strong denitrification within the secondary clarifier. This observation was also confirmed by the relationship obtained from the data sets 2 (Figures 4-2c & 4-2d). Therefore, the data recently collected and past data from the CCSD plant point to P-release and denitrification in the clarifiers.

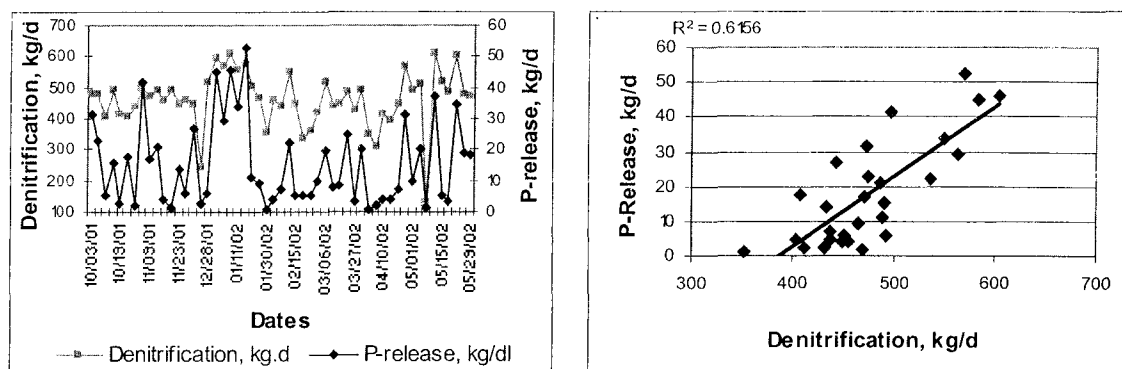


Figure 4-2a and 4-2b Correlation between Denitrification and P-release in clarifier using data set 1

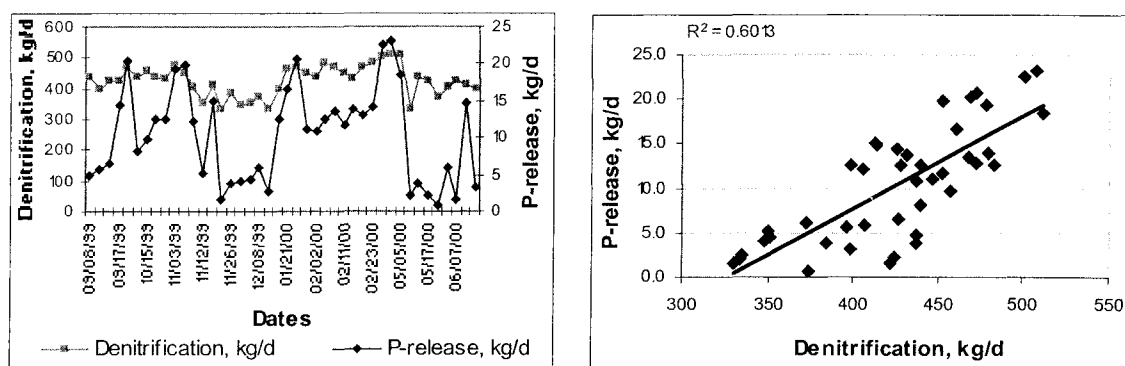


Figure 4-2c and 4-2d Correlation between Denitrification and P-release in clarifier using data set 2

4.3.2 Relationship between Denitrification and Effluent Suspended Solids (ESS)

Figures 4-3a to 4-3f characterizes the relationship between denitrification and ESS within the secondary clarifier for all three data sets; both denitrification and ESS were plotted by sampling date sequence. Linear regression analysis on denitrification and ESS yielded R^2 values varying from 0.6329 to 0.717, indicating fair correlation (Figure 4-3b). Denitrification and ESS follow similar trends. As denitrification increased, TSS in the clarifier effluent increased. High ESS concentrations in the secondary clarifier

effluent were observed during the period of strong denitrification. This observation suggests that increase in ESS concentrations is closely related to strong denitrification. Visual observations in several of the CCSD clarifiers indicate the presence of nitrogen bubbles resulting from denitrification. These bubbles serve as the carrier of solids to the clarifier effluent.

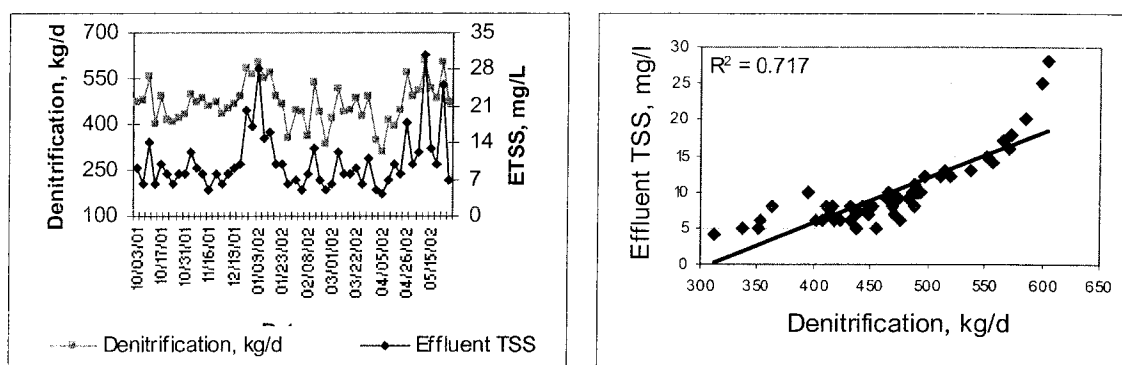


Figure 4-3a and 4-3b Correlation between Denitrification and Effluent Suspended Solids (ESS) in clarifier using data set 1

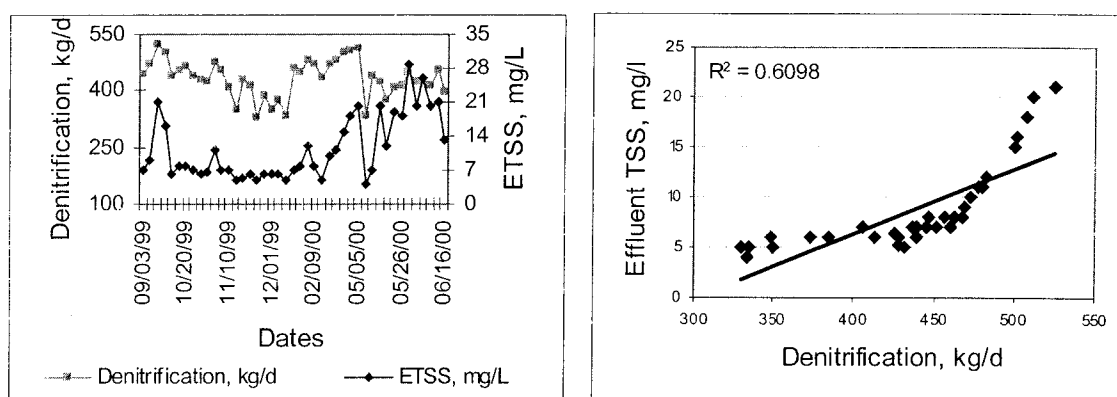


Figure 4-3c and 34-3d Correlation between Denitrification and Effluent Suspended Solids (ESS) in clarifier using data set 2

4.3.3 Relationship between Effluent Suspended Solids (ESS) and Effluent Total-P (ETP)

The relationship between ESS and ETP within the secondary clarifier for all three data sets was evaluated, plotting both ESS and ETP by sampling date sequence (Figure 4-4a to 4-4f). Both ESS and ETP show similar trends, ETP increases with the increase in ESS. Figure 4-4b indicates that there is good relationship between ESS and ETP (R^2 value of 0.8248). It was observed that high ESS resulted in high, effluent total-P concentrations within the secondary clarifier. This is expected, since biomass in the secondary clarifier contains polyphosphates (PP) taken up in the aeration basin. Therefore, an increase in the TSS in effluent means an increase in effluent total-P which indeed affects the plants efficiency to remove phosphorus.

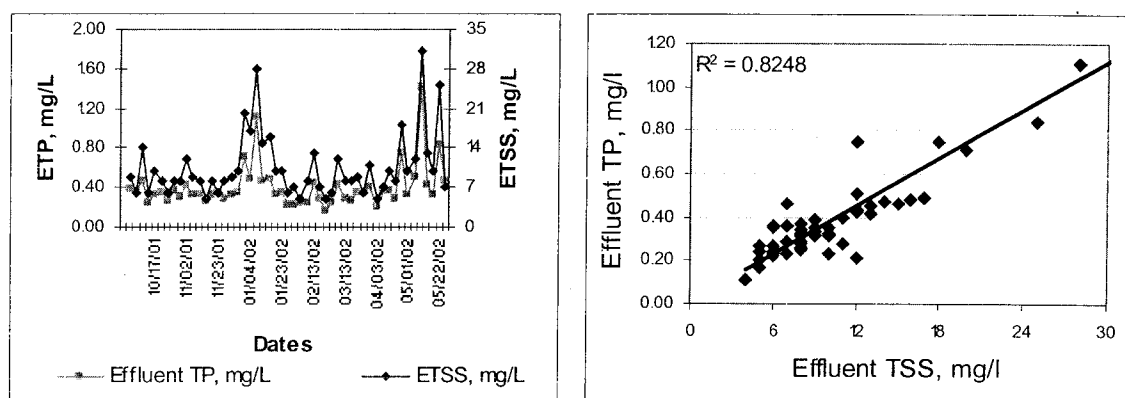


Figure 4-4a and 4-4b Correlation between Effluent Suspended Solids (ESS) and Effluent Total-P (ETP) in clarifier using data set 2

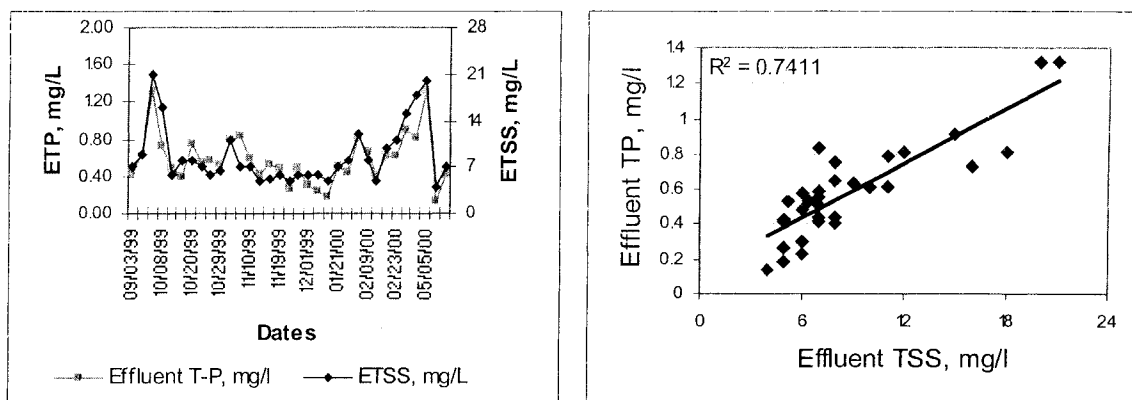


Figure 4-4c and 4-4d Correlation between Effluent Suspended Solids (ESS) and Effluent Total-P (ETP) in clarifier using data set 2

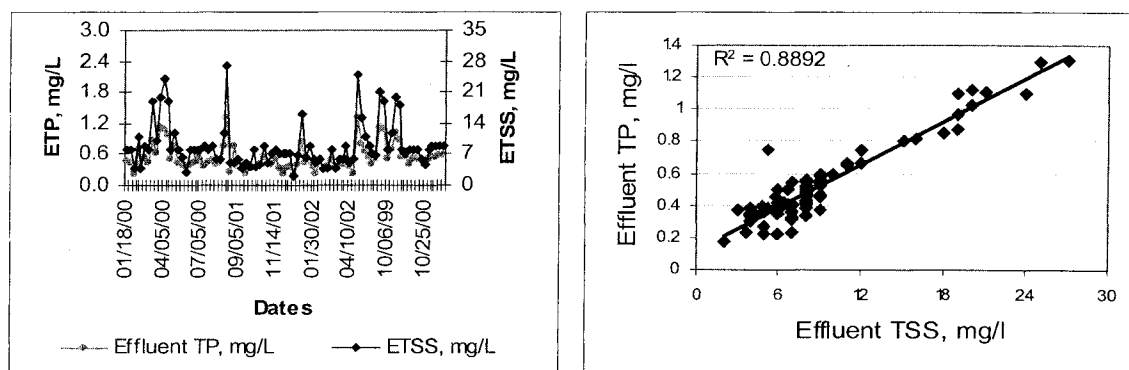


Figure 4-4e and 4-4f Correlation between Effluent Suspended Solids (ESS) and Effluent Total-P (ETP) in clarifier using data set 3

The phosphorus content of the solids at CCSD, on a dry weight basis, was calculated for the samples collected during the research period. It was found that the P content of the CCSD solids varied from 1.5 to 4.5% P (averaging 2.69%) (Figure 4-4g). One can estimate from these data, the potential increase in effluent phosphate concentration as a function of solids effluent concentrations. This relationship is shown in Figure 4-4g.

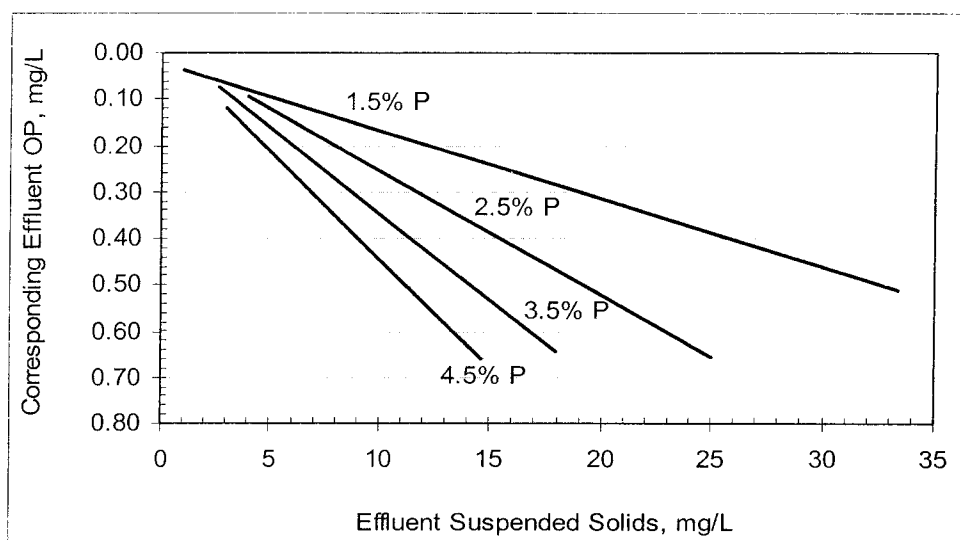


Figure 4-4g Theoretical ESS and its Corresponding ETP for various P-Content in the CCSD solids

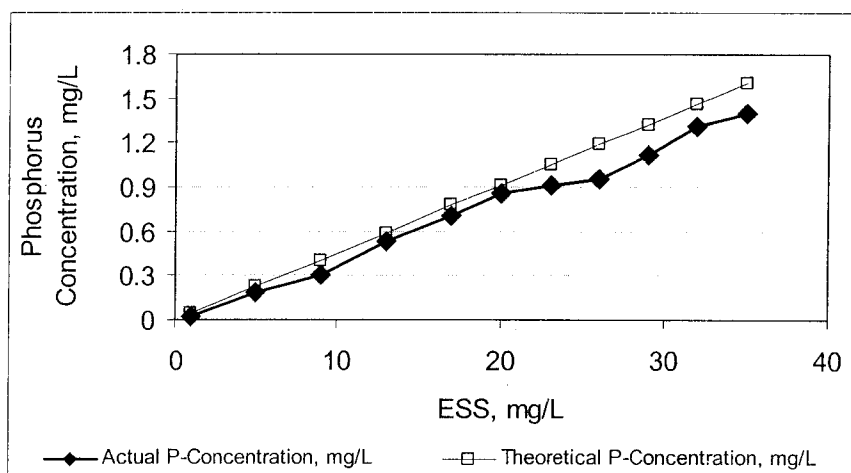


Figure 4-4h Comparison of Actual and Theoretical TP-Concentration for CCSD

For example, for effluent solids, a sludge containing 4.5% P would result in an increase in total phosphorus of 0.2 mg/L in the clarifier effluent.

When comparing the actual total P concentrations measured as a function of measured ESS, with the estimated total-P concentrations from Figure 4-4h. The difference between them can be accounted for by the OP concentrations in the effluent.

4.3.4 Relationship between Denitrification and Effluent Total-P (ETP)

For all three data sets, denitrification was plotted against ETP by sampling date sequence (Figure 4-5a to 4-5f) to evaluate the influence of denitrification on ETP. Linear regression analysis on denitrification and ETP showed moderate relationship between them yielding R^2 values of 0.6007 to 0.703. ETP increased with increase in denitrification, showing similar trends. The observation shows that strong denitrification resulted in high TP in the clarifier effluent for all three data sets.

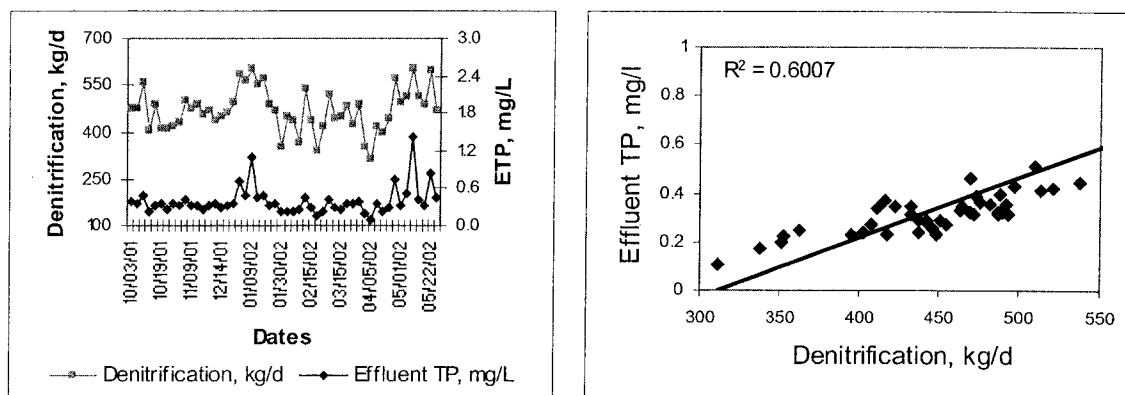


Figure 4-5a and 4-5b Correlation between Denitrification and Effluent Total-P (ETP) in clarifier using data set 1

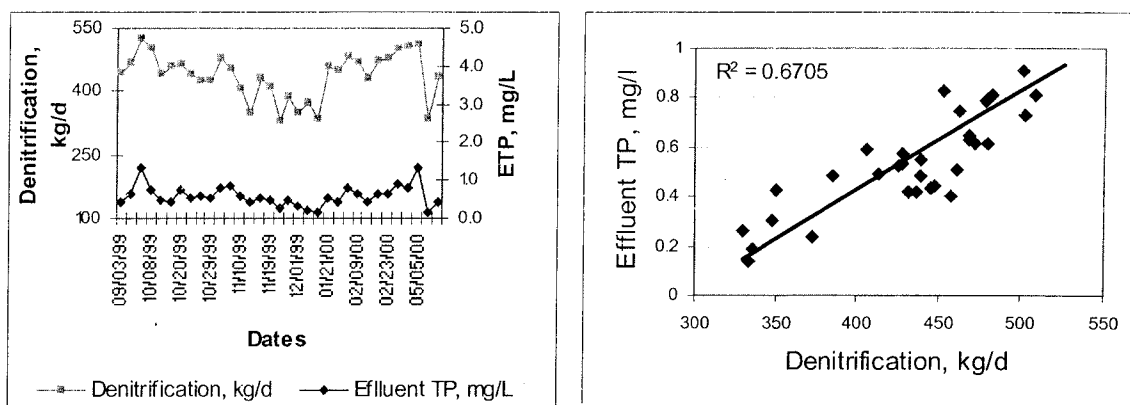


Figure 4-5c and 4-5d Correlation between Denitrification and Effluent Total-P (ETP) in clarifier using data set 2

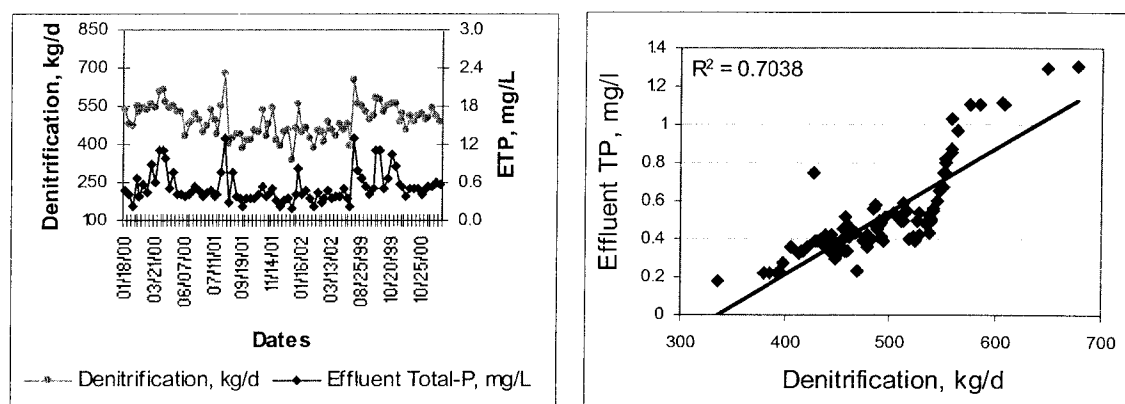


Figure 4-5a and 4-5b Correlation between Denitrification and ETP for data set 3

4.3.5 Relationship between Denitrification and Effluent Ortho-P (EOP)

To determine the relationship between denitrification and EOP within the secondary clarifier, both denitrification and EOP were plotted by sampling date sequence (Figure 4-6a to 4-6f) for all three data sets. Linear regression analysis on denitrification and EOP yielded R^2 values from 0.0813 to 0.3165, indicating a weak relationship between them. No variation in OP concentration was observed with varying denitrification levels.

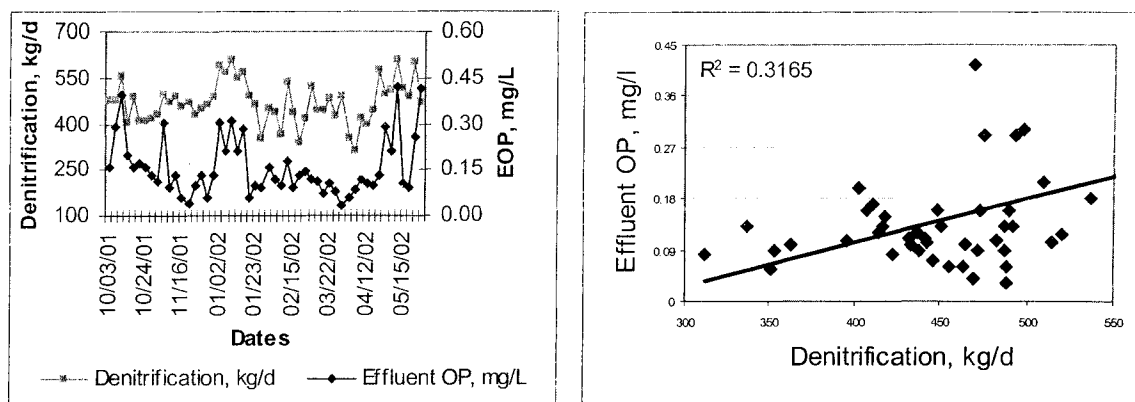


Figure 4-6a and 4-6b Correlation between Denitrification and Effluent Ortho-P (EOP) in clarifier using data set 1

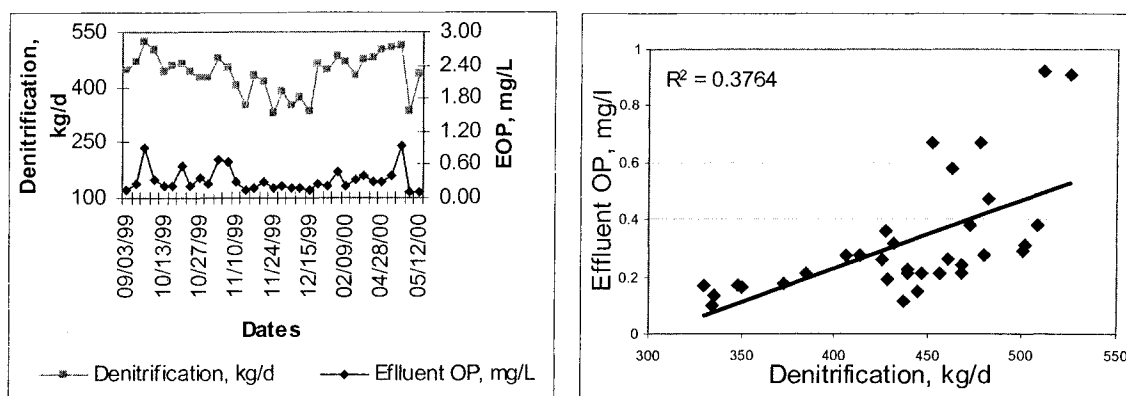


Figure 4-6e and 4-6f Correlation between Denitrification and Effluent Ortho-P (EOP) in clarifier using data set 2

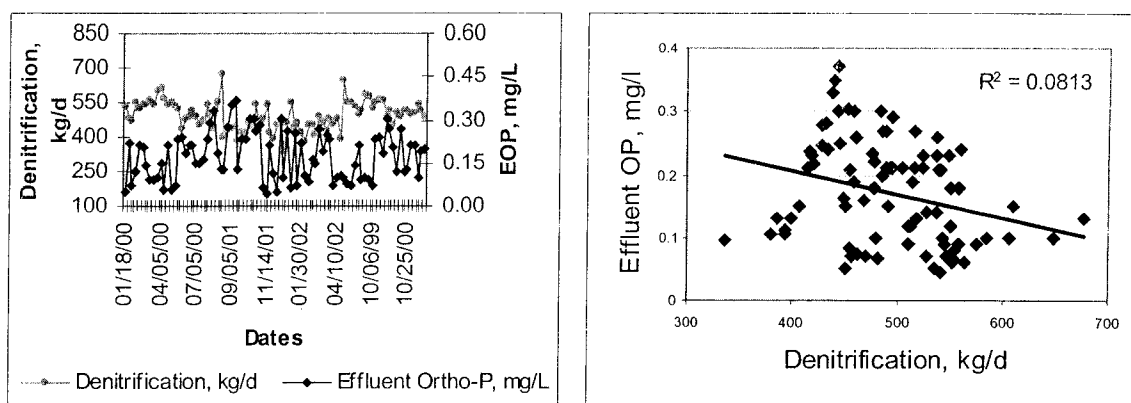


Figure 4-6e and 4-6f Correlation between Denitrification and Effluent Ortho-P (EOP) in clarifier using data set 3

4.3.6 Relationship between Denitrification and Dissolved Oxygen (DO) in the Sludge

To determine the effect of DO on the denitrification rates within the clarifier, both denitrification and DO were plotted by sampling date sequence (Figure 4-7a and 4-7b). Strong denitrification was observed with low DO concentration in the sludge. Linear regression analysis on denitrification and DO yielded a R^2 value of 0.6174, indicating fair correlation. Denitrification and DO followed a reverse trend, which was expected, since low DO values promote strong denitrification. The relationship clearly shows that low DO concentration has influenced denitrification rates within the secondary clarifier.

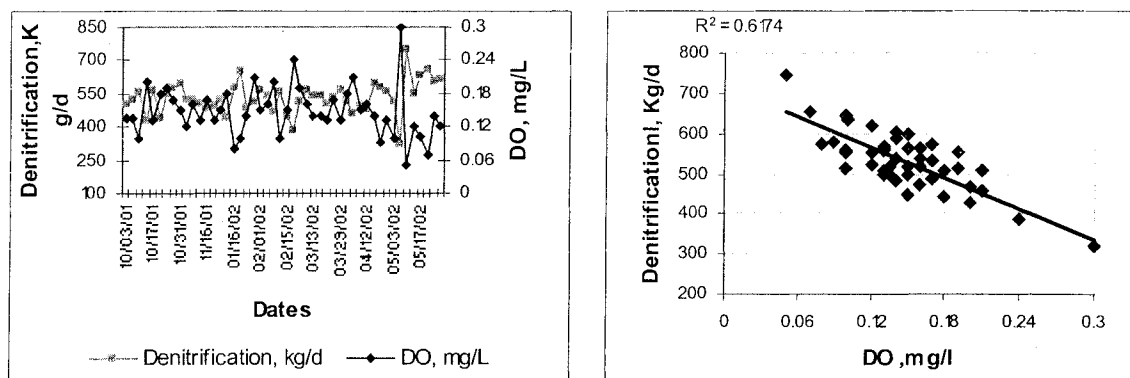


Figure 4-7a and 4-7b Correlation between Denitrification and Dissolved Oxygen (DO) in clarifier using data set 1

4.3.7 Relationship between Denitrification and Oxidation Reduction Potential (ORP) in sludge

To determine the influence of ORP on denitrification, both denitrification and ORP was plotted by sampling date sequence (Figure 4-8a) to determine the possibility of using ORP to control denitrification in the secondary clarifier. Although, denitrification and ORP seem to follow a reverse trend, their linear regression analysis yielded a poor R^2 value of 0.2708, suggesting weak relationship between them (Figure 4-8b).

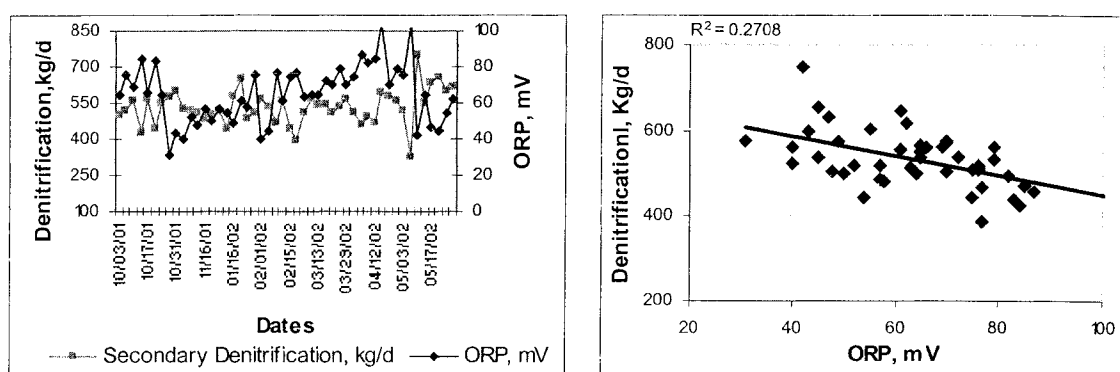


Figure 4-8a and 4-8b Correlation between Denitrification and Oxidation Reduction Potential (ORP) in clarifier using data set 1

4.3.8 Relationship between Denitrification and pH

The relationship between denitrification and pH increase in RAS were plotted by sampling date sequence (Figure 4-9a), since pH increase is the indicator of denitrification occurring within the clarifier. Linear regression analysis on denitrification and pH increase in the sludge yielded a R^2 value of 0.7256 indicating good correlation (Figure 4-9b). Denitrification and pH increase in the sludge seems to follow similar trends: where denitrification in the clarifier was strong, pH increase was high.

pH in influent to the clarifier was always lower than at the bottom of the clarifier, suggesting denitrification was occurring (Figure 4-9c). Whenever there was strong denitrification, pH values at the bottom were much higher than in the influent pH.

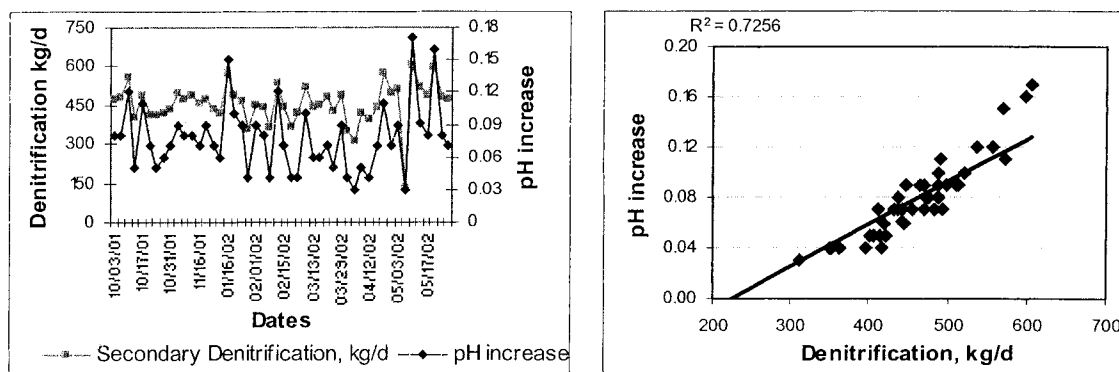


Figure 4-9a and 4-9 b Correlation between Denitrification and pH in clarifier using data set 1

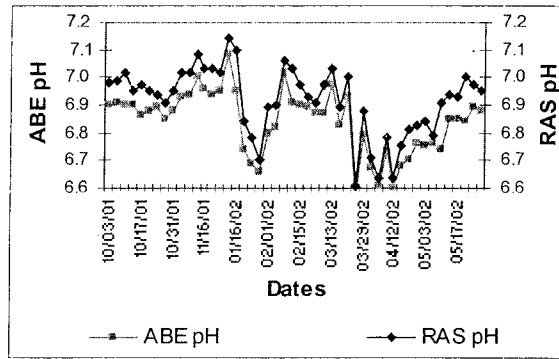


Figure 4-9c Correlation between Clarifier Influent pH and pH in the Sludge using data set 1

4.3.9 Relationship between Denitrification and Concentration of Alkalinity Recovered

To determine alkalinity recovery from denitrification at CCSD, both denitrification and concentration of alkalinity recovered were plotted by sampling date sequence (Figure 4-10a). Linear regression analysis on denitrification and concentration of alkalinity recover yielded a R^2 value of 0.7646, indicating good correlation (Figure 4-10b). Denitrification and concentration of alkalinity recovered followed a similar trend. This was expected, since it is known that denitrification produces alkalinity. It was observed that high denitrification resulted in a high RAS alkalinity concentration within the secondary clarifier. This observation was also confirmed by the other two data sets 2 and 3 (Figures 4-10c, d, e, & f).

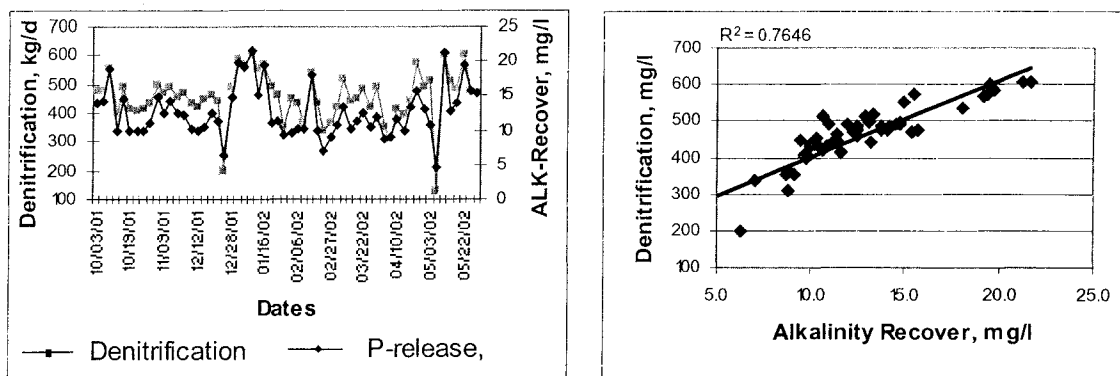


Figure 4-10a and 4-10b Correlation between Denitrification and Concentration of Alkalinity Recovered in clarifier using data set 1

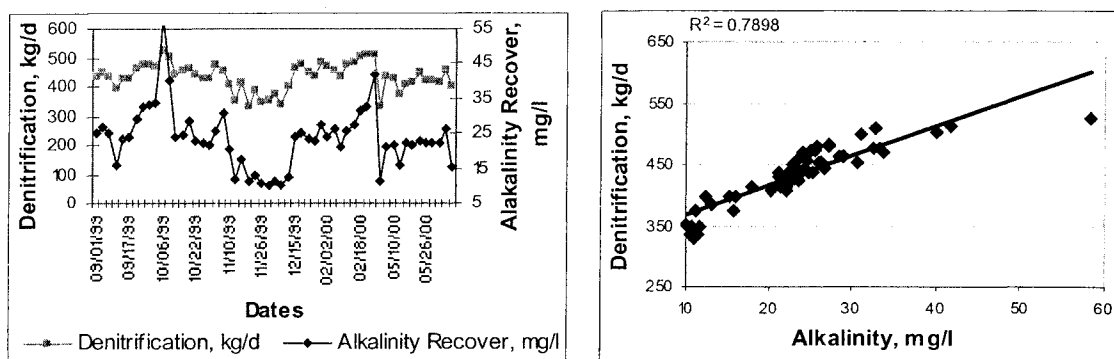


Figure 4-10c and 4-10d Correlation between Denitrification and Concentration of Alkalinity Recovered in clarifier using data set 2

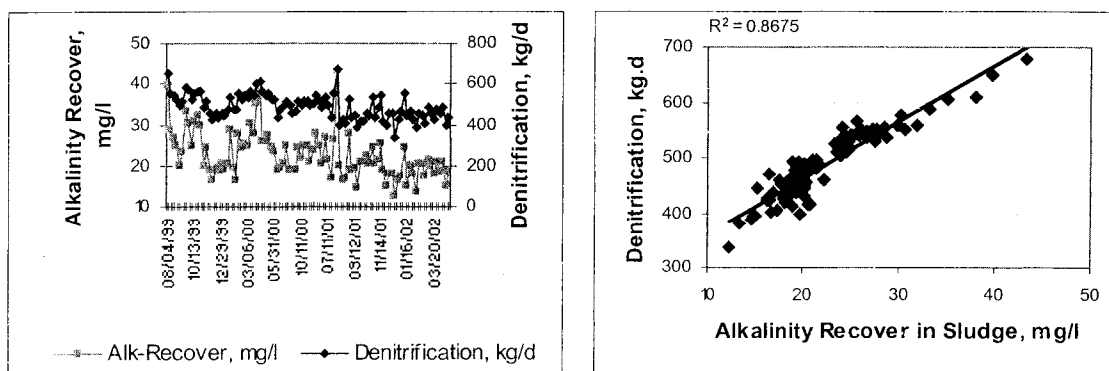


Figure 4-10e and 4-10f Correlation between Denitrification and Concentration of Alkalinity Recovered in clarifier using data set 3

4.3.10 Relationship between RAS Ortho-P and Effluent Ortho-P

To investigate whether the P-released at the bottom of the clarifier contributes to higher OP levels in the clarifier effluent, both, RAS OP and EOP were plotted by sampling date sequence (Figure 4-11a). Linear regression analysis on RAS Ortho-P and Effluent Ortho-P yielded a R^2 value of 0.441, indicating moderate to weak correlation (Figure 4-11b). RAS OP and EOP seem to follow more or less similar trends. It was observed that effluent OP increased with lower rate as OP in the RAS increased. This observation was also confirmed by the relationship obtained from data set 2 (Figures 4-11c & d).

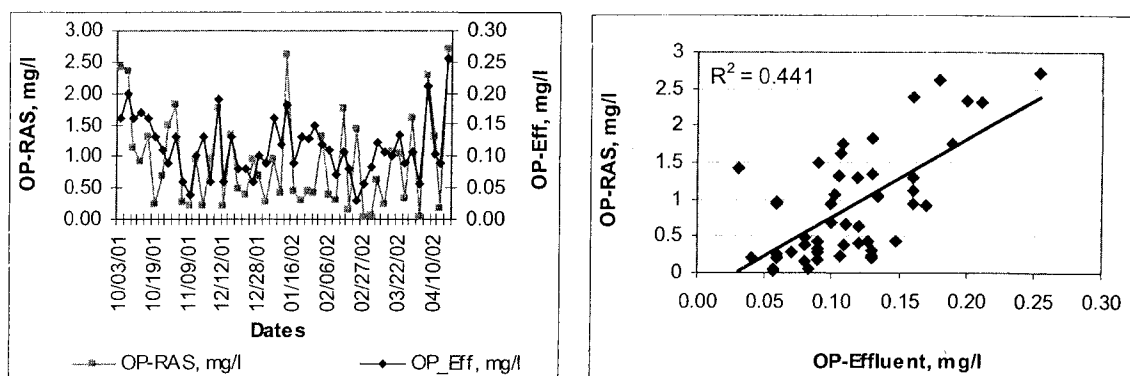


Figure 4-11a and 4-11b
clarifier using date set 1

Correlation between RAS Ortho-P and Effluent Ortho-P in

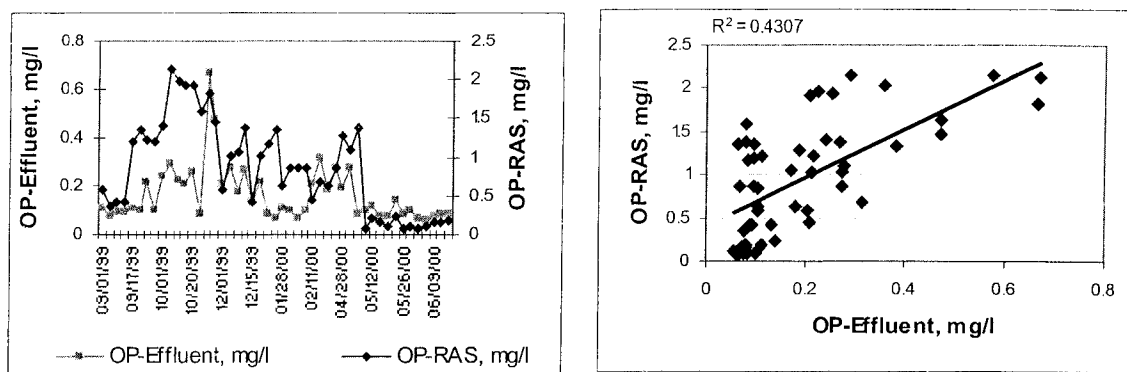


Figure 4-11c and 4-11d Correlation between RAS Ortho-P and Effluent Ortho-P in clarifier using data set 2

4.3.11 Relationship between Denitrification and Soluble Chemical Oxygen Demand (SCOD) in the Sludge

In order to evaluate the relationship between denitrification and SCOD in the sludge within the secondary clarifier, both denitrification and SCOD were plotted by sampling date sequence (Figure 4-12a). Linear regression analysis on denitrification and SCOD yielded a R^2 value of 0.7918, indicating good correlation. Denitrification and SCOD followed a similar trend. This result suggests that strong secondary denitrification occurred in the presence of high SCOD.

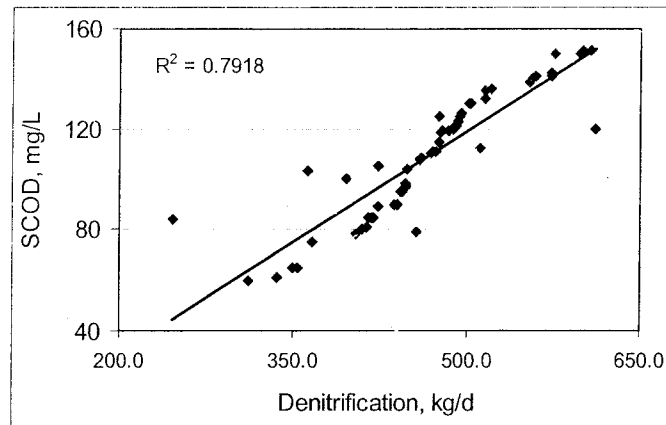


Figure 4-12a Correlation between Denitrification and SCOD in Sludge using data set 1

4.3.12 Relationship between P-release and Soluble Chemical Oxygen Demand (SCOD)

In addition to denitrification and SCOD relationship, the relationship between P-release and SCOD in the clarifier sludge was determined plotting both P-release and SCOD by sampling date sequence (Figure 4-13a). Linear regression analysis on P-release and SCOD yielded a R^2 value of 0.6159, indicating good correlation. P-release and SCOD followed similar trends as denitrification and SCOD did. High SCOD was measured during P-release, suggesting that sufficient SCOD was available for PAOs to release phosphorus within the clarifier.

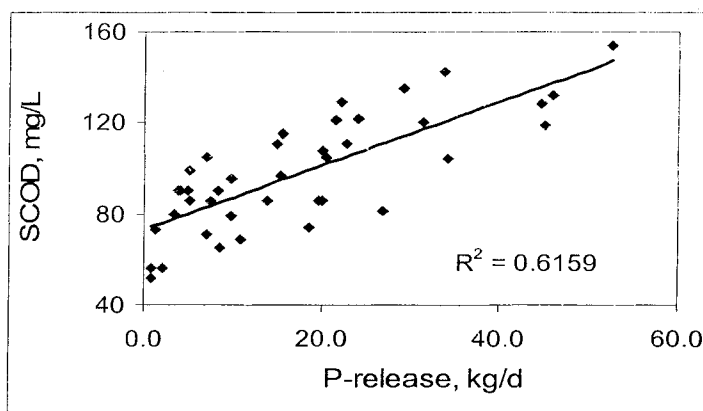


Figure 4-13a Correlation between P-release and SCOD) in the Sludge using data set 1

4.4 Conclusions

The results obtained from this study show that denitrification and P-release is directly related to denitrification occurring in the clarifier, suggesting that some similar conditions favor both denitrification and P-release within the sludge blanket.

The results also show that, for all three data sets, the presence of high SCOD and low DO within the clarifier blanket promote both denitrification and P-release. Low DO levels have induced the anaerobic conditions needed to produce SCOD by fermentation, providing sufficient carbon source for both denitrification and P-release within the clarifier. ORP did not show any significant influence on denitrification and P-release.

Denitrification within the clarifier partially recovered alkalinity by increasing the pH lowered during the nitrification. High OP was present in the RAS as the result of P-release within the sludge blanket. Strong denitrification affected the effluent quality of the CCSD plant with respect to suspended solids and phosphorus concentration.

CHAPTER 5

USE OF SLUDGE BLANKET HEIGHT AS A TOOL TO CONTROL DENITRIFICATION IN SECONDARY CLARIFIER

5.1 Introduction

The sludge blanket height (SBH) is one of the most important parameters for clarifier design. Without reliable predictions of sludge blanket height, neither maximum clarifier configuration nor equipment design are possible (Petr Grau, 1985). The variables that influence the sludge blanket heights are process parameters (solid concentration and recycle rate) and clarifier design parameters (Ekama et al., 1997).

The sludge blanket height can be increased by allowing higher MLSS flows into the clarifier. Sludge blanket height can also be increased by lowering the clarifier scrapper interval or scrapper velocity (Figure 4-1). Conversely, the sludge blanket height can be decreased by moving settled sludge out of the clarifier quickly. However, a higher sludge blanket in the secondary clarifier is undesirable for the following reasons (Ekama et al., 1997):

1. High sludge blankets in secondary clarifiers raise the density currents that travel along the top of the sludge blanket. Therefore, the closer this current is to the effluent weir when it strikes the end wall, the more direct is the flow path from inlet to outlet, and more

deleterious is the impact of the short-circuiting.

2. In a secondary clarifier with flocculator center well, as the distance between the sludge blanket and flocculation skirt gets smaller, flow velocities exiting the flocculation zone increase, resulting in the resuspension of sludge blanket solids.
3. Density currents tend to scour solids from the top of a sludge blanket, and the lesser the distance between the sludge blanket and the water surface, the more likely it is that scoured solids will not resettle into the sludge blanket.

It has been shown that the sludge blanket height has a strong influence on the denitrification occurring within clarifiers. An increase in the sludge blanket height can substantially increase denitrification in the clarifier, thus increasing the overall denitrification in the plant (Siegrist et al., 1995; and Koch et al., 1998). Therefore, the sludge blanket height may serve as a useful operating parameter to control denitrification in clarifiers.

It has been shown in the previous chapters that denitrification is occurring within the CCSD secondary clarifiers and it causes sporadic higher phosphorus (TP) levels in the secondary clarifier effluent. The higher TP levels are the results of rising of solids into the clarifier's effluent, carried by rising nitrogen gas bubbles resulting from denitrification. This fact, coupled with literature reports that denitrification is influenced by sludge blanket height supports the prospect of using sludge blanket height as a means of controlling denitrification. In the case of plants that operate on the one-sludge system mode, such a control would be useful to determine the "acceptable" amount of denitrification. That is, an amount that would allow for partial recovery of alkalinity but yet would not promote undesirable amounts of solids to rise to the clarifier effluent.

Denitrification within the biological reactor has been widely studied, whereas, denitrification within the sludge blanket is hardly reported in the literature (Hamilton et al., 1992; and Siegrist et al., 1995). In this chapter, the relationships between sludge blanket height and denitrification in CCSD clarifiers was established. An attempt was made to quantify an “acceptable” amount of denitrification as a function of sludge blanket height and the effluent quality requirements for CCSD.

5.2 Materials and Methods

Materials and methods used in this portion of the research are the same as those described for chapters 2 and 3, except that sludge blanket height measurements were taken.

5.2.1 Measurement of Sludge Blanket Height

The sludge blanket height was recorded at the same time as the denitrification influencing parameters (e.g. DO, SCOD, ORP, NO_3^- , NO_2^- , etc) were measured (Appendix F). The sludge blanket heights, at all three sampling points, were measured using a sludge judge. The sludge judge is a long pipe (20' long & 2" diameter), made out of transparent fiberglass pipe and fitted with an automatic closure. It is commonly used in wastewater treatment to control clarifier operation. Sludge blanket height was taken as the height at which a sharp change in apparent sludge density was observed (i.e. the level at which the concentration undergoes the greatest change).

To analyze the effect of sludge blanket height on denitrification and P-release, measured sludge blanket heights were correlated to several relevant parameters. The significance of the correlation coefficients was determined using two sample T-test with

95% confidence interval (Minitab Software). The results from this T-tests showed significant at the 95% confidence interval. A summary of the T-tests is shown in Appendix I.

5.3 Results and Discussion

5.3.1 Relationship between DO and Sludge Blanket Height (SBH) in the Clarifier

The relationship between DO and SBH within the secondary clarifier is plotted by sampling date (Figure 5-1). Linear regression analyses of DO and SBH yielded a strong R^2 value of 0.7591. This result indicates that high SBH promotes lower DO concentrations within the sludge blanket, inducing anaerobic conditions. Thus, the higher the SBH, the lower the DO values found within the clarifier. For the CCSD clarifier, SBH varied from 3.25 to 5.75 ft. For SBH around 3.5 ft, DO values were approximately 0.25 mg/L. For SBH of 5.5, DO values reduced about four fold to 0.06 mg/L (Figure 5-1).

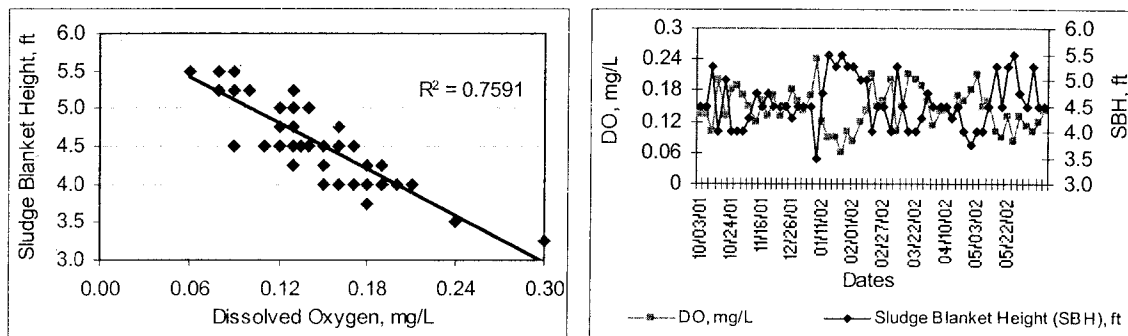


Figure 5-1 Relationship between DO and SBH in CCSD Clarifier # 4

5.3.2 Relationship between SCOD and Sludge Blanket Height (SBH) in the Clarifier

The relationship between soluble COD and SBH within the secondary clarifier is plotted by sampling date sequence in Figure 5-2. Linear regression analysis on SCOD and SBH yielded a strong correlation between these parameters (R^2 value of 0.8831). The results indicate that, for SBH of 3.5 ft, SCOD values are around 50 mg/L, but it triples at SBH of 5.5 ft (Figure 5-2).

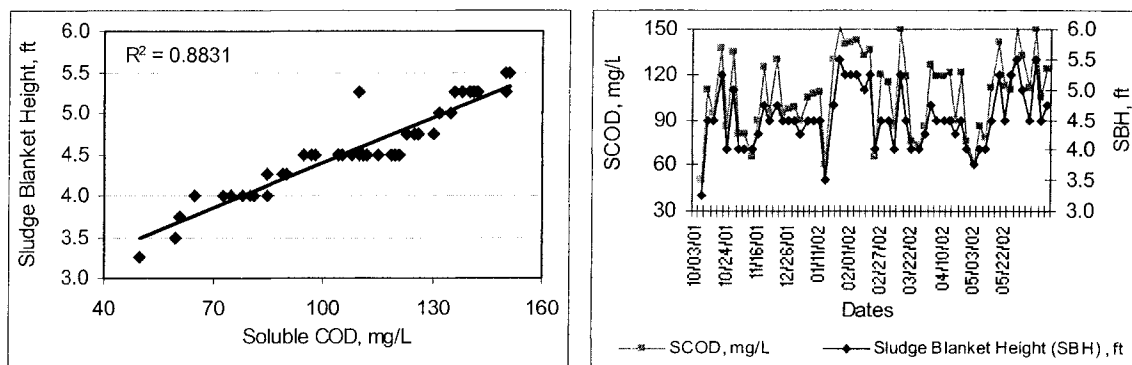


Figure 5-2 Relationship between SCOD and SBH in the Clarifier

5.3.3 Relationship between pH increase in sludge Blanket and Sludge Blanket Height (SBH) in the Clarifier

Figure 5-3 shows a strong relationship (R^2 value of 0.8089) between pH increase and SBH within the clarifier. The results indicate that during high SBH the pH within the sludge blanket increased as a result of the higher amount of denitrification occurring.

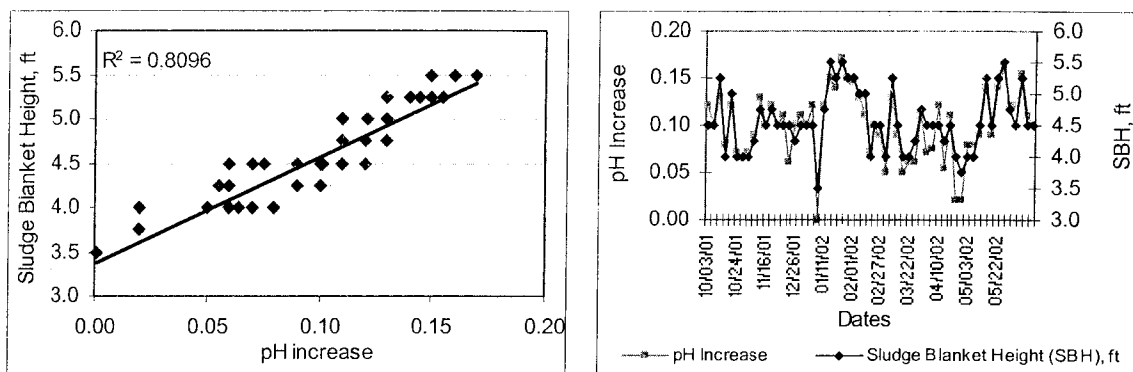


Figure 5-3 Relationship between pH increase in sludge Blanket and SBH

5.3.4 Relationship between Denitrification and Sludge Blanket Height (SBH) in the Clarifier

Denitrification rate versus SBH are plotted by sampling date sequence in Figure 5-4. Denitrification and SBH followed similar trends. Linear regression analysis yielded a R^2 value of 0.8869, indicating a strong correlation. Strong denitrification within the secondary clarifier was observed, during the period of high SBH. For SBHs around 3.5 ft, 295 kg/d $\text{NO}_3\text{-N}$ was denitrified. This rate doubled for SBHs of 5.5 ft.

The low DO and availability of SCOD during high SBH promoted strong denitrification within the sludge blanket. This is confirmed by the observed increase in sludge pH.

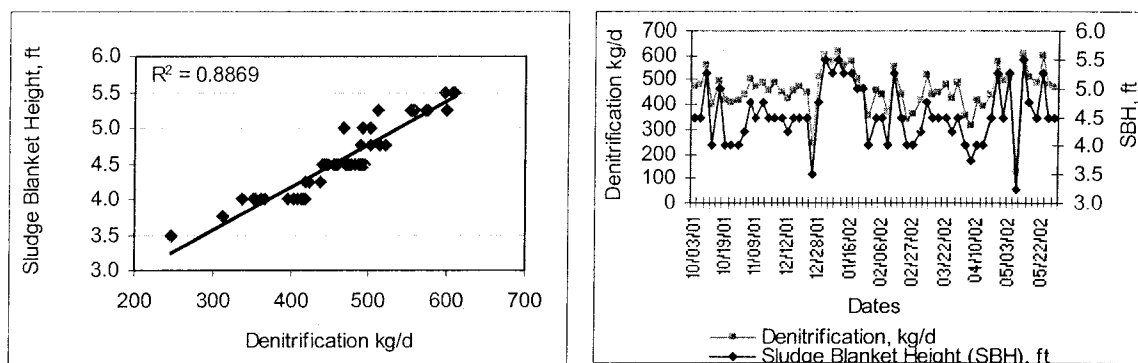


Figure 5-4 Relationship between Denitrification and SBH in the Clarifier

5.3.5 Relationship between P-release and Sludge Blanket Height (SBH) in the Clarifier

Similar results to those obtained for denitrification were found (Figure 5-5) when P-release within the clarifier was related to SBH. However, a lower correlation coefficient ($R^2 = 0.5437$) than that for denitrification was found. About 10 kg/day of phosphorus were released at SBHs 3.5 ft, while P-release by 4 times when SBH increased to 5.5 ft.

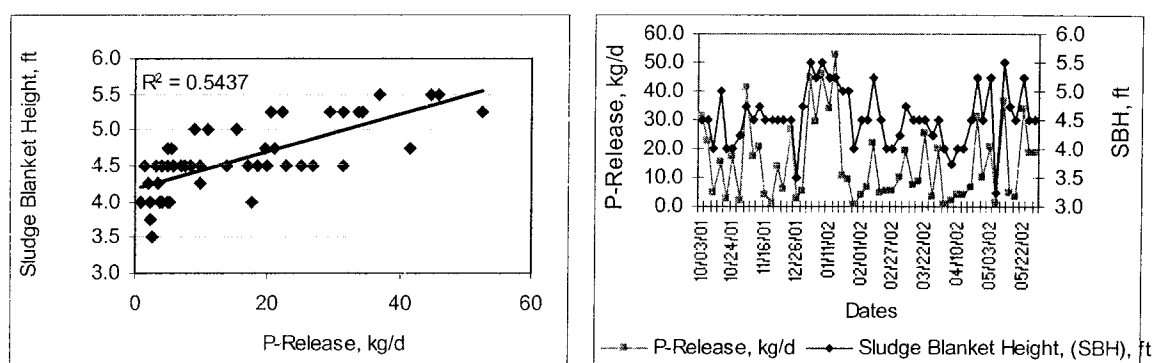


Figure 5-5 Relationships between P-release and SBH in the Clarifier

5.3.6 Relationship between Sludge Blanket Height (SBH) and Effluent Suspended Solids (ESS)

Linear regression analysis on SBH and ESS yielded a R^2 value of 0.7701, indicating good correlation (Figure 5-6). High ESS concentrations in the secondary clarifier effluent were observed during the period of high SBH. A significant increase in ESS concentrations is observed for small increases of SBH. ESS concentrations below 5 mg/L were observed for SBHs of 4 ft, while above 4.7 ft, ESS concentrations were greater than 10 mg/L (Appendix F). Parker et al. (2001) also observed high ESS concentration during high sludge blanket height, which confirms the above observation.

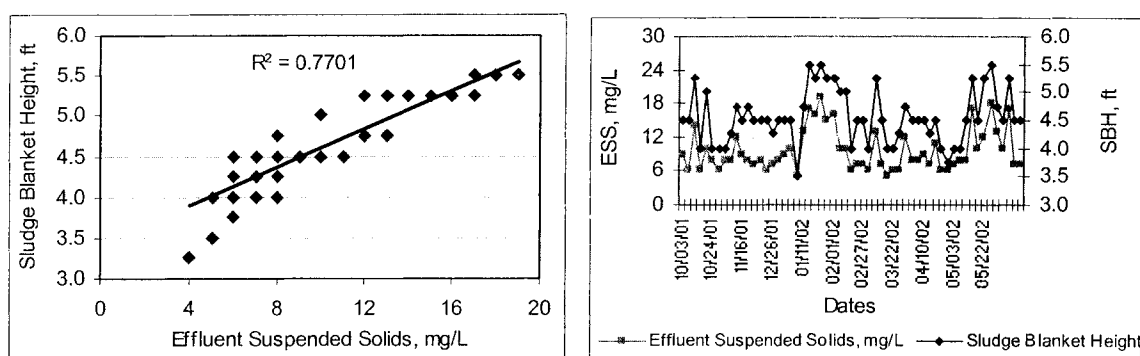


Figure 5-6 Relationship between SBH and Effluent Suspended Solids (ESS)

5.3.7 Relationship between Blanket Height (SBH) and Effluent Total Phosphorus (ETP)

Linear regression analysis of SBH and ETP yielded a R^2 value of 0.7257, indicating good correlation (Figure 5-7). Higher ESS concentrations will result in higher TP in the clarifier effluent because the solids contain polyphosphate. At CCSD, to keep

the desired total-P concentration in the clarifier effluent below 0.27 mg/L, it would be necessary to keep the SBH below 4.5 ft (Appendix F).

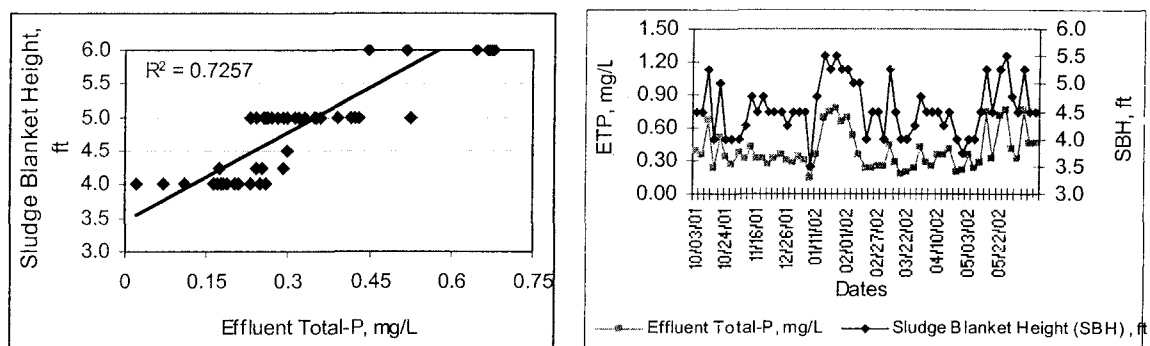


Figure 5-7 Relationship between SBH and Effluent Total Phosphorus (ETP)

5.4 Conclusions

The results of this research show a strong correlation between sludge blanket height, denitrification and P-release within the CCSD clarifier. In addition, the results also show a correlation between low DO and high SCOD levels with increased sludge blanket height. Thus, SBH could be used as an operational parameter to control denitrification in clarifiers.

To reach the desired SS concentration (< 5 mg/L) and TP concentration (< 0.27 mg/L), the sludge blanket height at CCSD should be kept below 4.5 ft. That would correspond to denitrification rate of < 430 kg $\text{NO}_3\text{-N/day}$, a pH increase of 0.1 units, and SCOD concentration < 110 mg/L.

The data generated in this research can be used as the starting point to control denitrification in the clarifiers at CCSD. To keep a lower sludge blanket height, CCSD

can either increase the clarifier scrapper velocity or the interval of scraping. However, such changes have to be implemented slowly to make sure sludge concentration of the settled sludge and the associated return flows are sufficient to maintain the needed mixed liquor suspended solids (MLSS) concentration in the aeration basin.

CHAPTER 6

APPLICATION OF FLUX THEORY AND STATE POINT ANALYSIS TO DENITRIFICATION CONTROL IN THE SECONDARY CLARIFIER

6.1 Introduction

The solid flux theory can be used for designing and analyzing performance of secondary clarifiers (Kynch, 1952; Yoshioka et al, 1957). A graphical procedure developed by Yoshioka et al. (1957) can be used to determine the limiting-solids handling capacity of clarifiers. Because a strong relationship was found between sludge blanket height and denitrification in chapter 5, it is worthwhile to explore whether the concept of solids flux could be used to control and assess the degree of denitrification occurring in clarifiers.

While the flux theory allows for the determination of the critical solids handling capacity of the clarifier, it does not correlate the conditions in the biological reactor (e.g. aeration tank) with the clarifier operation. State point analysis, however, can be used to couple the operation of the secondary clarifier and the aeration basin (Rittmann, 2001).

The position of the state point and the clarifier underflow line with respect to the solid flux curve, determines whether the clarifier is operating in underload or overload conditions. If the state point and the underflow operating line are within the solid flux curve, the clarifier is said to be in an underload condition. If either the state point or the

underflow line lies above the solid flux curve the clarifier goes into an overload condition. Because state point analysis reflects the loading conditions of the clarifier and because of the effects of clarifiers loading on denitrification, state point analysis could be used as an operational strategy to control clarifier denitrification as well.

In this study an attempt is made to use the concepts of solid flux and state point analysis as an operational tool to control denitrification in clarifier of BNR systems. Although, rising sludge blanket has been reported to promote denitrification (Siegrist et al., 1995; and Koch et al., 1999), this is the first attempt to use these concepts as an operational control tools for clarifier denitrification.

6.2 Materials and Methods

The concepts of solid flux and state point were correlated with denitrification and P-release data collected within the clarifier. The data on denitrification and P-release are the same collected in clarifier # 4 at the CCSD plant, for which collection and analytical procedure have been described in chapter 2, section 2.2 and chapter 3, section 3.2. The significance of the correction coefficients was determined using two sample T-test with 95% confidence interval (Minitab Software). The results from this T-tests showed significant at the 95% confidence interval. A summary of the T-tests is shown in Appendix J.

Column settling tests were performed to develop a solid flux curve for the CCSD sludge. The tests were conducted in a 2" diameter plexiglass column in which a range of concentrations of activated sludge was added. RAS, mixed liquor, and clarifier effluent were mixed in selected ratios to obtain suspended solids concentrations (X_i)

ranging from 2,000 to 12,000 mg/L. The sludge in the column was mixed well for 5 minutes prior to each test and then allowed to settle. The interface height (the zone between the clear water and the top of the settled sludge blanket) was recorded every 5 minutes for each concentration until the compression phase was reached (approximately 30 minutes, Appendix G). The interface height was recorded as a function of time and a plot generated from the height-time data pairs for each measured sludge concentration was constructed (Figure 6-1).

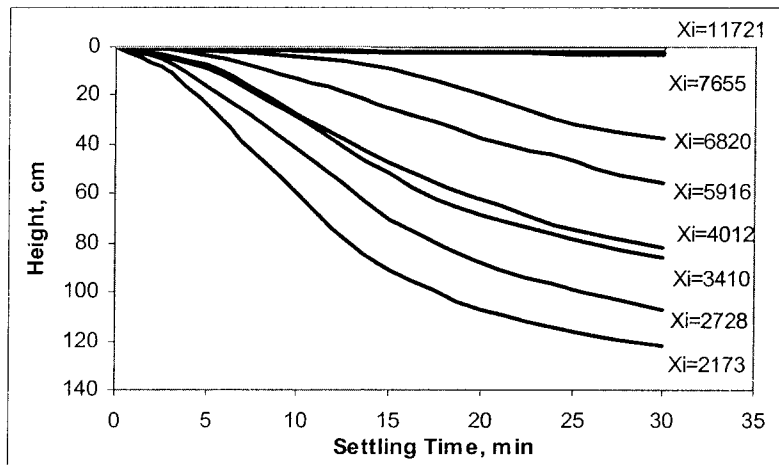


Figure 6-1 Interface height-time profile as a function of solids concentration for CCSD Sludge

6.3 Results and Discussion

6.3.1 Solid Flux Curve for CCSD

The sludge settling velocity (V) at each SS concentration (X_i) was calculated analytically by dividing the height of the interface by the settling time. Only the linear portion of the curve, corresponding to a constant settling velocity, was used in the

calculation (Appendix G). Solids flux ($G_s = V X_i$) was calculated using the obtained V (from Figure 6-1) values and their corresponding solids concentration (Appendix H). Each value of G_s represents the gravity settling flux per unit area of clarifier that would be expected to occur at the corresponding sludge concentration.

A settling flux curve was then plotted using calculated G_s values on the y-axis and its corresponding solids concentrations on the x-axis (Figure 6-2).

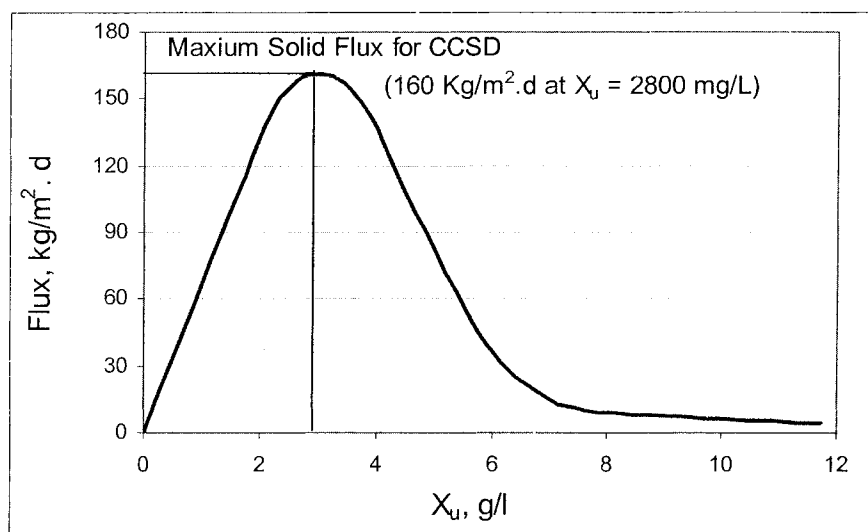


Figure 6-2 Solid Flux Curve for CCSD Plant

The obtained solid flux curve for the CCSD plant shows that the solid flux gradually increased as the X_u increased and reached the maximum value of 160 Kg/m².d at the X_u of 2,800 mg/L. Half the maximum solid flux value (80 Kg/m².d) was measured at the X_u value of 5,000 mg/L. The solid flux started decreasing as the X_u increased above 3,400 mg/L. The solid flux decreased slightly above X_u values of 7,700 mg/L.

6.3.2 Relationship between Solid Flux, Sludge Blanket Height, and Suspended Solid Concentrations

To evaluate the effect of solid flux on sludge blanket height and subsequently on clarifier SS underflow concentration, both sludge blanket height and SS were plotted against solid flux (Figures 6-3a & 6-3b, respectively). As expected, the linear regression analyses performed yielded good R^2 values of 0.7137 and 0.7296 for SBH and SS versus solid flux, respectively, showing strong relationship. The results obtained show that high solid flux in the CCSD clarifier results in higher sludge blanket, thus increasing the SS concentration within the blanket.

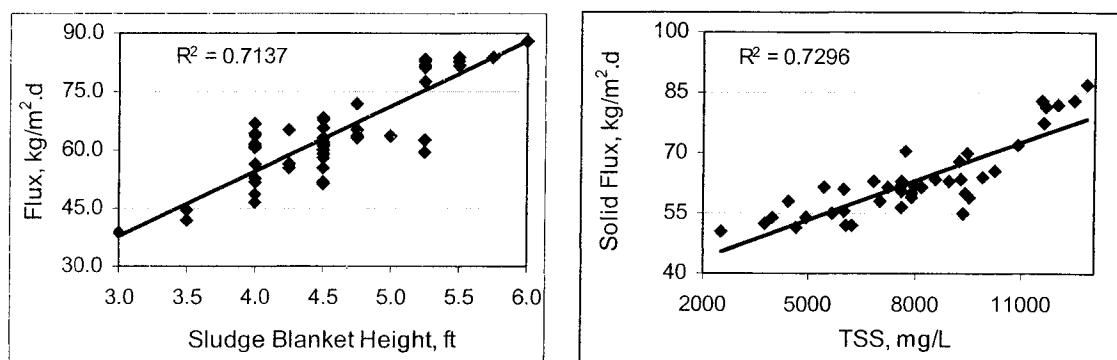


Figure 6-3a and 6-3b Relationship between Solid Flux, Sludge Blanket, and Suspended Solid Concentrations

6.3.3 Relationship between Solid Flux and DO in the sludge

Linear regression analysis on solid flux and DO within the blanket yielded a R^2 value of 0.7211, indicating good relationship (Figure 6-4). This demonstrates that the high solid flux within the clarifier reduced the DO levels within the blanket inducing anaerobic conditions. These DO levels were sufficiently low to promote denitrification.

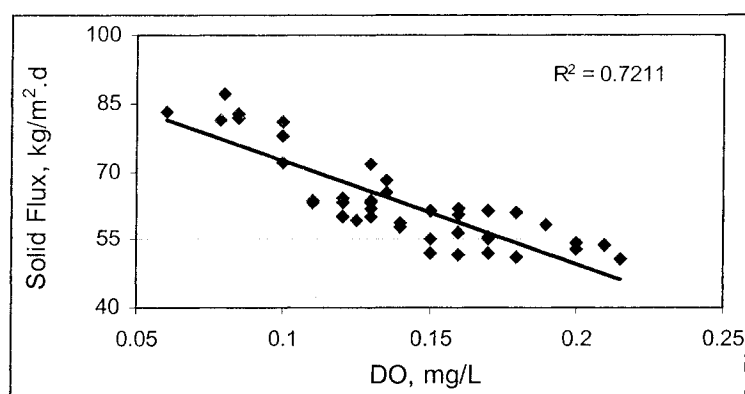


Figure 6-4 Relationship between Solid Flux and DO in the sludge

6.3.4 Relationship between Solid Flux and SCOD Concentration in the Sludge

Linear regression analysis between solid flux and SCOD also yielded a good R^2 value of 0.6683. The result obtained suggests that SCOD increased with the increase in solid flux.

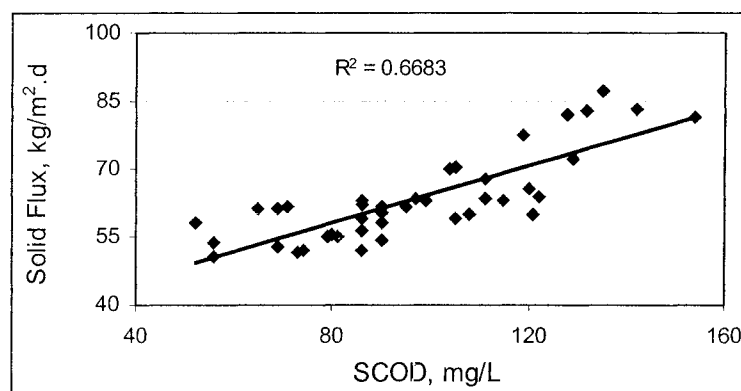


Figure 6-5 Relationship between Solid Flux and Denitrification in the sludge

6.3.5 Relationship between Solid Flux and Denitrification in the sludge

The relationship between solid flux and denitrification yielded a R^2 value of 0.7019, suggesting that denitrification increased with increased solid flux (Figure 6-6).

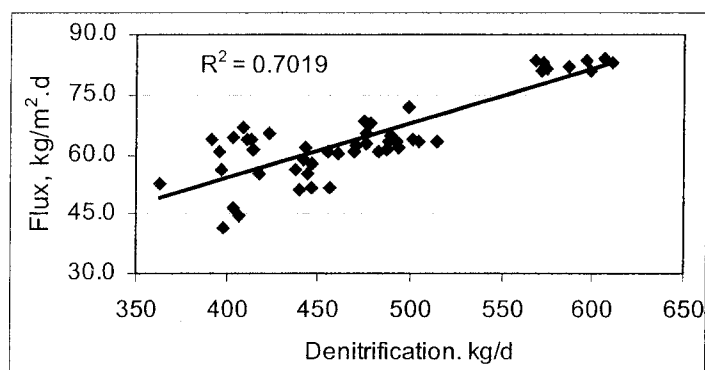


Figure 6-6 Relationship between Solid Flux and Denitrification in the sludge

6.3.6 Relationship between Solid Flux and P-release in the sludge

Linear regression analysis on the solid flux and P-release yielded a R^2 value of 0.6185, suggesting that P-release increased with the increase in solid flux (Figure 6-7).

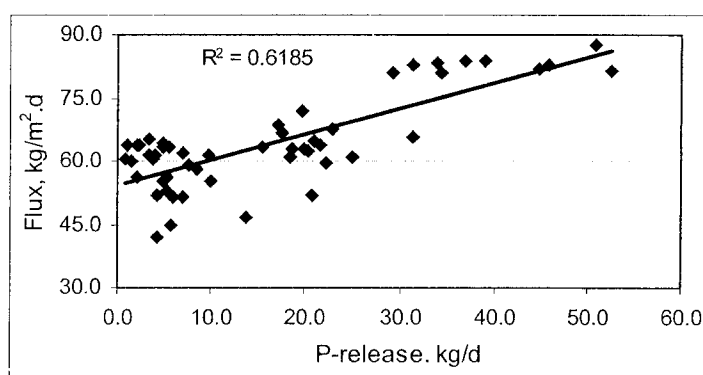


Figure 6-7 Relationship between Solid Flux and P-release in the sludge

As noted from the above correlation coefficients and from the results in chapter 4, both sludge blanket height and solid flux correlate well with denitrification and other parameters affecting denitrification in clarifiers. This was expected, since the height of the sludge blanket in the clarifier is a consequence of solid flux. However, the R^2 values found for the correlation between sludge blanket height and denitrification are larger than those for solid flux. It seems that both parameters could be used to control the rate of denitrification in clarifiers. For plant operational purposes, sludge blanket height measurement would be the simplest method to be used. However, for evaluation of the impacts of changing settling velocities (e.g. coagulant addition), solid flux would be the preferred method.

6.3.7 Utilization of Solid Flux Curve to Determine Operational Conditions in the Clarifier

The solid flux curve developed for the CCSD plant was used to investigate operating conditions in the clarifier. The observed operating conditions were then related to corresponding denitrification and P-release within the clarifier during that period. Figures 6-8, 6-9, and 6-10, show only representative data to avoid overcrowded graphs.

Figure 6-8 shows dates in which the clarifier underflow operating lines were below the solid flux curve, indicating that in these dates the CCSD clarifier # 4 was operated in underload conditions. Overload conditions were observed for solid fluxes greater than $75 \text{ kg/m}^2\text{.d}$ (Figure 6-9). It can be noted from Figures 6-6 and 6-7 that underload conditions promoted moderate denitrification ($< 500 \text{ kg/d}$) and P-release (< 30

kg/d) within the clarifier. The raw data obtained for solid fluxes under these clarifier-operating conditions are summarized in Appendix H.

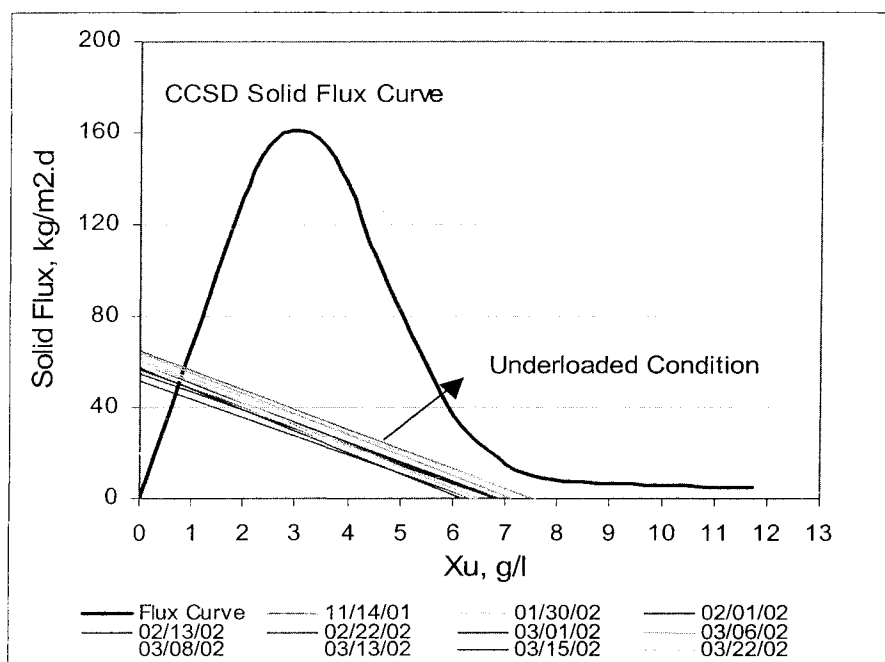


Figure 6-8 Representative Data of Underload Clarifier Conditions at CCSD

For some of the sampling dates, the solid flux increased as a result of increased sludge underflow concentration (X_u). The underflow operating lines for these dates were above the solid flux curve, indicating that the clarifier was operated under overload condition (Figure 6-9). The result shows that during overload conditions, the sludge blanket height increased as a consequence of the high solid flux (Figure 6-3a).

It can be clearly seen from Figures 6-6 and 5-7 that for high solid flux, above $75 \text{ Kg/m}^2.\text{d}$ (overload conditions) denitrification and P-release occurred. However, this overload condition can be controlled by increasing the underflow waste rate, until the underflow operating line falls below the solid flux curve (Keinath, 1985). Therefore, solid flux

could be used as an operating tool to control denitrification and P-release within the clarifier.

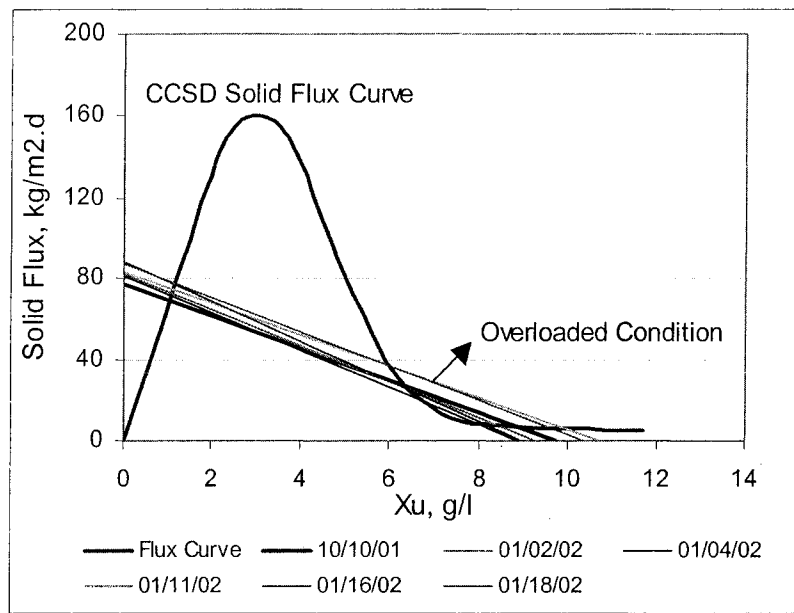


Figure 6-9 Representative Data of Overload Clarifier Conditions

State point analysis of the CCSD activated sludge system and development of appropriate control strategy can be best illustrated by Figures 6-10 and 6-11. Only two sampling dates, one representing underload and another overload conditions, are used to describe the operating state for the CCSD plant. Figure 6-10 shows that during underload conditions the MLSS in the basin was low (1,800, mg/L), whereas, it was high for the overload condition (2,800 mg/L). The OFR, for all the sampling dates did not vary much, therefore there was not much variation in the OFR operating line. However, large variations were observed in the underflow solids concentration (6,500 mg/L for underload condition and 9,400 for overload condition) (Figure 6-10).

Denitrification and P-release corresponding to the overload condition were 602 kg/d and 40.8 kg/d, respectively, while for underload conditions it was 453 kg/d and 4.2 kg/d, respectively. This observation was true for all detected overload and underload conditions (Figures 6-6 and 6-7, respectively).

Thus, overloading conditions should be avoided to minimize denitrification and P-release. That could be done by either decreasing the clarifier underflow concentration or decreasing the MLSS inside the aeration basin. The decrease in MLSS concentration may not be possible in all situations, because it depends on the efficiency of biodegradation in the basin. However, decreasing the underflow sludge concentration is possible by wasting sludge more quickly from the clarifier. The implementation of such procedure is dependent upon the capacities of the RAS and WAS pumps available in the plant.

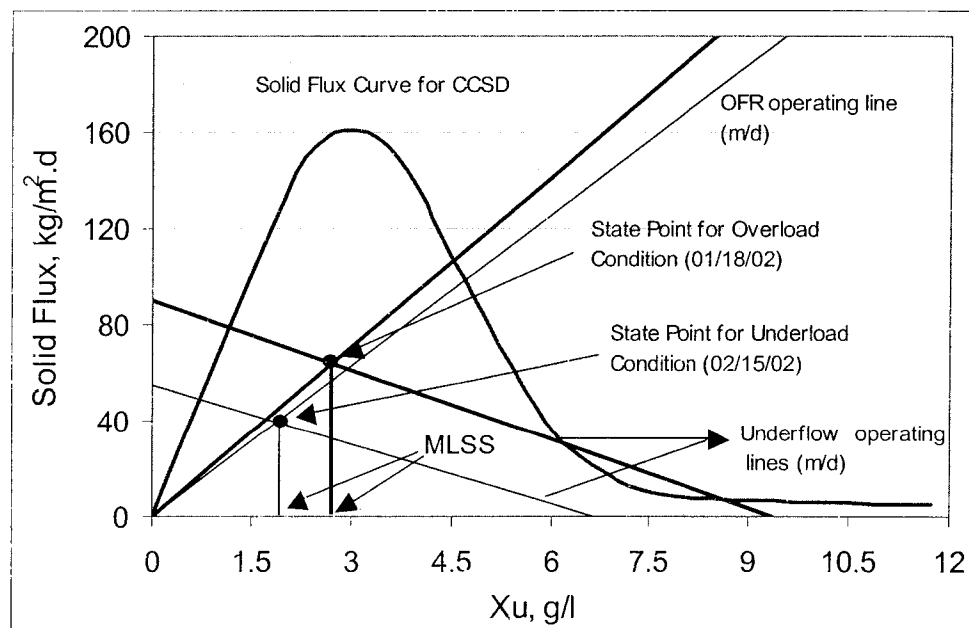


Figure 6-10 Overload and Underload Clarifier Conditions for CCSD Plant

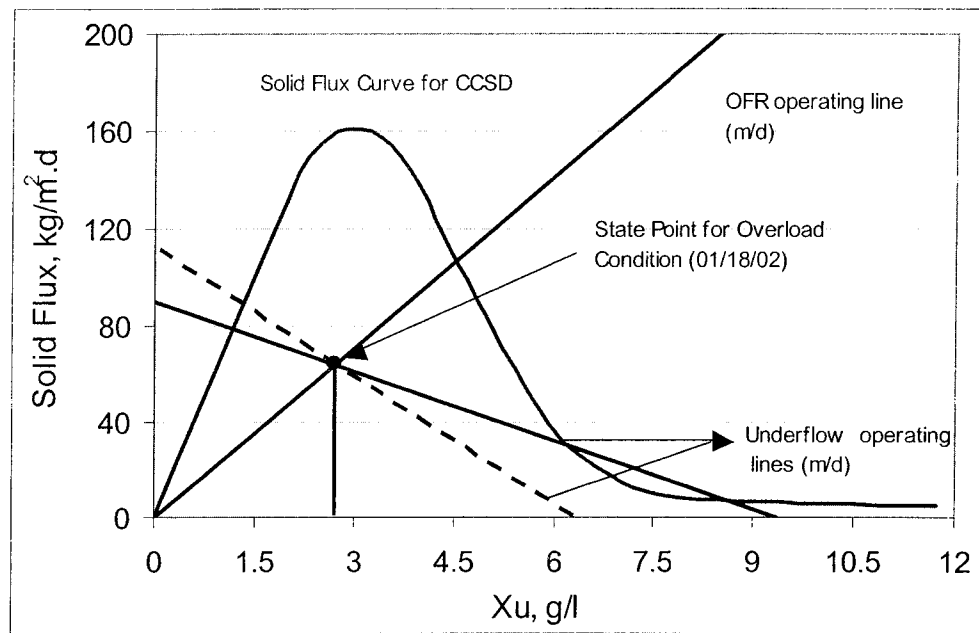


Figure 6-11 Control Strategy for Overload Condition

6.4 Conclusions

The results obtained show that solids flux was found to have influence on DO, SCOD, SS, and SBH in the clarifier. The DO decreased with the increase in the solid flux, while SCOD and SS increased as the solid flux increased. The increase in the SBH was observed as a consequence of increased solid flux.

The results from chapter 4 show that SBH correlates better with denitrification than with solid flux. A possible explanation for this observation is that the solid flux calculations involve several experimental and analytical procedures making the data more susceptible to errors. The sludge blanket height is a direct measurement parameter that can be directly correlated to denitrification.

The results obtained from chapter 4 and from this chapter indicate that solid flux, state point analysis and SBH could be used as operating tools to control denitrification

occurring within clarifiers. However, application of solid flux and state point as operating tools to control denitrification depends mainly on the RAS pump capacities to withdraw sludge.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions can be drawn from this study:

1. The results obtained from statistical analysis and from individual profiles show that denitrification as well as phosphorus release had occurred within the CCSD clarifier. Statistically significant evidence was found that both denitrification and p-release are strongly influenced by low DO and soluble COD levels within the clarifier.
2. The low DO levels found at the studied clarifier are within the reported DO range needed to promote denitrification. The soluble COD in the clarifier was found to increase along the vertical axis with higher values found in the bottom of the clarifier where the SS concentrations are higher. For all sampling points, suspended solids concentrations were found to correlate well with soluble COD concentrations. Thus, fermentation and solids lysis under low DO conditions generate the needed soluble COD that support both denitrification and P-release; Both phenomena require a low DO environment and a carbon source (e.g. soluble COD) to occur.

3. For all points sampled, pH, temperature, and ORP were found to have very little effect on denitrification and P-release. Strong evidence was found that the observed reduction in nitrate levels correlates very well with the increase in pH and nitrite concentration.
4. Denitrification within the clarifier partially recovered the alkalinity by increasing the pH lowered during the nitrification. High OP was present in the RAS as the result of P-release within the sludge blanket. Strong denitrification affected the effluent quality of the CCSD plant with respect to suspended solids and phosphorus concentration.
5. A strong correlation between sludge blanket height (SBH), denitrification and P-release within the CCSD clarifier was found. In addition, a strong correlation was found between low DO and high SCOD levels with increased sludge blanket height. Thus, SBH could be used by the CCSD as an operational parameter to control denitrification in clarifiers. This would consequently result in control of total-P in the clarifier effluent.
6. To reach the desired SS concentration (< 5 mg/L) and TP concentration (< 0.27 mg/L), the sludge blanket height at CCSD should be kept below 4.5 ft close to the wet well, corresponding to about 2.3 ft sludge blanket height close to the clarifier effluent weir. That would correspond to denitrification rate of < 430 kg $\text{NO}_3\text{-N/day}$, a pH increase of 0.1 units, and SCOD concentration < 110 mg/L.
7. The data generated in this research can be used as the starting point to control denitrification in the clarifiers at CCSD. To keep a lower sludge blanket height, CCSD can either increase the clarifier scrapper velocity or the interval of scrapping.

However, such changes have to be implemented slowly to make sure sludge concentration of the settled sludge and the associated return flows are sufficient to maintain the needed MLSS concentration in the aeration basin.

8. The data obtained in this research show that solids flux was found to have influence on DO, SCOD, SS, and SBH in the clarifier. The DO decreased with the increase in the solid flux, while SCOD and SS increased as the solid flux increased. The increase in the SBH was observed as a consequence of increased solid flux.
9. Historic data of the CCSD shows that, most of the time, the clarifiers operate under underload conditions. However, sporadically the clarifiers are overloaded. A strong correlation was found between overloaded clarifiers and the increase in total phosphorus (TP) concentration in the effluent. Increased TP is a consequence of rising of solids by nitrogen bubbles resulting from denitrification.
10. Sludge blanket height was found to correlate better with denitrification than with solid flux. A possible explanation for this observation is that, the solid flux calculations involve several experimental and analytical procedures making the data more susceptible to errors. The sludge blanket height is a direct measurement parameter that can be directly correlated to denitrification.
11. All three parameters, solid flux, state point analysis, and SBH could be used as operating tools to control denitrification occurring within clarifiers at the CCSD. However, application of solid flux and state point as operating tools to control denitrification depends mainly on the RAS pump capacities to withdraw sludge.

The following is recommended to avoid sporadic increases in phosphorus concentration at the CCSD plant:

1. To use sludge blanket height to control the amount of denitrification occurring within the CCSD clarifiers. Based on historic data, sludge blanket heights at the CCSD should be kept < 2.5 ft.
2. To use state point analysis to determine required conditions (e.g. MLSS concentrations) to be maintained in the aeration tank and clarifier underflow - to avoid overloading the clarifier. This can be done by using the solid flux curve and the flux calculation spreadsheet generated by UNLV for the CCSD plant.

APPENDIX A

RAW DATA MEASURED FOR CCSD CLARIFIER

Date: 10/3/2001										
Location Points	Point 1			Point 2			Point 3			ABE
	C _{1-S}	C ₁₋₁₀	C ₁₋₁₄	C _{2-S}	C ₂₋₁₀	C ₂₋₁₅	C _{3-S}	C ₃₋₁₀	C ₃₋₁₇	
NO ₃ ⁻ mg/L	13.44	13.41	13.35	13.41	13.44	5.94	13.38	13.51	1.92	13.12
NO ₂ ⁻ mg/L	0.05	0.05	0.12	0.05	0.05	0.68	0.05	0.05	0.90	0.05
Ortho - P mg/L	0.16	0.23	1.11	0.16	0.18	0.94	0.1	0.2	2.4	0.12
Total - P mg/L	0.39	4.81	36.88	0.25	0.13	1.07	0.2	1.03	126	37.34
Dissolved Oxygen, mg/L	0.26	0.25	0.23	0.24	0.23	0.23	0.24	0.19	0.135	1.86
ORP	97	95	95	90	81	80	75	74	64	116
pH	6.94	7.94	8.94	9.94	10.94	11.94	12.94	13.94	14.94	15.94
Temperature	27.65	27.68	27.69	27.61	27.65	27.66	27.66	27.7	27.65	27.71
Conductivity	1.52	1.53	1.53	1.53	1.56	1.54	1.54	1.55	1.5	1.62
Suspended Solids, mg/L	8	12	1040	12	56	10040	12	16	10231	2230
Sludge Volume Index	-	-	163	-	-	91	-	-	82	63
Soluble COD, mg/L	-	-	-	-	-	-	-	-	-	-
Date: 10/5/2001										
Location Points	Point 1			Point 2			Point 3			ABE
	C _{1-S}	C ₁₋₁₀	C ₁₋₁₄	C _{2-S}	C ₂₋₁₀	C ₂₋₁₅	C _{3-S}	C ₃₋₁₀	C ₃₋₁₇	
NO ₃ ⁻ mg/L	13.58	13.59	13.32	13.6	13.52	8.63	13.56	13.58	3.13	13.11
NO ₂ ⁻ mg/L	0.04	0.04	0.07	0.04	0.05	0.20	0.04	0.04	0.04	0.04
Ortho - P mg/L	0.29	0.34	0.56	0.29	0.37	0.62	0.21	0.36	1.96	0.35
Total - P mg/L	0.36	2.52	12.94	0.36	1.26	59.49	0.34	2.14	93	56.56
Dissolved Oxygen, mg/L	0.25	0.23	0.22	0.22	0.21	0.19	0.21	0.18	0.135	2.91
ORP	82	81	81	78	75	71	59	55	56	129
Temperature	27.71	27.7	27.7	27.7	27.71	27.2	27.69	27.7	27.68	27.75
Conductivity	1.54	1.56	1.56	1.55	1.54	1.55	1.55	1.52	1.56	1.63
pH	7.04	7.09	7.09	7.01	7.02	7.01	7.01	6.98	6.99	6.91
Suspended Solids, mg/L	8	28	640	44	40	6200	8	28	9213	2390
Sludge Volume Index			172			110			94	67
Soluble COD, mg/L	23	43	63	38	70	86	33	54	111	43

Date:		10/10/2001								
Location Points	Point 1			Point 2			Point 3			ABE
	C _{1-S}	C ₁₋₁₀	C ₁₋₁₄	C _{2-S}	C ₂₋₁₀	C ₂₋₁₅	C _{3-S}	C ₃₋₁₀	C ₃₋₁₇	
NO ₃ ⁻ mg/L	13.77	13.72	13.77	13.77	13.75	0.15	13.81	13.75	0.15	14.39
NO ₂ ⁻ mg/L	0.05	0.05	0.04	0.05	0.05	0.14	0.05	0.04	0.38	0.04
Ortho - P mg/L	0.62	0.16	0.04	0.05	0.05	12.82	0.17	0.15	3.96	0.14
Total - P mg/L	0.47	1.22	5.89	0.70	0.11	82.14	0.34	3.41	145.00	46.60
Dissolved Oxygen, mg/L	0.26	0.23	0.2	0.23	0.2	0.18	0.2	0.16	0.1	2.49
ORP	96	93	105	113	110	106	105	102	99	165
pH	6.89	6.85	6.89	6.95	6.92	6.95	6.96	6.96	7.02	6.90
Temperature	27.69	27.69	27.71	27.71	27.71	27.71	27.73	27.71	27.71	27.73
Conductivity	1.53	1.52	1.53	1.51	1.52	1.47	1.53	1.53	1.48	1.62
Suspended Solids, mg/L	24	36	640	20	16	11480	4	64	11600	2040
Sludge Volume Index			156			84			83	88
Soluble COD, mg/L	23	35	64	30	38	113	35	45	119	28

Date:		10/12/2001								
Location Points	Point 1			Point 2			Point 3			ABE
	C _{1-S}	C ₁₋₁₀	C ₁₋₁₄	C _{2-S}	C ₂₋₁₀	C ₂₋₁₅	C _{3-S}	C ₃₋₁₀	C ₃₋₁₇	
NO ₃ ⁻ mg/L	5.09	-	5.51	6.01	7.78	1.08	9.45	8.48	1.59	10.59
NO ₂ ⁻ mg/L	0.04	10.10	0.05	0.04	0.04	0.33	0.04	0.04	0.58	0.04
Ortho - P mg/L	0.20	0.04	1.63	0.27	0.27	3.74	0.23	0.25	0.35	0.19
Total - P mg/L	0.38	0.25	2.14	0.28	1.42	108.58	0.44	34.02	98.00	46.64
Dissolved Oxygen, mg/L	0.28	0.26	0.25	0.30	0.28	0.26	0.30	0.25	0.20	1.98
ORP	123	110	110	91	86	81	75	75	68	124
pH	6.90	6.91	6.92	6.93	6.93	6.93	6.93	6.93	6.95	6.90
Temperature	26.95	27.11	27.07	27.15	27.11	27.09	27.11	27.11	27.13	27.39
Conductivity	1.58	1.57	1.6	1.51	1.57	1.57	1.56	1.57	1.56	1.59
Suspended Solids, mg/L	14	36	1920	44	48	11720	40	4	4900	2320
Sludge Volume Index			73			82			81	52
Soluble COD, mg/L	28	43	59	33	59	97	54	86	90	54

10/17/2001

Location Points	Point 1			Point 2			Point 3			ABE
	C _{1-S}	C ₁₋₁₀	C ₁₋₁₄	C _{2-S}	C ₂₋₁₀	C ₂₋₁₅	C _{3-S}	C ₃₋₁₀	C ₃₋₁₇	
NO ₃ ⁻ mg/L	13.45	13.10	11.31	13.41	13.05	3.69	13.26	13.10	5.45	14.08
NO ₂ ⁻ mg/L	0.05	0.06	0.37	0.04	0.07	0.24	0.05	0.42	0.61	0.04
Ortho - P mg/L	0.16	0.16	2.51	0.14	0.16	0.49	0.17	0.14	1.13	0.14
Total - P mg/L	0.20	2.08	11.40	0.29	0.08	58.05	0.15	0.25	115.00	52.53
Dissolved Oxygen, mg/L	0.29	0.30	0.28	0.31	0.29	0.21	0.28	0.27	0.13	1.41
ORP	123	123	122	117	116	116	101	98	89	141
pH	6.88	6.88	6.88	6.91	6.89	6.93	6.92	6.91	6.97	6.86
Temperature	27.42	27.4	27.4	27.42	27.4	27.42	27.43	27.4	27.42	27.44
Conductivity	1.56	1.57	1.58	1.56	1.58	1.52	1.55	1.58	1.54	1.65
Suspended Solids, mg/L	4	36	3940	2	2	11960	2	352	8541	2280
Sludge Volume Index			81.21			76.92			73.15	78.94
Soluble COD, mg/L	18	25	54	33	43	119	23	43	97	33

Date: 10/19/2001

Location Points	Point 1			Point 2			Point 3			ABE
	C _{1-S}	C ₁₋₁₀	C ₁₋₁₄	C _{2-S}	C ₂₋₁₀	C ₂₋₁₅	C _{3-S}	C ₃₋₁₀	C ₃₋₁₇	
NO ₃ ⁻ mg/L	13.80	13.92	2.77	13.84	13.78	0.13	13.77	10.95	2.20	10.96
NO ₂ ⁻ mg/L	0.06	0.05	5.89	0.06	0.05	0.04	0.89	0.05	0.19	1.48
Ortho - P mg/L	0.17	0.31	1.02	0.12	0.21	1.24	0.02	0.10	0.12	0.15
Total - P mg/L	0.40	0.25	55.81	0.35	0.69	58.59	0.31	12.12	120.40	57.04
Dissolved Oxygen, mg/L	0.24	0.23	0.24	0.23	0.19	0.19	0.21	0.18	0.18	1.90
ORP	57	56	55	54	54	52	50	43	49	94
pH	6.91	6.91	6.91	6.91	6.90	6.90	6.91	6.90	6.95	6.88
Temperature	27.37	27.34	27.34	27.36	27.34	27.36	27.37	27.34	27.34	27.34
Conductivity	1.55	1.56	1.55	1.55	1.54	1.52	1.5	1.53	1.54	1.62
Suspended Solids, mg/L	6	4	1300	2	32	9660	20	28	11360	2760
Sludge Volume Index			162			99			84	69
Soluble COD, mg/L	25	54	75	54	64	108	43	62	141	40

Date: 10/24/2001

Location Points	Point 1			Point 2			Point 3			ABE
	C _{1-S}	C ₁₋₁₀	C ₁₋₁₄	C _{2-S}	C ₂₋₁₀	C ₂₋₁₅	C _{3-S}	C ₃₋₁₀	C ₃₋₁₇	
NO ₃ ⁻ mg/L	12.93	12.80	9.11	12.82	12.88	6.27	12.48	12.72	10.89	13.57
NO ₂ ⁻ mg/L	0.04	0.04	0.29	0.04	0.04	0.34	0.14	0.06	0.12	0.04
Ortho - P mg/L	0.16	0.14	0.90	0.14	0.13	0.67	0.14	0.13	1.30	0.15
Total - P mg/L	0.27	4.63	41.13	0.49	0.99	55.15	0.79	1.63	107.00	48.47
Dissolved Oxygen, mg/L	0.18	0.18	0.16	0.17	0.16	0.12	0.2	0.19	0.19	1.61
ORP	55	55	55	53	54	51	52	49	42	89
pH	6.97	6.97	6.95	6.95	6.95	6.96	6.96	6.95	6.94	6.89
Temperature	27.03	27.03	27.03	27.03	27.03	27.03	26.99	27.03	27.03	27.05
Conductivity	1.57	1.57	1.56	1.55	1.57	1.5	1.55	1.56	1.52	1.64
Suspended Solids, mg/L	24	68	6108	48	84	10160	72	24	10760	1950
Sludge Volume Index			93			93			79	97
Soluble COD, mg/L	28	43	54	54	64	119	33	54	109	30

Date: 10/26/2001

Location Points	Point 1			Point 2			Point 3			ABE
	C _{1-S}	C ₁₋₁₀	C ₁₋₁₄	C _{2-S}	C ₂₋₁₀	C ₂₋₁₅	C _{3-S}	C ₃₋₁₀	C ₃₋₁₇	
NO ₃ ⁻ mg/L	13.26	13.10	11.58	13.16	13.12	0.13	13.07	13.08	11.51	13.78
NO ₂ ⁻ mg/L	0.06	0.07	1.26	0.04	0.05	1.59	0.06	0.04	0.09	0.04
Ortho - P mg/L	0.13	0.10	4.76	0.11	0.06	0.46	0.08	0.10	0.24	0.22
Total - P mg/L	-	-	-	-	-	-	-	-	87.00	-
Dissolved Oxygen, mg/L	0.24	0.23	0.23	0.23	0.19	0.19	0.22	0.18	0.17	1.80
ORP	57.00	56.00	55.00	54.00	54.00	52.00	49.00	43.00	31.00	90.00
pH	6.90	7.00	6.95	7.08	6.94	6.91	6.95	6.93	6.91	6.85
Temperature	27.03	27.03	27.03	27.03	27.03	27.03	26.99	27.03	27.03	27.05
Conductivity	1.55	1.56	1.55	1.55	1.54	1.52	1.54	1.53	1.5	1.62
Suspended Solids, mg/L	20	68	2060	16	12	12940	80	144	5421	2510
Sludge Volume Index			73			71			69	76
Soluble COD, mg/L	24	54	64	33	75	144	39	64	119	43

Date: 10/31/2001

Location Points	Point 1			Point 2			Point 3			ABE
	C _{1-S}	C ₁₋₁₀	C ₁₋₁₄	C _{2-S}	C ₂₋₁₀	C ₂₋₁₅	C _{3-S}	C ₃₋₁₀	C ₃₋₁₇	
NO ₃ ⁻ mg/L	12.91	13.03	8.98	12.94	13.33	12.03	12.92	13.08	12.23	14.71
NO ₂ ⁻ mg/L	0.12	0.10	0.76	0.12	0.11	0.09	0.11	0.11	0.07	0.19
Ortho - P mg/L	0.11	0.21	3.50	0.13	-0.13	0.08	0.10	0.10	0.07	0.08
Total - P mg/L	0.12	1.19	66.86	0.13	-0.66	46.32	-0.09	-2.16	97.00	49.52
Dissolved Oxygen, mg/L	0.14	0.13	0.13	0.13	0.12	0.11	0.14	0.14	0.15	1.57
ORP	49	50	50	48	49	48	45	44	43	83
pH	6.91	6.91	6.91	6.91	6.90	6.90	6.91	6.90	6.95	6.88
Temperature	26.71	26.71	26.71	26.73	26.71	26.73	26.71	26.71	26.73	26.78
Conductivity	1.57	1.57	1.58	1.56	1.59	1.52	1.56	1.57	1.54	1.66
Suspended Solids, mg/L	1	82	7500	10	8	3340	7	14	8020	2032
Sludge Volume Index			117			72			70	74
Soluble COD, mg/L	13	47	97	34	64	79	54	86	136	36

Date: 11/2/2001

Location Points	Point 1			Point 2			Point 3			ABE
	C _{1-S}	C ₁₋₁₀	C ₁₋₁₄	C _{2-S}	C ₂₋₁₀	C ₂₋₁₅	C _{3-S}	C ₃₋₁₀	C ₃₋₁₇	
NO ₃ ⁻ mg/L	13.13	12.90	7.38	12.70	12.74	7.04	13.03	12.98	1.80	13.15
NO ₂ ⁻ mg/L	0.08	0.09	1.23	0.20	0.15	0.19	0.07	0.07	0.04	0.04
Ortho - P mg/L	0.80	0.04	0.05	0.06	0.04	0.07	0.06	0.06	0.90	0.05
Total - P mg/L	0.11	1.14	17.89	0.21	1.22	59.37	0.03	0.07	136.00	54.45
Dissolved Oxygen, mg/L	0.16	0.12	0.12	0.14	0.11	0.10	0.17	0.12	0.12	2.10
ORP	68	67	66	61	59	57	51	44	40	95
pH	7.01	7.01	7.01	7.02	7.01	7.01	7.02	7.01	7.02	6.93
Temperature	26.7	26.69	26.69	26.71	26.69	26.71	26.71	26.69	26.71	26.73
Conductivity	1.54	1.57	1.57	1.54	1.54	1.5	1.56	1.57	1.52	1.63
Suspended Solids, mg/L	11	39	3520	7	25	7560	2	8	11340	2052
Sludge Volume Index			54			95			86	63
Soluble COD, mg/L	13	86	93	43	86	108	43	43	90	38

Date: 11/9/2001

Location Points	Point 1			Point 2			Point 3			ABE
	C _{1-S}	C ₁₋₁₀	C ₁₋₁₄	C _{2-S}	C ₂₋₁₀	C ₂₋₁₅	C _{3-S}	C ₃₋₁₀	C ₃₋₁₇	
NO ₃ ⁻ mg/L	13.52	13.49	0.14	13.55	13.48	7.87	13.48	13.59	3.34	13.28
NO ₂ ⁻ mg/L	0.05	0.05	0.04	0.05	0.05	0.16	0.06	0.04	0.04	0.05
Ortho - P mg/L	0.09	0.01	12.52	-0.01	0.10	0.05	0.07	0.03	3.50	0.80
Total - P mg/L	0.14	4.06	58.05	0.05	3.17	58.55	0.20	1.88	119.50	55.27
Dissolved Oxygen, mg/L	0.24	0.24	0.23	0.25	0.2	0.17	0.22	0.19	0.16	1.8
ORP	91	92	92	81	74	66	72	64	52	98
pH	7.04	7.03	7.03	7.03	7.03	7.03	7.03	7.02	7.02	6.94
Temperature	26.21	26.21	26.21	26.21	26.21	26.23	26.23	26.23	26.25	26.27
Conductivity	1.55	1.55	1.56	1.55	1.55	1.54	1.57	1.56	1.51	1.66
Suspended Solids, mg/L	3	76	8240	4	4	7780	7	2	11740	2004
Sludge Volume Index			117			117			83	75
Soluble COD, mg/L	12	86	119	43	86	108	53	54	123	43

Date: 11/14/2001

Location Points	Point 1			Point 2			Point 3			ABE
	C _{1-S}	C ₁₋₁₀	C ₁₋₁₄	C _{2-S}	C ₂₋₁₀	C ₂₋₁₅	C _{3-S}	C ₃₋₁₀	C ₃₋₁₇	
NO ₃ ⁻ mg/L	13.62	13.64	13.00	13.71	13.68	2.71	13.64	13.68	1.34	13.51
NO ₂ ⁻ mg/L	0.04	0.05	0.18	0.05	0.04	0.12	0.05	0.05	0.04	0.04
Ortho - P mg/L	0.13	0.07	1.48	0.28	0.02	0.00	0.09	0.06	1.82	0.17
Total - P mg/L	0.26	1.32	27.06	0.57	3.99	54.30	0.36	0.71	109.00	49.05
Dissolved Oxygen, mg/L	0.2	0.17	0.17	0.2	0.16	0.12	0.23	0.14	0.13	1.98
ORP	81	83	80	79	79	54	60	59	48	90
pH	7.10	7.10	7.10	7.09	7.09	7.10	7.07	7.07	7.08	7.00
Temperature	25.85	25.86	25.86	25.86	25.86	25.88	25.82	25.86	25.9	25.93
Conductivity	1.52	1.54	1.53	1.52	1.54	1.51	1.52	1.55	1.48	1.62
Suspended Solids, mg/L	36	86	1880	14	43	10100	6	58	12320	1982
Sludge Volume Index			128			97			80	81
Soluble COD, mg/L	28	54	90	44	59	108	64	97	125	33

Date: 11/16/2001

Location Points	Point 1			Point 2			Point 3			ABE
	C _{1-S}	C ₁₋₁₀	C ₁₋₁₄	C _{2-S}	C ₂₋₁₀	C ₂₋₁₅	C _{3-S}	C ₃₋₁₀	C ₃₋₁₇	
NO ₃ ⁻ mg/L	14.80	13.01	8.02	14.21	12.14	8.32	13.42	9.32	2.14	12.56
NO ₂ ⁻ mg/L	0.11	0.04	0.10	0.01	0.05	0.23	0.02	0.21	0.96	0.02
Ortho - P mg/L	0.06	0.07	2.19	0.06	0.06	0.06	0.06	0.06	2.26	0.04
Total - P mg/L	0.33	2.06	41.04	0.12	0.69	55.01	0.13	1.18	91.23	45.03
Dissolved Oxygen, mg/L	0.26	0.23	0.22	0.24	0.22	0.2	0.28	0.23	0.17	2.01
ORP	104	103	102	72	81	84	74	71	57	118
pH	7.01	7.02	7.04	7.01	7.02	7.03	6.95	6.99	7.03	6.96
Temperature	24.82	24.8	24.82	24.83	24.8	24.81	24.81	24.79	24.82	24.84
Conductivity	1.55	1.55	1.55	1.54	1.55	1.55	1.55	1.55	1.5	1.64
Suspended Solids, mg/L	10	56	3860	16	28	9200	17	50	9900	2352
Sludge Volume Index			166			107			99	77
Soluble COD, mg/L	28	54	86	58	66	108	54	75	64	43

Date: 11/21/2001

Location Points	Point 1			Point 2			Point 3			ABE
	C _{1-S}	C ₁₋₁₀	C ₁₋₁₄	C _{2-S}	C ₂₋₁₀	C ₂₋₁₅	C _{3-S}	C ₃₋₁₀	C ₃₋₁₇	
NO ₃ ⁻ mg/L	11.70	11.67	10.94	11.74	11.70	0.79	11.70	11.72	0.50	12.32
NO ₂ ⁻ mg/L	0.04	0.04	0.15	0.04	0.03	0.05	0.03	0.03	0.09	0.04
Ortho - P mg/L	0.04	0.07	1.27	0.06	0.03	4.22	0.04	0.05	0.21	0.07
Total - P mg/L	0.21	70.00	45.69	0.56	0.03	59.18	0.05	0.55	89.50	43.10
Dissolved Oxygen, mg/L	0.17	0.13	0.12	0.16	0.12	0.11	0.16	0.14	0.13	2.21
ORP	83	82	81	83	83	79	80	79	79	123
pH	6.95	6.95	6.97	6.95	6.96	7.00	6.95	6.96	7.03	6.94
Temperature	24.72	24.72	24.71	24.73	24.73	24.73	24.73	24.74	24.73	24.81
Conductivity	1.52	1.52	1.53	1.52	1.53	1.53	1.53	1.55	1.55	1.63
Suspended Solids, mg/L	5	26	4210	7	15	8421	12	21	9423	2561
Sludge Volume Index			170			110			95	84
Soluble COD, mg/L	13	35	80	43	54	98	54	80	60	53

Date: 11/23/2001										
Location Points	Point 1			Point 2			Point 3			ABE
	C _{1-S}	C ₁₋₁₀	C ₁₋₁₄	C _{2-S}	C ₂₋₁₀	C ₂₋₁₅	C _{3-S}	C ₃₋₁₀	C ₃₋₁₇	
NO ₃ ⁻ mg/L	11.52	11.41	11.83	11.53	11.29	0.15	11.51	11.28	5.58	13.23
NO ₂ ⁻ mg/L	0.37	0.28	0.60	0.35	0.32	0.14	0.33	0.31	1.35	0.62
Ortho - P mg/L	0.10	0.06	0.96	0.08	0.08	8.14	0.04	0.06	0.94	0.06
Total - P mg/L	0.50	0.22	6.92	0.64	0.56	59.68	0.33	0.13	127.00	60.45
Dissolved Oxygen, mg/L	0.16	0.16	0.12	0.15	0.14	0.12	0.16	0.15	0.15	2.31
ORP	75	74	71	75	72	72	73	71	57	115
pH	6.99	6.99	6.98	6.98	6.99	7.15	6.95	6.96	7.02	6.95
Temperature	24.3	24.31	24.3	24.3	24.32	24.32	24.35	24.35	24.36	24.42
Conductivity	1.58	1.58	1.58	1.57	1.58	1.56	1.56	1.54	1.52	1.67
Suspended Solids, mg/L	12	30	3500	10	20	8654	6	40	6042	2600
Sludge Volume Index			172			111			100	72
Soluble COD, mg/L	15	71	98	43	58	120	54	75	52	62
Date: 12/12/2001										
Location Points	Point 1			Point 2			Point 3			ABE
	C _{1-S}	C ₁₋₁₀	C ₁₋₁₄	C _{2-S}	C ₂₋₁₀	C ₂₋₁₅	C _{3-S}	C ₃₋₁₀	C ₃₋₁₇	
NO ₃ ⁻ mg/L	13.60	12.53	11.23	13.25	13.20	12.85	13.74	12.54	3.28	11.11
NO ₂ ⁻ mg/L	0.02	0.03	0.08	0.03	0.07	0.09	0.21	0.07	0.47	0.23
Ortho - P mg/L	0.30	0.02	14.24	0.01	0.04	0.97	0.05	0.06	0.60	0.45
Total - P mg/L	0.27	0.32	36.92	0.27	0.52	63.17	0.11	0.70	103.00	31.94
Dissolved Oxygen, mg/L	0.25	0.23	0.21	0.22	0.2	0.19	0.23	0.21	0.18	1.85
ORP	81	80	80	78	76	69	60	55	54	125
Conductivity	7.14	7.14	7.13	7.09	7.11	7.09	7.08	7.13	7.14	7.08
pH	23.10	23.51	23.53	23.51	23.51	23.51	23.52	23.50	23.50	23.57
Temperature	1.55	1.54	1.55	1.56	1.54	1.54	1.54	1.54	1.56	1.64
Suspended Solids, mg/L	10	53	3660	17	27	9000	17	50	9500	2780
Sludge Volume Index			77			53			52	76
Soluble COD, mg/L	23	23	54	33	43	108	23	33	59	41

Date: 12/14/2001

Location Points	Point 1			Point 2			Point 3			ABE
	C _{1-S}	C ₁₋₁₀	C ₁₋₁₄	C _{2-S}	C ₂₋₁₀	C ₂₋₁₅	C _{3-S}	C ₃₋₁₀	C ₃₋₁₇	
NO ₃ ⁻ mg/L	15.30	14.95	14.20	14.86	14.30	12.21	14.78	13.65	4.12	12.87
NO ₂ ⁻ mg/L	0.02	0.03	0.09	0.02	0.04	0.06	0.33	0.05	0.20	0.05
Ortho - P mg/L	0.13	0.12	8.83	0.12	0.13	0.09	0.13	0.12	0.20	0.05
Total - P mg/L	0.29	2.60	61.24	0.29	0.43	46.19	0.29	1.85	59.00	26.95
Dissolved Oxygen, mg/L	-	-	-	-	-	-	-	-	-	-
ORP	-	-	-	-	-	-	-	-	-	-
pH	-	-	-	-	-	-	-	-	-	-
Temperature	-	-	-	-	-	-	-	-	-	-
Conductivity	-	-	-	-	-	-	-	-	-	-
Suspended Solids, mg/L	8	55	1580	6	27	6600	9	5	7400	2210
Sludge Volume Index			108			68			62	77
Soluble COD, mg/L	21	33	64	23	23	86	54	43	121	23

Date: 12/19/2001

Location Points	Point 1			Point 2			Point 3			ABE
	C _{1-S}	C ₁₋₁₀	C ₁₋₁₄	C _{2-S}	C ₂₋₁₀	C ₂₋₁₅	C _{3-S}	C ₃₋₁₀	C ₃₋₁₇	
NO ₃ ⁻ mg/L	13.70	13.54	12.98	13.54	13.11	10.12	13.21	11.57	2.56	12.11
NO ₂ ⁻ mg/L	0.02	0.66	0.13	0.02	0.09	0.21	0.09	0.99	0.46	0.07
Ortho - P mg/L	0.06	0.39	12.93	0.06	0.37	1.16	0.07	0.05	0.96	2.74
Total - P mg/L	0.08	0.60	33.10	0.08	0.53	4.96	0.09	0.38	41.48	0.19
Dissolved Oxygen, mg/L	-	-	-	-	-	-	-	-	-	-
ORP	-	-	-	-	-	-	-	-	-	-
pH	-	-	-	-	-	-	-	-	-	-
Temperature	-	-	-	-	-	-	-	-	-	-
Conductivity	-	-	-	-	-	-	-	-	-	-
Suspended Solids, mg/L	9	50	1900	8	17	6720	9	1	6900	2160
Sludge Volume Index			95			52			51	83
Soluble COD, mg/L	19	47	64	33	43	99	35	43	108	33

Date: 12/21/2001

Location Points	Point 1			Point 2			Point 3			ABE
	C _{1-S}	C ₁₋₁₀	C ₁₋₁₄	C _{2-S}	C ₂₋₁₀	C ₂₋₁₅	C _{3-S}	C ₃₋₁₀	C ₃₋₁₇	
NO ₃ ⁻ mg/L	11.38	11.00	11.26	11.17	10.75	0.21	11.17	11.57	2.06	11.04
NO ₂ ⁻ mg/L	0.08	0.09	0.13	0.05	0.08	1.10	0.06	0.08	0.05	0.08
Ortho - P mg/L	0.19	0.10	0.20	0.14	0.21	3.10	0.13	0.12	1.76	0.13
Total - P mg/L	0.28	1.75	54.03	0.38	0.33	56.64	0.13	2.80	25.50	19.95
Dissolved Oxygen, mg/L	-	-	-	-	-	-	-	-	-	-
ORP	-	-	-	-	-	-	-	-	-	-
pH	-	-	-	-	-	-	-	-	-	-
Temperature	-	-	-	-	-	-	-	-	-	-
Conductivity	-	-	-	-	-	-	-	-	-	-
Suspended Solids, mg/L	2	80	480	1	13	2260	6	8	1820	2360
Sludge Volume Index			167			80			77	89
Soluble COD, mg/L	35	59	64	28	43	75	43	54	85	33

Date: 12/26/2001

Location Points	Point 1			Point 2			Point 3			ABE
	C _{1-S}	C ₁₋₁₀	C ₁₋₁₄	C _{2-S}	C ₂₋₁₀	C ₂₋₁₅	C _{3-S}	C ₃₋₁₀	C ₃₋₁₇	
NO ₃ ⁻ mg/L	11.41	11.71	0.08	10.76	10.46	10.41	11.71	11.20	4.06	6.77
NO ₂ ⁻ mg/L	1.01	1.13	6.86	0.96	2.63	0.67	5.08	1.42	0.13	0.09
Ortho - P mg/L	0.06	0.05	2.11	0.06	0.06	0.09	0.05	0.05	0.21	0.07
Total - P mg/L	0.23	1.90	57.06	0.07	-1.44	28.65	0.22	0.50	68.14	31.68
Dissolved Oxygen, mg/L	-	-	-	-	-	-	-	-	-	-
ORP	-	-	-	-	-	-	-	-	-	-
pH	-	-	-	-	-	-	-	-	-	-
Temperature	-	-	-	-	-	-	-	-	-	-
Conductivity	-	-	-	-	-	-	-	-	-	-
Suspended Solids, mg/L	15	46	1000	9	16	3440	7	5	3570	2220
Sludge Volume Index			120			58			50	86
Soluble COD, mg/L	23	43	54	40	43	75	47	54	151	33

Date:		12/28/2001								
Location Points	Point 1			Point 2			Point 3			ABE
	C _{1-S}	C ₁₋₁₀	C ₁₋₁₄	C _{2-S}	C ₂₋₁₀	C ₂₋₁₅	C _{3-S}	C ₃₋₁₀	C ₃₋₁₇	
NO ₃ ⁻ mg/L	14.20	13.26	12.23	14.00	11.28	9.87	13.98	11.58	2.10	12.48
NO ₂ ⁻ mg/L	0.51	0.26	5.01	0.27	1.46	1.25	3.28	0.90	5.22	3.15
Ortho - P mg/L	0.13	0.14	5.05	0.12	0.07	0.07	0.03	0.11	1.34	0.11
Total - P mg/L	0.21	54.41	0.52	0.12	0.25	10.64	0.39	-0.08	39.80	36.50
Dissolved Oxygen, mg/L	-	-	-	-	-	-	-	-	-	-
ORP	-	-	-	-	-	-	-	-	-	-
pH	-	-	-	-	-	-	-	-	-	-
Temperature	-	-	-	-	-	-	-	-	-	-
Conductivity	-	-	-	-	-	-	-	-	-	-
Suspended Solids, mg/L	16	34	3700	19	20	2780	14	19	8965	1950
Sludge Volume Index			49			65			60	72
Soluble COD, mg/L	28	43	64	35	54	64	43	54	63	23
Date:		1/2/2002								
Location Points	Point 1			Point 2			Point 3			ABE
	C _{1-S}	C ₁₋₁₀	C ₁₋₁₄	C _{2-S}	C ₂₋₁₀	C ₂₋₁₅	C _{3-S}	C ₃₋₁₀	C ₃₋₁₇	
NO ₃ ⁻ mg/L	13.00	12.11	7.65	13.26	12.77	6.87	13.03	10.54	0.02	14.12
NO ₂ ⁻ mg/L	0.06	0.12	1.23	0.09	1.00	1.33	0.09	0.10	3.22	0.65
Ortho - P mg/L	0.06	0.08	6.77	0.06	0.07	0.28	0.06	0.06	4.12	1.30
Total - P mg/L	0.09	1.28	10.35	0.08	0.76	2.98	0.09	1.73	75.00	23.58
Dissolved Oxygen, mg/L	-	-	-	-	-	-	-	-	-	-
ORP	-	-	-	-	-	-	-	-	-	-
pH	-	-	-	-	-	-	-	-	-	-
Temperature	-	-	-	-	-	-	-	-	-	-
Conductivity	-	-	-	-	-	-	-	-	-	-
Suspended Solids, mg/L	19	70	3020	49	18	2960	27	23	11999	2400
Sludge Volume Index			66			61			58	75
Soluble COD, mg/L	33	43	75	33	35	54	43	48	82	33

Date: 1/4/2002										
Location Points	Point 1			Point 2			Point 3			ABE
	C _{1-S}	C ₁₋₁₀	C ₁₋₁₄	C _{2-S}	C ₂₋₁₀	C ₂₋₁₅	C _{3-S}	C ₃₋₁₀	C ₃₋₁₇	
NO ₃ ⁻ mg/L	14.00	13.54	12.54	13.87	12.65	5.02	13.66	11.25	0.02	13.47
NO ₂ ⁻ mg/L	0.09	0.10	1.02	0.02	0.03	1.11	0.10	1.00	2.90	0.35
Ortho - P mg/L	0.08	0.07	0.08	0.20	0.09	0.07	0.09	0.08	2.08	0.06
Total - P mg/L	0.30	0.13	10.70	0.30	0.21	23.26	0.12	0.16	17.70	74.17
Dissolved Oxygen, mg/L	-	-	-	-	-	-	-	-	-	-
ORP	-	-	-	-	-	-	-	-	-	-
pH	-	-	-	-	-	-	-	-	-	-
Temperature	-	-	-	-	-	-	-	-	-	-
Conductivity	-	-	-	-	-	-	-	-	-	-
Suspended Solids, mg/L	2	79	420	1	10	3180	7	7	12800	2390
Sludge Volume Index			71			66			68	71
Soluble COD, mg/L	16	61	64	33	54	75	43	47	87	38

Date: 1/9/2002										
Location Points	Point 1			Point 2			Point 3			ABE
	C _{1-S}	C ₁₋₁₀	C ₁₋₁₄	C _{2-S}	C ₂₋₁₀	C ₂₋₁₅	C _{3-S}	C ₃₋₁₀	C ₃₋₁₇	
NO ₃ ⁻ mg/L	13.90	13.25	13.00	13.65	11.87	7.03	13.19	10.36	0.09	15.12
NO ₂ ⁻ mg/L	0.03	0.04	0.10	0.02	0.03	0.09	0.05	0.10	1.12	0.09
Ortho - P mg/L	0.08	0.09	0.04	0.05	0.05	0.26	0.05	0.04	3.39	0.04
Total - P mg/L	0.09	5.31	1.06	0.06	5.27	4.13	0.05	1.66	40	39.5
Dissolved Oxygen, mg/L	-	-	-	-	-	-	-	-	-	-
ORP	-	-	-	-	-	-	-	-	-	-
pH	-	-	-	-	-	-	-	-	-	-
Temperature	-	-	-	-	-	-	-	-	-	-
Conductivity	-	-	-	-	-	-	-	-	-	-
Suspended Solids, mg/L	22	21	2820	7	38	4140	15	10	11542	3230
Sludge Volume Index			71			56			57	65
Soluble COD, mg/L	33	64	75	43	59	86	43	86	83	48

Date:	1/11/2002									
Location Points	Point 1			Point 2			Point 3			ABE
	C _{1-S}	C ₁₋₁₀	C ₁₋₁₄	C _{2-S}	C ₂₋₁₀	C ₂₋₁₅	C _{3-S}	C ₃₋₁₀	C ₃₋₁₇	
NO ₃ ⁻ mg/L	14.39999962	14.03	13.65	14.29	13.08	7.24	14.3	11.57	0.054	13.26
NO ₂ ⁻ mg/L	0.023658	0.014258	0.05684	0.05487	0.07854	0.021554	0.095545	0.099854	1.023	0.05
Ortho - P mg/L	0.09	0.08	0.07	0.08	0.08	0.33	0.08	0.08	5.43	0.06
Total - P mg/L	0.46	9.39	4.67	0.08	2.24	24.97	0.08	7.29	41	21.35
Dissolved Oxygen, mg/L	-	-	-	-	-	-	-	-	-	-
ORP	-	-	-	-	-	-	-	-	-	-
pH	-	-	-	-	-	-	-	-	-	-
Temperature	-	-	-	-	-	-	-	-	-	-
Conductivity	-	-	-	-	-	-	-	-	-	-
Suspended Solids, mg/L	8	67	1720	17	19	2070	18	35	12450	2100
Sludge Volume Index			64			68			71	76
Soluble COD, mg/L	21	43	64	28	38	75	43	54	83.2002046	21
Date:	1/16/2002									
Location Points	Point 1			Point 2			Point 3			ABE
	C _{1-S}	C ₁₋₁₀	C ₁₋₁₄	C _{2-S}	C ₂₋₁₀	C ₂₋₁₅	C _{3-S}	C ₃₋₁₀	C ₃₋₁₇	
NO ₃ ⁻ mg/L	14.69999981	13.65	11.57	14.3	13.65	4.35	14.1	10.54	0.036	13.58
NO ₂ ⁻ mg/L	0.023154	0.05684	0.09747	0.04689	0.07654	0.32516	0.04698	0.067945	0.9827	0.25
Ortho - P mg/L	0.11	0.1	0.34	0.1	0.1	0.1	0.13	0.1	4.13	0.12
Total - P mg/L	0.24	1.81	1.32	0.26	3.21	29.66	0.64	0.3	82	22.9
Dissolved Oxygen, mg/L	0.24	0.23	0.21	0.21	0.2	0.2	0.18	0.15	0.08	1.75
ORP	85	82	81	74	70	64	71	65	60	112
pH	7.04	7.09	7.09	7.01	7.02	7.01	7.01	7.02	7.10	6.95
Temperature	21.78	21.76	21.75	21.76	21.75	21.75	21.75	21.76	21.74	21.8
Conductivity	1.54	1.55	1.54	1.54	1.54	1.53	1.54	1.55	1.55	1.62
Suspended Solids, mg/L	2	79	210	1	10	1590	7	7	11658	2390
Sludge Volume Index			143			88			85	79
Soluble COD, mg/L	18	54	64	23	33	86	23	38	81.5482835	32

Date:		1/18/2002								
Location Points	Point 1			Point 2			Point 3			ABE
	C _{1-S}	C ₁₋₁₀	C ₁₋₁₄	C _{2-S}	C ₂₋₁₀	C ₂₋₁₅	C _{3-S}	C ₃₋₁₀	C ₃₋₁₇	
NO ₃ ⁻ mg/L	15.59	15.31	10.36	15.08	14.16	9.95	15.48	15.33	12.64	19.16
NO ₂ ⁻ mg/L	0.40	0.29	0.36	27.04	0.16	0.31	0.27	0.24	0.27	0.40
Ortho - P mg/L	0.06	0.06	0.32	0.08	0.06	0.09	0.06	0.06	0.95	0.06
Total - P mg/L	0.26	0.64	32.12	0.2	0.61	22.79	0.21	0.19	22.5	8.45
Dissolved Oxygen, mg/L	0.14	0.13	0.11	0.13	0.13	0.11	0.12	0.12	0.12	1.82
ORP	65	64	62	64	62	61	63	62	61	98
pH	6.75	6.75	6.76	6.75	6.76	6.76	6.75	6.76	6.84	6.74
Temperature	23.9	23.89	23.89	23.89	23.89	23.89	23.89	23.89	23.89	23.91
Conductivity	1.51	1.51	1.52	1.53	1.52	1.52	1.52	1.55	1.55	1.64
Suspended Solids, mg/L	38	62	400	5	9	7020	4	19	3740	2410
Sludge Volume Index			100			78			70	71
Soluble COD, mg/L	30	54	64	33	75	108	43	73	52.6980085	23
Date:		1/23/2002								
Location Points	Point 1			Point 2			Point 3			ABE
	C _{1-S}	C ₁₋₁₀	C ₁₋₁₄	C _{2-S}	C ₂₋₁₀	C ₂₋₁₅	C _{3-S}	C ₃₋₁₀	C ₃₋₁₇	
NO ₃ ⁻ mg/L	13.93	11.26	11.13	12.02	12.8	9.64	13.02	12.39	1.42	13.97
NO ₂ ⁻ mg/L	0.07	1.23	0.74	0.31	0.17	0.06	0.32	0.05	0.06	0.01
Ortho - P mg/L	0.10	0.09	0.10	0.10	0.09	0.11	0.09	0.08	0.69	0.07
Total - P mg/L	0.15	-1.32	-3.24	0.18	0.87	54.73	0.23	0.38	36	45.82
Dissolved Oxygen, mg/L	0.21	0.2	0.2	0.21	0.21	0.19	0.19	0.19	0.14	1.65
ORP	95	93	91	80	72	67	71	65	58	110
pH	6.70	6.73	6.75	6.74	6.78	6.81	6.67	6.67	6.78	6.69
Temperature	22.12	22.1	22.12	22.11	22.11	22.1	22.13	22.11	22.11	22.15
Conductivity	1.57	1.56	1.54	1.55	1.53	1.53	1.52	1.53	1.53	1.65
Suspended Solids, mg/L	7	62	400	5	9	7020	4	19	3140	2410
Sludge Volume Index			100			82			79	71
Soluble COD, mg/L	28	43	64	33	64	108	43	75	105	43

Date: 1/30/2002										
Location Points	Point 1			Point 2			Point 3			ABE
	C _{1-S}	C ₁₋₁₀	C ₁₋₁₄	C _{2-S}	C ₂₋₁₀	C ₂₋₁₅	C _{3-S}	C ₃₋₁₀	C ₃₋₁₇	
NO ₃ ⁻ mg/L	14.24	14.19	14.22	14.15	13.8	14.03	13.9	14.24	13.28	14.88
NO ₂ ⁻ mg/L	0.069	0.059	0.084	0.065	0.094	0.078	0.060	0.055	0.149	0.273
Ortho - P mg/L	0.09	0.1	0.09	0.1	0.09	0.08	0.12	0.1	0.08	0.09
Total - P mg/L	0.24	2.32	1.24	0.24	0.09	4.42	0.25	0.43	27	49.36
Dissolved Oxygen, mg/L	0.23	0.21	0.21	0.23	0.2	0.2	0.21	0.2	0.21	1.79
ORP	97	92	91	75	69	65	74	68	56	106
pH	6.65	6.76	6.74	6.72	6.75	6.75	6.68	6.66	6.70	6.66
Temperature	21.5	21.51	21.53	21.51	21.51	21.53	21.54	21.52	21.51	21.57
Conductivity	1.55	1.55	1.55	1.56	1.54	1.54	1.53	1.54	1.52	1.68
Suspended Solids, mg/L	17	48	107	9	7	675	7	3	1625	2250
Sludge Volume Index			93			59			55	62
Soluble COD, mg/L	28	61	64	48	51	54	43	48	151	47
Date: 2/1/2002										
Location Points	Point 1			Point 2			Point 3			ABE
	C _{1-S}	C ₁₋₁₀	C ₁₋₁₄	C _{2-S}	C ₂₋₁₀	C ₂₋₁₅	C _{3-S}	C ₃₋₁₀	C ₃₋₁₇	
NO ₃ ⁻ mg/L	13.48	13.22	1.32	13.31	13.04	13.39	14.03	13.94	3.24	15.45
NO ₂ ⁻ mg/L	0.211	0.154	0.259	0.162	0.103	0.237	0.144	0.208	0.083	0.624
Ortho - P mg/L	0.16	0.14	0.18	0.17	0.15	0.12	0.16	0.15	0.14	0.09
Total - P mg/L	0.23	-0.21	1.31	0.29	0.81	19.61	0.28	0.40	70.00	48.34
Dissolved Oxygen, mg/L	0.18	0.18	0.12	0.16	0.12	0.1	0.16	0.15	0.15	1.92
ORP	85	50	48	48	44	42	41	41	40	95
pH	6.8	6.81	6.86	6.8	6.81	6.82	6.81	6.83	6.89	6.8
Temperature	22.5	22.51	22.51	22.53	22.51	22.51	22.5	22.52	22.51	22.56
Conductivity	1.52	1.52	1.53	1.52	1.53	1.53	1.52	1.53	1.53	1.61
Suspended Solids, mg/L	5	15	178	1	16	2050	12	10	7825	2000
Sludge Volume Index			112			78			78	70
Soluble COD, mg/L	16	33	33	13	23	33	54	33	135	54

Date:		2/6/2002								
Location Points	Point 1			Point 2			Point 3			ABE
	C _{1-S}	C ₁₋₁₀	C ₁₋₁₄	C _{2-S}	C ₂₋₁₀	C ₂₋₁₅	C _{3-S}	C ₃₋₁₀	C ₃₋₁₇	
NO ₃ ⁻ mg/L	12.86	12.88	12.92	12.84	12.87	6.41	12.82	12.81	7.82	14.1
NO ₂ ⁻ mg/L	0.079	0.143	0.156	0.086	0.147	0.504	0.074	0.135	0.192	0.187
Ortho - P mg/L	0.12	0.11	0.13	0.12	0.12	0.36	0.13	0.12	0.41	0.07
Total - P mg/L	0.24	0.05	1.15	0.27	0.6	6.69	0.34	0.22	96	44.84
Dissolved Oxygen, mg/L	0.18	0.17	0.17	0.17	0.15	0.15	0.2	0.21	0.16	1.72
ORP	50	50	48	48	44	42	41	41	40	84
pH	6.87	6.88	6.88	6.87	6.88	6.90	6.85	6.89	6.90	6.82
Temperature	22.12	22.12	22.15	22.13	22.12	22.13	22.13	22.14	22.13	22.19
Conductivity	1.56	1.54	1.54	1.58	1.58	1.56	1.55	1.55	1.55	1.68
Suspended Solids, mg/L	9	64	159	6	26	7325	9	4	7725	2325
Sludge Volume Index			63			112			110	65
Soluble COD, mg/L	23	43	54	33	43	86	45	64	105	49

Date:		2/8/2002								
Location Points	Point 1			Point 2			Point 3			ABE
	C _{1-S}	C ₁₋₁₀	C ₁₋₁₄	C _{2-S}	C ₂₋₁₀	C ₂₋₁₅	C _{3-S}	C ₃₋₁₀	C ₃₋₁₇	
NO ₃ ⁻ mg/L	13.25	12.94	12.35	13.47	12.95	6.04	13.65	13.11	8.62	12.33
NO ₂ ⁻ mg/L	0.12	0.2	0.18	0.1	0.19	0.34	0.16	0.17	0.11	0.57
Ortho - P mg/L	0.01	0.21	0.22	0.065	0.15	0.61	0.06	0.06	0.09	0.08
Total - P mg/L	0.42	0.17	0.19	0.34	0.46	25.03	0.06	0.28	49.12	36.43
Dissolved Oxygen, mg/L	0.24	0.19	0.16	0.21	0.19	0.19	0.2	0.2	0.2	1.99
ORP	74	76	76	74	75	77	76	76	77	108
pH	7.03	7.01	7.02	7.02	7.02	7.1	7.03	7.03	7.06	7.02
Temperature	22.1	22	22.1	22.1	22.15	22.1	22.1	22	22	22.2
Conductivity	1.54	1.54	1.55	1.56	1.54	1.53	1.53	1.53	1.54	1.6
Suspended Solids, mg/L	5	80	1780	10	32	7560	1	4	6320	3520
Sludge Volume Index			79			99			104	48
Soluble COD, mg/L	19	43	54	51	75	86	45	64	132	64

Date:		2/13/2002								
Location Points	Point 1			Point 2			Point 3			ABE
	C _{1-S}	C ₁₋₁₀	C ₁₋₁₄	C _{2-S}	C ₂₋₁₀	C ₂₋₁₅	C _{3-S}	C ₃₋₁₀	C ₃₋₁₇	
NO ₃ ⁻ mg/L	12.44	12.71	10.81	12.4	12.68	5.18	12.39	12.52	0.15	15.7
NO ₂ ⁻ mg/L	0.43	0.62	0.47	0.42	0.61	0.78	0.4	0.52	1.58	0.95
Ortho - P mg/L	0.18	0.53	0.74	0.18	0.21	0.73	0.18	0.19	2.62	0.09
Total - P mg/L	0.19	1.74	2.01	0.21	2.08	48.29	0.2	1.47	91.4	39.81
Dissolved Oxygen, mg/L	6.9	6.9	6.91	6.92	6.91	6.92	6.92	6.92	7.03	6.91
ORP	84	86	86	87	88	88	88	89	91	125
pH	6.9	6.9	6.91	6.92	6.91	6.92	6.92	6.92	7.03	6.91
Temperature	22.8	22.8	22.8	22.82	22.81	22.81	22.83	22.81	22.81	22.84
Conductivity	1.5	1.49	1.51	1.51	1.52	1.5	1.51	1.52	1.51	1.59
Suspended Solids, mg/L	11	98	2520	0	49	5500	2	14	10880	3200
Sludge Volume Index			103			95			89	56
Soluble COD, mg/L	23	43	75	33	48	54	63	43	97	48

Date:		2/15/2002								
Location Points	Point 1			Point 2			Point 3			ABE
	C _{1-S}	C ₁₋₁₀	C ₁₋₁₄	C _{2-S}	C ₂₋₁₀	C ₂₋₁₅	C _{3-S}	C ₃₋₁₀	C ₃₋₁₇	
NO ₃ ⁻ mg/L	11.99	12.94	9.99	13.04	11.95	3.27	12.95	13.03	0.15	13.47
NO ₂ ⁻ mg/L	0.19	0.15	0.43	0.11	0.17	3.68	0.11	0.13	0.04	0.20
Ortho - P mg/L	0.09	0.13	3.88	0.11	0.14	0.39	0.08	0.13	0.44	0.09
Total - P mg/L	0.29	0.76	43.24	0.31	1.75	36.12	0.34	0.96	145.80	40.09
Dissolved Oxygen, mg/L	0.17	0.17	0.13	0.16	0.16	0.12	0.154	0.15	0.145	2.11
ORP	95	95	93	94	94	95	94	95	95	131
pH	6.95	6.95	6.99	6.94	6.95	7	6.94	6.95	6.97	6.9
Temperature	23.88	23.87	23.87	23.86	23.86	23.86	23.86	23.86	23.85	23.9
Conductivity	1.53	1.52	1.52	1.53	1.52	1.52	1.53	1.54	1.52	1.62
Suspended Solids, mg/L	9	99	7880	0	8	4280	2	28	13260	2320
Sludge Volume Index			95			70			69	60
Soluble COD, mg/L	18	86	109	17	43	51	32	41	141	54

Date: 2/22/2002

Location Points	Point 1			Point 2			Point 3			ABE
	C _{1-S}	C ₁₋₁₀	C ₁₋₁₄	C _{2-S}	C ₂₋₁₀	C ₂₋₁₅	C _{3-S}	C ₃₋₁₀	C ₃₋₁₇	
NO ₃ ⁻ mg/L	14.5	14.11	13.56	14.58	14.36	13.99	14.87	12.54	10.23	13.24
NO ₂ ⁻ mg/L	0.021354	0.03254	0.03699	0.541236	0.02879	0.088745	0.05574	0.04697	0.998547	0.012457
Ortho - P mg/L	0.13	0.14	2.63	0.17	0.12	0.11	0.12	0.11	0.30	0.08
Total - P mg/L	0.24	1.21	32.95	0.40	0.68	10.93	0.29	0.32	91.00	44.35
Dissolved Oxygen, mg/L	-	-	-	-	-	-	-	-	-	-
ORP	-	-	-	-	-	-	-	-	-	-
pH	-	-	-	-	-	-	-	-	-	-
Temperature	-	-	-	-	-	-	-	-	-	-
Conductivity	-	-	-	-	-	-	-	-	-	-
Suspended Solids, mg/L	9	120	2140	15	11	3760	5	27	7600	2480
Sludge Volume Index			192			173			118	56
Soluble COD, mg/L	28	68	94	47	64	97	48	75	138	54

Date: 2/27/2002

Location Points	Point 1			Point 2			Point 3			ABE
	C _{1-S}	C ₁₋₁₀	C ₁₋₁₄	C _{2-S}	C ₂₋₁₀	C ₂₋₁₅	C _{3-S}	C ₃₋₁₀	C ₃₋₁₇	
NO ₃ ⁻ mg/L	13.40	10.66	6.63	12.04	11.02	5.74	11.39	11.29	2.24	9.63
NO ₂ ⁻ mg/L	0.27	0.34	0.53	0.26	0.32	0.67	0.31	0.31	0.44	0.60
Ortho - P mg/L	0.13	0.17	0.27	0.14	0.16	0.30	0.14	0.16	0.44	0.14
Total - P mg/L	0.21	0.06	2.42	0.26	0.18	4.57	0.22	0.11	31.80	75.52
Dissolved Oxygen, mg/L	0.2	0.2	0.19	0.21	0.2	0.19	0.22	0.21	0.2	2.31
ORP	81	79	78	80	78	74	78	72	68	108
pH	6.88	6.87	6.85	6.88	6.87	6.85	6.87	6.87	6.93	6.89
Temperature	23.56	23.56	23.54	23.56	23.56	23.56	23.56	23.57	23.56	23.63
Conductivity	18	54	64	43	64	85	54	43	132	33
Suspended Solids, mg/L	1	26	3640	3	33	6340	1	3	5740	2340
Sludge Volume Index			104			109			110	73
Soluble COD, mg/L	18	54	64	43	64	85	54	43	132	33

Date:		3/1/2002								
Location Points	Point 1			Point 2			Point 3			ABE
	C _{1-S}	C ₁₋₁₀	C ₁₋₁₄	C _{2-S}	C ₂₋₁₀	C ₂₋₁₅	C _{3-S}	C ₃₋₁₀	C ₃₋₁₇	
NO ₃ ⁻ mg/L	13.93	13.73	13.02	13.98	13.92	12.85	14.03	13.94	8.16	14.75
NO ₂ ⁻ mg/L	0.16	0.17	0.09	0.00	0.16	0.07	0.15	0.16	0.49	0.18
Ortho - P mg/L	0.15	0.17	0.15	0.16	0.16	0.12	0.15	0.16	0.43	0.02
Total - P mg/L	0.24	0.51	2.71	0.22	0.06	0.68	3.45	0.07	76.90	87.17
Dissolved Oxygen, mg/L	0.14	0.14	0.12	0.15	0.13	11	0.16	0.15	0.19	1.98
ORP	75	75	71	75	74	74	75	70	63	101
pH	6.85	6.85	6.89	6.84	6.85	6.9	6.87	6.87	6.91	6.87
Temperature	23.91	23.92	23.92	23.91	23.91	23.93	23.92	23.92	23.93	23.98
Conductivity	1.53	1.53	1.52	1.53	1.54	1.54	1.55	1.53	1.55	1.66
Suspended Solids, mg/L	11	47	2820	7	10	8820	9	16	9340	2490
Sludge Volume Index			103			99			96	100
Soluble COD, mg/L	18	33	75	23	38	86	28	32	120	41
Date:		3/6/2002								
Location Points	Point 1			Point 2			Point 3			ABE
	C _{1-S}	C ₁₋₁₀	C ₁₋₁₄	C _{2-S}	C ₂₋₁₀	C ₂₋₁₅	C _{3-S}	C ₃₋₁₀	C ₃₋₁₇	
NO ₃ ⁻ mg/L	10.31	13.11	11.34	12.80	11.38	4.39	12.82	12.85	3.07	16.02
NO ₂ ⁻ mg/L	0.17	0.36	1.02	0.22	0.98	0.69	0.20	0.28	0.96	0.40
Ortho - P mg/L	0.12	0.15	0.19	0.13	0.14	0.51	0.11	0.14	1.30	0.06
Total - P mg/L	0.23	0.33	2.61	0.23	0.20	4.65	0.44	0.01	78.70	83.28
Dissolved Oxygen, mg/L	0.15	0.14	0.12	0.145	0.14	0.12	0.14	0.13	0.16	2.35
ORP	81	80	77	80	79	75	78	75	69	112
pH	6.91	6.91	6.93	6.91	6.92	6.93	6.91	6.91	6.97	6.9
Temperature	23.95	23.96	23.96	23.96	23.95	23.96	23.96	23.96	23.95	24.01
Conductivity	1.61	1.61	1.6	1.62	1.62	1.6	1.63	1.62	1.59	1.71
Suspended Solids, mg/L	5	67	2182	2	14	4120	8	13	7180	2940
Sludge Volume Index			101			100			97	99
Soluble COD, mg/L	18	33	66	18	23	75	23	33	86	45

Date: 3/8/2002										
Location Points	Point 1			Point 2			Point 3			ABE
	C _{1-S}	C ₁₋₁₀	C ₁₋₁₄	C _{2-S}	C ₂₋₁₀	C ₂₋₁₅	C _{3-S}	C ₃₋₁₀	C ₃₋₁₇	
NO ₃ ⁻ mg/L	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
NO ₂ ⁻ mg/L	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
Ortho - P mg/L	0.11	0.13	0.18	0.10	0.12	0.10	0.13	0.10	0.39	0.04
Total - P mg/L	NR	NR	NR	NR	NR	NR	NR	NR	90.00	NR
Dissolved Oxygen, mg/L	0.15	0.14	0.14	0.15	0.13	0.11	0.15	0.15	0.11	2.45
ORP	82	82	80	81	78	76	83	79	72	130
pH	6.95	6.95	6.96	6.95	6.96	6.96	6.96	6.96	7.04	6.93
Temperature	23.67	23.67	23.68	23.67	23.67	23.67	23.67	23.68	23.67	23.76
Conductivity	1.58	1.58	1.57	1.57	1.56	1.55	1.57	1.57	1.55	1.64
Suspended Solids, mg/L	4	23	3420	10	17	9060	10	13	10100	2910
Sludge Volume Index			99			96			94	89
Soluble COD, mg/L	18	33	46	23	33	75	28	43	118.723289	44
Date: 3/13/2002										
Location Points	Point 1			Point 2			Point 3			ABE
	C _{1-S}	C ₁₋₁₀	C ₁₋₁₄	C _{2-S}	C ₂₋₁₀	C ₂₋₁₅	C _{3-S}	C ₃₋₁₀	C ₃₋₁₇	
NO ₃ ⁻ mg/L	13.37	13.08	13.31	13.65	12.69	12.37	13.69	13.96	7.33	15.06
NO ₂ ⁻ mg/L	0.07	0.24	0.16	0.11	0.36	0.22	0.09	0.09	0.29	0.06
Ortho - P mg/L	0.07	0.09	0.05	0.06	0.08	0.43	0.06	0.06	0.58	0.06
Total - P mg/L	0.28	5.43	58.86	0.19	14.02	103.54	0.21	3.56	87.00	105.05
Dissolved Oxygen, mg/L	0.16	0.15	0.12	0.16	0.14	0.13	0.14	0.14	0.14	2.27
ORP	78	77	76	78	78	72	78	73	65	117
pH	6.98	6.98	6.99	6.98	6.98	6.98	6.99	6.98	7.03	6.97
Temperature	23.56	23.56	23.56	23.56	23.56	23.56	23.56	23.56	23.55	23.6
Conductivity	1.59	1.58	1.55	1.58	1.55	1.55	1.56	1.55	1.52	1.61
Suspended Solids, mg/L	6	17	4540	12	21	10160	18	6	10760	2970
Sludge Volume Index			99			94			91	88
Soluble COD, mg/L	23	64	86	33	75	86	38	108	112	54

Date: 3/15/2002										
Location Points	Point 1			Point 2			Point 3			ABE
	C _{1-S}	C ₁₋₁₀	C ₁₋₁₄	C _{2-S}	C ₂₋₁₀	C ₂₋₁₅	C _{3-S}	C ₃₋₁₀	C ₃₋₁₇	
NO ₃ ⁻ mg/L	13.07	13.72	13.29	14.40	14.30	3.99	13.53	13.89	6.88	14.57
NO ₂ ⁻ mg/L	0.34	0.21	0.07	0.07	0.06	0.91	0.11	0.22	0.38	0.04
Ortho - P mg/L	0.11	0.69	2.10	0.13	0.14	0.54	0.09	0.22	1.75	0.07
Total - P mg/L	0.25	5.13	76.90	0.46	20.39	77.71	0.62	1.81	62.30	97.30
Dissolved Oxygen, mg/L	0.19	0.15	0.14	0.18	0.15	0.12	0.15	0.14	0.14	1.98
ORP	85	84	84	86	82	80	83	76	72	113
pH	6.84	6.84	6.85	6.85	6.85	6.86	6.85	6.85	6.89	6.83
Temperature	23.61	23.61	23.61	23.64	23.63	23.61	23.61	23.62	23.61	23.72
Conductivity	1.56	1.54	1.54	1.55	1.56	1.52	1.54	1.54	1.52	1.6
Suspended Solids, mg/L	12	70	3720	60	20	6920	20	9	6980	2720
Sludge Volume Index			137			123			122	77
Soluble COD, mg/L	33	46	75	46	64	89	46	54	98	48
Date: 3/22/2002										
Location Points	Point 1			Point 2			Point 3			ABE
	C _{1-S}	C ₁₋₁₀	C ₁₋₁₄	C _{2-S}	C ₂₋₁₀	C ₂₋₁₅	C _{3-S}	C ₃₋₁₀	C ₃₋₁₇	
NO ₃ ⁻ mg/L	13.96	13.72	3.71	12.75	14.20	2.31	15.90	12.64	1.75	14.16
NO ₂ ⁻ mg/L	0.25	0.04	0.08	0.28	0.04	1.02	0.44	0.05	0.04	0.29
Ortho - P mg/L	0.08	0.08	0.08	0.07	0.08	0.13	0.07	0.09	0.15	0.05
Total - P mg/L	0.24	5.39	61.89	0.29	9.77	106.64	0.39	1.45	39.70	127.30
Dissolved Oxygen, mg/L	0.18	0.16	0.15	0.18	0.18	0.15	0.19	0.17	0.13	2.53
ORP	85	84	80	86	79	84	86	77	70	122
pH	6.95	6.95	6.96	6.95	6.95	6.96	6.95	6.95	7	6.93
Temperature	23.56	23.54	23.55	23.55	23.55	23.55	23.57	23.58	23.58	23.67
Conductivity	1.61	1.6	1.58	1.61	1.58	1.57	1.56	1.56	1.55	1.64
Suspended Solids, mg/L	2	47	5160	10	24	3920	34	17	5780	2440
Sludge Volume Index			138			135			126	82
Soluble COD, mg/L	23	43	85	26	46	78	33	43	107.584738	51

Date: 3/27/2002										
Location Points	Point 1			Point 2			Point 3			ABE
	C _{1-S}	C ₁₋₁₀	C ₁₋₁₄	C _{2-S}	C ₂₋₁₀	C ₂₋₁₅	C _{3-S}	C ₃₋₁₀	C ₃₋₁₇	
NO ₃ ⁻ mg/L	12.76	12.96	12.51	13.11	12.33	4.54	12.80	12.19	8.01	14.44
NO ₂ ⁻ mg/L	0.26	0.30	0.45	0.26	0.39	1.29	0.28	0.67	0.74	0.07
Ortho - P mg/L	0.03	0.05	0.08	0.13	0.07	0.02	0.09	0.51	1.44	0.01
Total - P mg/L	5.00	5.13	19.64	0.38	15.33	69.40	-0.98	2.70	66.50	41.19
Dissolved Oxygen, mg/L	0.23	0.13	0.13	0.18	0.13	0.12	0.18	0.16	0.17	2.45
ORP	77	86	85	86	86	85	85	81	79	121
pH	6.6	6.59	6.59	6.59	6.59	6.6	6.58	6.59	6.61	6.56
Temperature	23.4	2.38	23.38	23.4	23.38	23.38	23.41	23.38	23.4	23.42
Conductivity	1.76	1.82	1.82	1.8	1.8	1.78	1.79	1.8	1.76	1.85
Suspended Solids, mg/L	0	11	1320	10	8	6500	1	11	5960	2840
Sludge Volume Index			114			112			116	183
Soluble COD, mg/L	23	64	75	33	64	97	38	75	55	18
Date: 3/29/2002										
Location Points	Point 1			Point 2			Point 3			ABE
	C _{1-S}	C ₁₋₁₀	C ₁₋₁₄	C _{2-S}	C ₂₋₁₀	C ₂₋₁₅	C _{3-S}	C ₃₋₁₀	C ₃₋₁₇	
NO ₃ ⁻ mg/L	13.52	13.40	11.92	13.11	12.98	6.54	12.37	11.74	5.96	15.90
NO ₂ ⁻ mg/L	0.15	0.04	0.50	0.12	0.30	1.98	0.78	1.84	0.78	0.27
Ortho - P mg/L	0.06	0.07	0.05	0.06	0.08	0.07	0.06	0.07	0.04	0.05
Total - P mg/L	-0.56	4.56	50.98	0.13	8.17	84.53	0.21	0.84	41.00	214.46
Dissolved Oxygen, mg/L	0.21	0.19	0.18	0.17	0.17	0.17	0.19	0.18	0.13	2.8
ORP	124	124	122	120	120	116	115	113	110	144
pH	6.83	6.83	6.85	6.84	6.84	6.86	6.84	6.86	6.88	6.79
Temperature	23.69	23.65	23.65	23.65	23.65	23.65	23.65	23.64	26.65	26.71
Conductivity	1.79	1.79	1.78	1.77	1.77	1.75	1.79	1.78	1.77	1.88
Suspended Solids, mg/L	16	24	1920	104	167	4380	6	3	6840	2500
Sludge Volume Index			156			148			135	112
Soluble COD, mg/L	23	28	75	23	33	89	28	43	63	48

Date:		4/3/2002								
Location Points	Point 1			Point 2			Point 3			ABE
	C _{1-S}	C ₁₋₁₀	C ₁₋₁₄	C _{2-S}	C ₂₋₁₀	C ₂₋₁₅	C _{3-S}	C ₃₋₁₀	C ₃₋₁₇	
NO ₃ ⁻ mg/L	11.94	13.15	13.09	13.64	13.36	9.79	13.12	13.38	11.72	14.15
NO ₂ ⁻ mg/L	0.13	0.15	0.09	0.13	0.16	0.36	0.12	0.16	0.24	0.03
Ortho - P mg/L	0.08	0.07	0.06	0.08	0.08	0.08	0.08	0.08	0.06	0.04
Total - P mg/L	0.23	5.84	56.46	0.17	17.66	138.14	0.25	1.47	44.00	363.08
Dissolved Oxygen, mg/L	0.22	0.21	0.20	0.21	0.19	0.18	0.22	0.21	0.18	2.55
ORP	76	777	76	75	75	75	76	76	75	125
pH	6.67	6.68	6.69	6.68	6.68	6.69	6.68	6.69	6.71	6.67
Temperature	23.96	23.96	23.96	23.96	23.96	23.96	23.96	23.94	23.96	23.98
Conductivity	1.5	1.5	1.49	1.5	1.49	1.45	1.49	1.48	1.46	1.56
Suspended Solids, mg/L	13	128	1400	8	12	4620	17	11	4420	2500
Sludge Volume Index			157			156			152	104
Soluble COD, mg/L	18	33	43	23	38	75	28	75	58	43
Date:		4/5/2002								
Location Points	Point 1			Point 2			Point 3			ABE
	C _{1-S}	C ₁₋₁₀	C ₁₋₁₄	C _{2-S}	C ₂₋₁₀	C ₂₋₁₅	C _{3-S}	C ₃₋₁₀	C ₃₋₁₇	
NO ₃ ⁻ mg/L	13.42	11.98	12.20	12.31	11.73	8.60	12.08	12.48	10.60	12.55
NO ₂ ⁻ mg/L	0.74	0.16	0.12	0.15	0.19	0.61	0.18	0.20	0.31	0.04
Ortho - P mg/L	0.12	0.10	1.82	0.08	0.07	0.06	0.09	0.02	0.13	0.05
Total - P mg/L	0.51	7.26	7.25	0.19	18.65	150.87	0.49	5.90	48.50	218.00
Dissolved Oxygen, mg/L	0.17	0.16	0.14	0.14	0.13	0.12	0.15	0.15	0.21	2.12
ORP	117	116	116	117	118	115	117	116	113	142
pH	6.61	6.62	6.63	6.62	6.62	6.64	6.62	6.62	6.64	6.61
Temperature	24.2	24.19	24.2	24.2	24.2	24.2	24.2	24.21	24.2	24.19
Conductivity	1.53	1.52	1.52	1.51	1.53	1.49	1.52	1.53	1.5	1.63
Suspended Solids, mg/L	1	211	480	15	23	5560	12	26	3980	2460
Sludge Volume Index			167			135			118	122
Soluble COD, mg/L	23	33	54	38	43	97	48	75	54	33

Date: 4/10/2002										
Location Points	Point 1			Point 2			Point 3			ABE
	C _{1-S}	C ₁₋₁₀	C ₁₋₁₄	C _{2-S}	C ₂₋₁₀	C ₂₋₁₅	C _{3-S}	C ₃₋₁₀	C ₃₋₁₇	
NO ₃ ⁻ mg/L	13.86	13.34	12.24	12.83	13.48	11.66	12.58	12.17	6.15	14.27
NO ₂ ⁻ mg/L	0.12	0.12	0.27	0.24	0.11	0.22	0.25	0.28	0.40	0.04
Ortho - P mg/L	0.11	0.11	0.21	0.11	0.09	0.09	0.10	0.09	0.23	0.09
Total - P mg/L	0.40	5.29	40.03	0.27	18.53	105.47	0.22	6.82	57.50	122.26
Dissolved Oxygen, mg/L	0.13	0.1	0.1	0.15	0.14	0.13	0.17	0.16	0.15	2.47
ORP	121	105	106	132	132	130	125	126	123	135
pH	6.77	6.77	6.77	6.78	6.78	6.79	6.78	6.78	6.78	6.73
Temperature	24.27	24.22	24.24	24.24	24.22	24.22	24.27	24.24	24.24	24.27
Conductivity	1.61	1.62	1.6	1.6	1.62	1.59	1.59	1.61	1.59	1.67
Suspended Solids, mg/L	10	70	2100	40	110	2900	20	60	7220	2580
Sludge Volume Index			119			114			108	112
Soluble COD, mg/L	18	38	64	33	48	70	28	54	61	43

Date: 4/12/2002										
Location Points	Point 1			Point 2			Point 3			ABE
	C _{1-S}	C ₁₋₁₀	C ₁₋₁₄	C _{2-S}	C ₂₋₁₀	C ₂₋₁₅	C _{3-S}	C ₃₋₁₀	C ₃₋₁₇	
NO ₃ ⁻ mg/L	15.24	13.21	13.25	13.18	13.15	0.26	13.58	13.38	5.69	13.47
NO ₂ ⁻ mg/L	0.12	0.09	0.10	0.11	0.11	0.04	0.06	0.11	0.34	0.31
Ortho - P mg/L	0.10	0.10	0.15	0.10	0.11	0.28	0.11	0.11	1.06	0.31
Total - P mg/L	0.57	5.41	15.90	0.21	3.32	82.94	0.31	2.42	53.80	143.19
Dissolved Oxygen, mg/L	0.12	0.11	0.1	0.13	0.13	0.12	0.15	0.14	0.16	2.47
ORP	108	106	106	124	124	123	125	122	121	140
pH	6.62	6.63	6.64	6.62	6.63	6.64	6.62	6.63	6.64	6.6
Temperature	24.62	24.6	24.6	24.62	24.59	24.6	24.64	24.59	24.6	24.64
Conductivity	1.59	1.58	1.55	1.58	1.55	1.58	1.57	1.57	1.57	1.63
Suspended Solids, mg/L	10	60	680	0	40	2300	5	30	7600	2620
Sludge Volume Index			103			65			118	99
Soluble COD, mg/L	23	64	97	64	75	108	86	108	61	64

Date: 4/24/2002

Location Points	Point 1			Point 2			Point 3			ABE
	C _{1-S}	C ₁₋₁₀	C ₁₋₁₄	C _{2-S}	C ₂₋₁₀	C ₂₋₁₅	C _{3-S}	C ₃₋₁₀	C ₃₋₁₇	
NO ₃ ⁻ mg/L	13.94	15.17	15.23	15.25	15.08	13.09	15.12	15.15	10.94	16.04
NO ₂ ⁻ mg/L	0.06	0.06	0.05	0.05	0.06	0.12	0.06	0.06	0.13	0.04
Ortho - P mg/L	0.13	0.12	1.57	0.15	0.12	0.25	0.13	0.18	2.05	0.02
Total - P mg/L	0.29	5.14	3.08	0.28	8.36	37.30	0.28	1.72	75.80	231.56
Dissolved Oxygen, mg/L	0.12	0.11	0.1	0.11	0.1	0.09	0.11	0.1	0.14	1.9
ORP	122	122	122	122	121	121	121	121	115	120
pH	6.72	6.72	6.73	6.73	6.73	6.73	6.73	6.73	6.75	6.68
Temperature	24.64	24.6	24.61	24.62	24.6	24.62	24.66	24.6	24.6	24.68
Conductivity	1.486	1.484	1.488	1.487	1.485	1.46	1.483	1.484	1.45	1.52
Suspended Solids, mg/L	30	90	380	40	140	3060	70	50	7620	3060
Sludge Volume Index			79			72			118	65
Soluble COD, mg/L	33	48	72	33	48	89	42	54	62	52

Date: 4/26/2002

Location Points	Point 1			Point 2			Point 3			ABE
	C _{1-S}	C ₁₋₁₀	C ₁₋₁₄	C _{2-S}	C ₂₋₁₀	C ₂₋₁₅	C _{3-S}	C ₃₋₁₀	C ₃₋₁₇	
NO ₃ ⁻ mg/L	12.82	13.89	13.80	13.92	13.78	5.21	11.85	13.85	0.27	14.74
NO ₂ ⁻ mg/L	0.07	0.07	0.12	0.07	0.07	0.18	0.14	0.07	0.07	0.07
Ortho - P mg/L	0.09	0.10	0.94	0.10	0.09	0.10	0.09	0.09	0.63	0.04
Total - P mg/L	0.21	5.23	8.72	0.16	4.12	41.40	0.25	1.08	67.00	81.03
Dissolved Oxygen, mg/L	0.19	0.18	0.13	0.19	0.18	0.1	0.18	0.16	0.09	3.85
ORP	91	91	90	90	89	87	87	87	86	185
pH	6.76	6.76	6.77	6.76	6.76	6.77	6.72	6.77	6.81	6.7
Temperature	24.72	24.6	24.6	24.61	24.6	24.6	24.64	24.6	24.6	24.75
Conductivity	1.52	1.53	1.52	1.53	1.53	1.52	1.53	1.52	1.51	1.6
Suspended Solids, mg/L	10	90	620	50	100	3460	10	110	9840	3340
Sludge Volume Index			113			84			96	81
Soluble COD, mg/L	18	42	58	28	48	75	28	54	95	45

Date: 5/1/2002

Location Points	Point 1			Point 2			Point 3			ABE
	C _{1-S}	C ₁₋₁₀	C ₁₋₁₄	C _{2-S}	C ₂₋₁₀	C ₂₋₁₅	C _{3-S}	C ₃₋₁₀	C ₃₋₁₇	
NO ₃ ⁻ mg/L	13.63	13.69	9.23	13.59	13.60	11.04	13.59	13.62	5.07	14.63
NO ₂ ⁻ mg/L	0.44	0.18	2.56	0.16	0.15	0.39	0.35	0.27	0.54	0.29
Ortho - P mg/L	0.11	0.12	0.09	0.10	0.11	0.08	0.09	0.11	1.62	0.13
Total - P mg/L	0.18	5.20	0.89	0.15	6.29	119.47	0.04	1.52	57.00	134.21
Dissolved Oxygen, mg/L	0.17	0.15	0.13	0.15	0.14	0.14	0.24	0.17	0.13	3.6
ORP	84	83	80	84	84	80	86	84	74	151
pH	6.78	6.78	6.79	6.79	6.79	6.8	6.78	6.78	6.83	6.76
Temperature	24.5	24.42	24.42	24.42	24.42	24.42	24.42	24.42	24.4	24.53
Conductivity	1.57	1.57	1.54	1.57	1.56	1.54	1.56	1.55	1.53	1.66
Suspended Solids, mg/L	6	50	2160	8	33	5280	20	60	8160	3580
Sludge Volume Index			102			100			116	73
Soluble COD, mg/L	18	28	43	23	33	64	23	64	85	33

Date: 5/3/2002

Location Points	Point 1			Point 2			Point 3			ABE
	C _{1-S}	C ₁₋₁₀	C ₁₋₁₄	C _{2-S}	C ₂₋₁₀	C ₂₋₁₅	C _{3-S}	C ₃₋₁₀	C ₃₋₁₇	
NO ₃ ⁻ mg/L	14.76	10.20	0.26	13.94	13.72	13.63	13.62	13.69	0.26	13.60
NO ₂ ⁻ mg/L	0.11	0.58	0.06	0.06	0.36	0.20	0.21	0.36	0.06	0.31
Ortho - P mg/L	0.06	0.05	0.04	0.06	0.06	0.17	0.06	0.05	0.03	0.04
Total - P mg/L	0.11	5.06	2.84	0.16	6.26	72.61	0.19	1.72	69.00	129.50
Dissolved Oxygen, mg/L	0.15	0.14	0.14	0.14	0.13	0.11	0.14	0.12	0.1	3.32
ORP	100	100	100	100	100	92	90	90	74	141
pH	6.77	6.77	6.79	6.78	6.78	6.79	6.78	6.8	6.84	6.75
Temperature	24.8	24.77	24.79	24.79	24.77	24.79	24.83	24.79	24.81	24.88
Conductivity	1.62	1.62	1.61	1.61	1.62	1.6	1.62	1.6	1.6	1.68
Suspended Solids, mg/L	7	35.4	4690	3.8	28	5920	40	170	8502	2999.8
Sludge Volume Index			94			91			91	80
Soluble COD, mg/L	18	23	64	18	33	75	33	64	119	43

Date: 5/8/2002										
Location Points	Point 1			Point 2			Point 3			ABE
	C _{1-S}	C ₁₋₁₀	C ₁₋₁₄	C _{2-S}	C ₂₋₁₀	C ₂₋₁₅	C _{3-S}	C ₃₋₁₀	C ₃₋₁₇	
NO ₃ ⁻ mg/L	15.18	15.00	14.57	14.48	0.35	14.64	14.71	14.57	14.81	7.81
NO ₂ ⁻ mg/L	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.35
Ortho - P mg/L	0.21	0.08	0.08	0.13	0.10	0.07	0.12	0.09	1.30	0.05
Total - P mg/L	0.07	6.22	39.16	0.12	10.42	136.94	0.08	0.82	61.20	123.14
Dissolved Oxygen, mg/L	0.16	0.15	0.13	0.15	0.11	0.07	0.09	0.09	0.09	1.75
ORP	89	87	85	89	88	83	88	87	83	119
pH	6.78	6.78	6.79	6.78	6.78	6.79	6.78	6.78	6.79	6.76
Temperature	25.07	25.05	25.05	25.07	25.05	25.07	25.11	25.05	25.07	25.16
Conductivity	1.63	1.63	1.6	1.63	1.63	1.59	1.61	1.61	1.54	1.7
Suspended Solids, mg/L	27	230	2000	19	70	6640	10	10	7580	3220
Sludge Volume Index			100			128			127	78
Soluble COD, mg/L	23	48	58	23	48	87	28	54	65	48
Date: 5/10/2002										
Location Points	Point 1			Point 2			Point 3			ABE
	C _{1-S}	C ₁₋₁₀	C ₁₋₁₄	C _{2-S}	C ₂₋₁₀	C ₂₋₁₅	C _{3-S}	C ₃₋₁₀	C ₃₋₁₇	
NO ₃ ⁻ mg/L	12.27	14.49	13.95	13.82	14.05	7.39	14.20	15.35	10.47	17.67
NO ₂ ⁻ mg/L	0.21	0.13	0.09	0.18	0.17	0.10	0.18	0.20	0.34	0.09
Ortho - P mg/L	0.10	0.11	0.12	0.11	0.12	0.12	0.10	0.12	1.31	0.09
Total - P mg/L	0.12	5.52	60.94	0.29	2.72	87.69	0.20	-2.34	56.00	126.68
Dissolved Oxygen, mg/L	0.14	0.11	0.11	0.15	0.14	0.13	0.13	0.12	0.06	1.25
ORP	84	82	81	81	78	68	75	75	55	103
pH	6.76	6.76	6.76	6.75	6.76	6.77	6.75	6.75	6.91	6.73
Temperature	25.12	25.07	25.07	25.09	25.07	25.09	25.09	25.07	25.09	25.16
Conductivity	1.64	1.65	1.66	1.66	1.66	1.64	1.66	1.66	1.58	1.76
Suspended Solids, mg/L	35	270	2560	50	70	3700	50	30	5620	5620
Sludge Volume Index			102			124			158	74
Soluble COD, mg/L	30	52	75	43	54	108	43	64	55	48

Date:		5/15/2002								
Location Points	Point 1			Point 2			Point 3			ABE
	C _{1-S}	C ₁₋₁₀	C ₁₋₁₄	C _{2-S}	C ₂₋₁₀	C ₂₋₁₅	C _{3-S}	C ₃₋₁₀	C ₃₋₁₇	
NO ₃ ⁻ mg/L	13.51	12.27	12.02	12.20	12.27	9.39	12.30	12.31	2.75	13.90
NO ₂ ⁻ mg/L	0.19	0.20	0.21	0.20	0.21	0.46	0.18	0.20	0.89	0.09
Ortho - P mg/L	0.09	0.10	0.12	0.09	0.09	0.09	0.08	0.09	0.07	0.08
Total - P mg/L	0.15	5.19	30.25	0.16	5.85	82.27	0.17	3.95	79.00	205.68
Dissolved Oxygen, mg/L	0.15	0.14	0.123	0.14	0.14	0.13	0.14	0.13	0.11	3.6
ORP	66	68	69	70	71	69	70	70	65	142
pH	6.86	6.86	6.87	6.87	6.86	6.87	6.86	6.86	6.94	6.85
Temperature	25.7	25.7	25.7	25.72	25.7	25.7	25.7	25.7	25.72	25.7
Conductivity	1.65	1.66	1.63	1.65	1.67	1.61	1.65	1.65	1.61	1.73
Suspended Solids, mg/L	4	100	840	30	60	5180	10	130	9320	9320
Sludge Volume Index			179			68			61	82
Soluble COD, mg/L	16	28	48	23	38	87	23	64	63	41

Date:		5/17/2002								
Location Points	Point 1			Point 2			Point 3			ABE
	C _{1-S}	C ₁₋₁₀	C ₁₋₁₄	C _{2-S}	C ₂₋₁₀	C ₂₋₁₅	C _{3-S}	C ₃₋₁₀	C ₃₋₁₇	
NO ₃ ⁻ mg/L	14.38	13.38	13.22	13.57	13.43	12.09	13.57	13.50	10.98	15.27
NO ₂ ⁻ mg/L	0.15	0.14	0.15	0.15	0.15	0.20	0.15	0.14	0.24	0.06
Ortho - P mg/L	0.25	0.45	0.63	0.25	0.30	0.76	0.22	0.26	2.71	0.31
Total - P mg/L	0.16	5.09	35.37	0.18	9.61	141.08	0.01	1.49	54.00	150.76
Dissolved Oxygen, mg/L	0.13	0.13	0.12	0.14	0.12	0.11	0.13	0.11	0.13	1.9
ORP	56	56	55	55	55	54	55	53	47	93
pH	6.88	6.89	6.9	6.89	6.89	6.9	6.89	6.89	6.93	6.85
Temperature	26	25.99	25.99	25.99	25.99	25.98	25.99	25.99	25.97	26
Conductivity	1.68	1.65	1.64	1.65	1.65	1.64	1.65	1.65	1.6	1.71
Suspended Solids, mg/L	5	40	480	5	20	3540	3	50	4640	4640
Sludge Volume Index			146			136			134	83
Soluble COD, mg/L	16	23	43	18	33	87	18	43	51	38

Date:	5/22/2002									
Location Points	Point 1			Point 2			Point 3			ABE
	C _{1-S}	C ₁₋₁₀	C ₁₋₁₄	C _{2-S}	C ₂₋₁₀	C ₂₋₁₅	C _{3-S}	C ₃₋₁₀	C ₃₋₁₇	
NO ₃ ⁻ mg/L	13.25	14.37	13.20	14.41	14.32	9.06	14.38	14.34	4.15	16.42
NO ₂ ⁻ mg/L	0.18	0.20	0.20	0.18	0.18	0.44	0.17	0.18	0.73	0.06
Ortho - P mg/L	0.33	0.49	0.52	0.19	0.39	0.80	0.26	0.39	1.03	0.52
Total - P mg/L	0.38	5.33	15.95	0.39	-2.80	67.54	0.37	-5.63	85.00	187.04
Dissolved Oxygen, mg/L	0.13	0.11	0.11	0.14	0.13	0.12	0.15	0.14	0.07	1.50
ORP	71	71	70	74	74	70	73	66	52	106
pH	6.9	6.89	6.89	6.89	6.89	6.9	6.89	6.89	7	6.84
Temperature	25.68	25.68	25.68	25.67	25.67	25.68	25.67	25.67	25.68	25.78
Conductivity	1.69	1.7	1.66	1.71	1.7	1.64	1.68	1.68	1.65	1.76
Suspended Solids, mg/L	2	50	1620	1	20	6220	1	20	9480	9480
Sludge Volume Index			105			103			102	95
Soluble COD, mg/L	15	23	45	16	31	87	16	31	70	45
Date:	5/24/2002									
Location Points	Point 1			Point 2			Point 3			ABE
	C _{1-S}	C ₁₋₁₀	C ₁₋₁₄	C _{2-S}	C ₂₋₁₀	C ₂₋₁₅	C _{3-S}	C ₃₋₁₀	C ₃₋₁₇	
NO ₃ ⁻ mg/L	12.54	12.22	10.35	13.21	12.44	11.36	12.85	12.44	9.65	14.57
NO ₂ ⁻ mg/L	0.12	0.22	0.25	0.03	0.10	0.21	0.10	0.21	0.55	0.06
Ortho - P mg/L	0.21	0.38	0.10	0.43	0.88	1.29	0.40	0.91	0.43	0.09
Total - P mg/L	0.75	5.26	8.66	0.64	10.05	93.64	0.28	1.23	79.00	119.06
Dissolved Oxygen, mg/L	0.16	0.14	0.13	0.13	0.13	0.13	0.16	0.15	0.14	2.15
ORP	80	80	79	79	79	74	77	76	55	112
pH	6.93	6.93	6.93	6.93	6.93	6.93	6.93	6.93	6.97	6.89
Temperature	25.87	25.87	25.89	25.87	25.87	25.89	25.87	25.87	25.92	25.95
Conductivity	1.69	1.678	1.67	1.69	1.067	1.66	1.68	1.67	1.62	1.73
Suspended Solids, mg/L	7	20	1200	5	20	3740	2	20	10620	6213
Sludge Volume Index			100			96			89	68
Soluble COD, mg/L	18	23	43	18	31	75	18	31	52	38

Date:		5/29/2002								
Location Points	Point 1			Point 2			Point 3			ABE
	C _{1-S}	C ₁₋₁₀	C ₁₋₁₄	C _{2-S}	C ₂₋₁₀	C ₂₋₁₅	C _{3-S}	C ₃₋₁₀	C ₃₋₁₇	
NO ₃ ⁻ mg/L	13.65	13.54	11.25	14.00	13.22	13.20	13.54	13.09	11.25	15.47
NO ₂ ⁻ mg/L	0.00	0.03	0.21	0.10	0.23	0.45	0.03	0.13	0.28	0.75
Ortho - P mg/L	0.21	0.38	0.10	0.43	0.88	1.29	0.40	0.91	0.43	0.09
Total - P mg/L	0.21	5.29	39.27	0.45	25.32	104.20	0.88	17.80	9.30	0.09
Dissolved Oxygen, mg/L	0.13	0.13	0.13	0.14	0.13	0.13	0.17	0.15	0.14	2.31
ORP	78	78	71	70	70	69	72	72	62	116
pH	6.92	6.92	6.93	6.92	6.92	6.93	6.92	6.92	6.95	6.88
Temperature	26.63	26.63	26.65	26.63	26.63	26.63	26.65	26.63	26.63	26.75
Conductivity	1.75	1.73	1.71	1.73	1.72	1.69	1.73	1.75	1.68	1.81
Suspended Solids, mg/L	-	-	-	-	-	-	-	-	-	6000
Sludge Volume Index										
Soluble COD, mg/L	-	-	-	-	-	-	-	-	61	-

APPENDIX B

REGRESSION ANALYSIS

Table 1: Regression Analysis for Measured Variables (DO, pH, SS, SCOD, Temperature, and ORP) and Nitrate Increase as Response Variable

Regression Analysis Point 1

The regression equation is

$$\text{Nitrate Decrease} = 14.8 - 19.3 \text{ DO} - 0.78 \text{ pH} + 0.0001421 \text{ SS} + 0.07149 \text{ SCOD} + 0.06114 \text{ Temp} - 0.0126 \text{ ORP}$$

Predictor	Coef	StDev	T	P
Constant	14.80	11.33	0.142	0.6714
DO	-19.338	7.738	-2.50	0.008
ORP	-0.01259	0.01017	-1.214	0.225
pH	-0.780	1.573	-0.50	0.623
SS	0.00014213	0.0002217	1.90	0.056
SCOD	0.071486	0.01657	14.52	0.000
Temp	0.061140	0.08921	0.69	0.1496

S = 1.090 R-Sq = 89.14% R-Sq(adj) = 87.14%

Regression Analysis Point 2

The regression equation is

$$\text{Nitrate Decrease} = 9.60 - 61.0 \text{ DO} + 0.33 \text{ pH} + 0.000221 \text{ SS} + 0.01428 \text{ SCOD} - 0.0939 \text{ Temp} + 0.00143 \text{ ORP}$$

Predictor	Coef	StDev	T	P
Constant	9.6014	9.973	0.96	0.314
DO	-61.038	8.725	-7.00	0.000
ORP	0.001433	0.01065	0.14	0.287
pH	0.328	1.518	0.22	0.830
SS	0.0002206	0.0001658	1.33	0.092
SCOD	0.014277	0.01502	2.85	0.007
Temp	-0.09390	0.08033	-1.17	0.650

S = 0.9328 R-Sq = 914.3% R-Sq(adj) = 93.3%

Regression Analysis Point 3

The regression equation is

$$\text{Nitrate Decrease} = 14.0 - 51.0 \text{ DO} + 0.214 \text{ pH} + 0.000286 \text{ SS} + 0.05914 \text{ SCOD} + 0.083 \text{ Temp} - 0.0125 \text{ ORP}$$

Predictor	Coef	StDev	T	P
Constant	3.98	12.65	0.31	0.755
DO	-50.99	13.65	-3.73	0.001
ORP	-0.012502	0.009918	-1.26	0.216
pH	0.236	1.668	0.114	0.888
SS	0.00028614	0.0002139	1.314	0.090
SCOD	0.059142	0.01829	3.25	0.003
Temp	0.0827	0.1153	0.72	0.147

S = 1.121 R-Sq = 93.9% R-Sq(adj) = 92.8%

Table 2: Regression Analysis with Nitrate Decrease as Response Variable, Nitrite Increase, pH increase and DO as Independent Variables

Regression Analysis Point 1

The regression equation is

$$\text{Nitrate Decrease} = 5.148 + 0.660 \text{ Nitrite Increase} - 25.1 \text{ DO} + 29.14 \text{ pH}$$

Predictor	Coef	StDev	T	P
Constant	5.1480	1.103	14.97	0.000
Nitrite	0.6595	0.11435	14.60	0.000
pH	29.392	7.279	14.01	0.000
ESS	13.5142	5.2114	14.01	0.008

S = 0.8972 R-Sq = 92.1% R-Sq(adj) = 91.5%

Regression Analysis Point 2

The regression equation is

$$\text{Nitrate Decrease-2} = 13.3 + 1.66 \text{ Nitrite Increase-2} - 59.7 \text{ DO-2} + 13.0 \text{ pH-2}$$

Predictor	Coef	StDev	T	P
Constant	13.258	1.571	8.144	0.000
Nitrite	1.6631	0.5592	2.970	0.005
pH-2	13.020	9.185	1.142	0.061
ESS	11.5142	5.000	2.010	0.011

S = 0.91467 R-Sq = 93.6% R-Sq(adj) = 93.1%

Regression Analysis Point 3

The regression equation is

$$\text{Nitrate Decrease-3} = 7.52 + 1.214 \text{ Nitrite Increase-3} - 33.7 \text{ DO-3} + 145.0 \text{ pH-3}$$

Predictor	Coef	StDev	T	P
Constant	7.518	1.955	3.85	0.000
Nitrite	1.2358	0.3611	3.142	0.002
pH-3	414.985	8.960	5.02	0.000
ESS	18.1214	7.001	1.032	0.023

S = 1.025 R-Sq = 914.14% R-Sq(adj) = 93.9%

Table 3: Regression Analysis for Measured Variables (DO, pH, SS, SCOD, Temperature, and ORP) and OP Release as Response Variable

Regression Analysis Point 1

The regression equation is

$$\text{OP, mg/L} = -1.58 - 14.9 \text{ DO, mg/L} + 0.439 \text{ pH} - 0.000038 \text{ SS, mg/L} \\ + 0.0316 \text{ SCOD, mg/L} - 0.0102 \text{ Temp, } ^\circ\text{C} - 0.00572 \text{ ORP, mV}$$

Predictor	Coef	StDev	T	P
Constant	-1.576	4.897	-0.32	0.750
DO, mg/L	-14.891	5.382	-2.77	0.009
pH	0.4392	0.6077	0.72	0.475
SS, mg/L	-0.00003789	0.00008308	-0.46	0.651
SCOD, mg	0.031600	0.008934	3.54	0.005
Temp, $^{\circ}\text{C}$	-0.01018	0.06095	-0.17	0.868
ORP, mV	-0.005724	0.005826	-0.98	0.333

S = 0.6792 R-Sq = 79.6% R-Sq(adj) = 76.0%

Regression Analysis Point 2

The regression equation is

$$\text{OP, mg/L} = 4.60 - 21.0 \text{ DO, mg/L} - 0.502 \text{ pH} - 0.000130 \text{ SS, mg/L} \\ + 0.0366 \text{ SCOD, mg/L} + 0.0425 \text{ Temp, } ^\circ\text{C} - 0.00288 \text{ ORP, mV}$$

Predictor	Coef	StDev	T	P
Constant	4.596	6.415	0.72	0.479
DO, mg/L	-21.005	6.248	-3.36	0.004
pH	-0.5021	0.8735	-0.57	0.569
SS, mg/L	-0.00013003	0.00009567	-1.36	0.183
SCOD, mg	0.03660	0.01008	3.63	0.005
Temp, $^{\circ}\text{C}$	0.04248	0.06449	0.66	0.515
ORP, mV	-0.002877	0.005418	-0.53	0.599

S = 0.6336 R-Sq = 82.3% R-Sq(adj) = 79.1%

Regression Analysis Point 3

The regression equation is

$$\text{OP, mg/L} = 8.02 - 20.6 \text{ DO, mg/L} - 1.10 \text{ pH} - 0.000116 \text{ SS, mg/L} \\ + 0.0380 \text{ SCOD, mg/L} + 0.0550 \text{ Temp, } ^\circ\text{C} - 0.00170 \text{ ORP, mV}$$

Predictor	Coef	StDev	T	P
Constant	8.019	6.547	1.22	0.229
DO, mg/L	-20.635	6.074	-3.40	0.002
pH	-1.0957	0.8914	-1.23	0.227
SS, mg/L	-0.00011589	0.00009389	-1.23	0.226
SCOD, mg	0.037981	0.009892	3.84	0.001
Temp, $^{\circ}\text{C}$	0.05498	0.06356	0.86	0.393
ORP, mV	-0.001698	0.005502	-0.31	0.759

S = 0.6152 R-Sq = 83.3% R-Sq(adj) = 80.3%

APPENDIX C

MASS BALANCE ON DENITRIFICATION

Table 1: Nitrate Mass Balance on the Clarifier for Data Set 1

Date	Q_i	NO_3^- (INF)	Q_r	Q_e	NO_3^- (RAS)	Q_{eff}	NO_3^- (EFF)	Nitrate removed in Sludge kg/d
10/03/01	10.07	13.12	3.13	0.161	1.92	10.07	13.44	476
10/05/01	10.45	13.11	3.24	0.163	3.13	10.45	13.58	478
10/10/01	10.30	14.39	3.19	0.174	0.15	10.30	13.77	558
10/12/01	10.61	10.59	3.28	0.152	1.59	10.61	5.09	404
10/17/01	10.57	14.08	3.26	0.159	5.45	10.57	13.45	492
10/19/01	10.65	10.96	3.25	0.131	2.20	10.65	13.80	413
10/24/01	10.76	13.57	3.31	0.172	10.89	10.76	12.93	409
10/26/01	11.01	13.78	3.38	0.168	11.51	11.01	13.26	419
10/31/01	10.74	14.71	3.30	0.163	12.23	10.74	12.91	437
11/02/01	10.54	13.15	3.26	0.164	1.80	10.54	13.13	501
11/09/01	10.31	13.28	3.22	0.163	3.34	10.31	13.52	475
11/14/01	9.91	13.51	3.09	0.172	1.34	9.91	13.62	490
11/16/01	10.23	12.56	3.25	0.181	2.14	10.23	14.80	458
11/21/01	10.69	12.32	3.29	0.157	0.50	10.69	11.70	491
11/23/01	10.40	13.23	3.29	0.160	5.58	10.40	11.52	447
12/12/01	10.52	11.11	1.39	0.144	3.28	10.52	13.60	423
12/14/01	10.53	12.87	3.24	0.149	4.12	10.53	15.30	459
12/19/01	11.08	12.11	3.41	0.154	2.56	11.08	13.70	473
12/21/01	11.37	11.04	3.48	0.150	2.06	11.37	11.38	446
12/26/01	11.85	6.77	3.58	0.154	4.06	11.85	11.41	246
12/28/01	11.52	12.48	3.49	0.158	2.10	11.52	14.20	514
01/02/02	11.18	14.12	3.45	0.159	0.02	11.18	13.00	596
01/04/02	11.23	13.47	3.46	0.156	0.02	11.23	14.00	572
01/09/02	10.70	15.12	3.29	0.159	0.09	10.70	13.90	610
01/11/02	11.11	13.26	3.40	0.147	0.05	11.11	14.40	556
01/16/02	11.21	13.58	3.25	0.147	0.04	11.21	14.70	575
01/18/02	8.92	19.16	2.88	0.139	12.64	8.92	15.59	602
01/23/02	9.13	13.97	2.54	0.133	1.42	9.13	13.93	468
01/30/02	9.04	14.88	2.92	0.136	13.28	9.04	14.24	355
02/01/02	9.64	15.45	2.93	0.130	9.24	9.64	13.48	456
02/06/02	10.07	14.10	3.14	0.133	7.82	10.07	12.86	440
02/08/02	10.07	12.33	3.00	0.136	8.62	10.07	13.25	367
02/13/02	9.34	15.70	2.99	0.114	0.15	9.34	12.44	453
02/15/02	8.75	13.47	2.83	0.122	0.15	8.75	11.99	444
02/22/02	9.10	13.24	2.93	0.135	10.23	9.10	14.50	337
02/27/02	10.66	9.63	2.83	0.128	2.24	10.66	13.40	363
03/01/02	9.19	14.75	2.93	0.144	8.16	9.19	13.93	418
03/06/02	9.33	16.02	3.69	0.144	3.07	9.33	10.31	521
03/13/02	9.47	15.06	3.36	0.149	7.33	9.47	13.69	442
03/15/02	9.78	14.57	3.41	0.150	6.88	9.78	13.37	446
03/22/02	9.46	14.16	3.42	0.149	1.75	9.46	13.07	483
03/27/02	9.78	14.44	3.50	0.15	8.01	9.78	12.96	423
03/29/02	9.46	15.90	3.41	0.15	5.96	9.46	12.76	488
04/03/02	9.52	14.15	3.43	0.15	11.72	9.52	13.52	351
04/05/02	9.61	12.55	3.45	0.15	10.60	9.61	11.94	312
04/10/02	9.19	14.27	3.32	0.15	6.15	9.19	13.42	415
04/12/02	9.24	13.47	3.34	0.15	5.69	9.24	12.86	396
04/24/02	9.73	16.04	3.40	0.15	10.94	9.73	15.24	443
04/26/02	10.33	14.74	3.35	0.16	0.27	10.33	13.94	572
05/01/02	10.12	14.63	3.30	0.15	5.07	10.12	12.82	494
05/03/02	9.99	13.60	3.30	0.15	0.26	9.99	2.63	510

Date	Q_{in}	NO_3^- (INF)	Q_r	Q_e	NO_3^- (RAS)	Q_{eff}	NO_3^- (EFF)	Nitrate removed in Sludge kg/d
05/08/02	10.91	7.81	3.30	0.15	14.81	10.91	14.76	129
05/10/02	11.17	17.67	3.40	0.15	10.47	11.17	15.18	606
05/15/02	10.48	13.90	3.35	0.15	2.75	10.48	12.27	514
05/17/02	10.94	15.27	3.32	0.15	10.98	10.94	13.51	487
05/22/02	10.55	16.42	3.39	0.15	4.15	10.55	14.38	599
05/24/02	10.94	14.57	3.30	0.15	9.65	10.94	13.25	476
05/29/02	10.55	15.47	3.30	0.15	11.25	10.55	12.54	470

Table 2: Nitrate Mass Balance on the Clarifier for Data Set 2

DATE	Qi	NO3-(INF)	Qr	Qw	NO3 mg/l RAS	Qe	NO3 (Eff)	N-Removal in Sludge kg/d
09/01/99	10.33	13.04	3.19	0.15	5.80	10.33	12.17	436
09/03/99	9.54	12.72	3.23	0.15	1.06	9.54	12.37	445
09/08/99	10.97	12.27	3.10	0.15	5.79	10.97	10.74	438
09/10/99	10.27	13.00	3.16	0.15	8.66	10.27	11.56	396
09/15/99	10.25	13.30	3.15	0.15	7.14	10.25	11.86	426
09/17/99	10.33	13.73	3.18	0.15	8.80	10.33	12.19	425
09/22/99	10.6	13.72	3.27	0.15	6.61	10.60	11.67	464
09/24/99	10.63	14.20	3.25	0.15	7.39	10.63	12.82	475
09/29/99	10.4	14.26	3.20	0.15	6.71	10.40	12.81	475
10/01/99	10.25	14.18	3.16	0.15	6.43	10.25	12.33	469
10/06/99	10.29	15.11	3.38	0.15	4.72	10.29	12.44	525
10/08/99	10.36	15.40	3.19	0.15	7.99	10.36	13.31	502
10/13/99	11.08	13.27	3.39	0.16	8.66	11.08	12.24	440
10/15/99	11.34	13.41	3.42	0.16	8.71	11.34	12.03	457
10/20/99	11.59	13.55	3.51	0.17	9.41	11.59	12.51	463
10/22/99	11.3	13.41	3.42	0.16	9.83	11.30	12.78	440
10/27/99	11.18	12.73	3.39	0.16	8.22	11.18	12.56	428
10/29/99	10.87	13.28	3.32	0.16	9.16	10.87	12.59	425
11/03/99	11.66	13.36	3.51	0.17	7.93	11.66	12.26	478
11/05/99	11.24	13.42	3.40	0.16	8.76	11.24	12.48	452
11/10/99	10.29	13.08	2.89	0.14	9.01	10.29	12.68	406
11/12/99	10.01	12.59	3.04	0.14	10.51	10.01	12.59	350
11/17/99	10.95	13.22	3.08	0.15	9.74	10.95	12.93	428
11/19/99	10.75	13.04	3.05	0.14	9.66	10.75	12.84	413
11/24/99	9.76	12.28	3.06	0.14	10.15	9.76	12.14	330
11/26/99	10.15	13.41	3.17	0.15	10.31	10.15	12.45	385
12/01/99	10.25	11.97	3.16	0.15	9.24	10.25	11.87	348
12/03/99	10.23	12.31	3.18	0.15	9.87	10.23	12.15	352
12/08/99	10.54	12.25	3.20	0.15	9.09	10.54	12.28	373
12/10/99	10.45	4.14	3.26	0.15	8.47	10.45	12.16	54
12/15/99	10.21	11.50	3.32	0.16	8.26	10.21	11.58	335
12/17/99	10.19	12.86	3.14	0.15	7.75	10.19	11.45	399
01/21/00	10.49	14.18	3.22	0.15	7.95	10.49	12.54	461
01/26/00	10.32	15.02	3.19	0.15	8.95	10.32	12.84	473
01/28/00	10.4	14.13	3.21	0.15	8.51	10.40	12.59	447
02/02/00	10.26	13.66	3.17	0.15	7.37	10.26	11.91	437
02/04/00	10.45	14.41	3.22	0.15	6.81	10.45	12.67	483
02/09/00	10.31	14.18	3.18	0.15	6.69	10.31	12.50	468
02/11/00	10.3	14.45	3.18	0.15	8.69	10.30	12.91	453
02/16/00	8.97	15.44	2.64	0.12	8.79	8.97	13.39	432
02/18/00	10.55	14.37	3.25	0.15	7.79	10.55	12.61	473
02/23/00	10.93	14.16	3.35	0.16	7.94	10.93	12.60	480
04/28/00	10.45	14.44	3.52	0.17	5.01	10.45	10.99	501
05/03/00	10.18	13.86	3.43	0.16	1.86	10.18	10.48	508
05/05/00	9.51	14.96	3.47	0.16	1.93	9.51	11.47	511

DATE	Qi	NO3-(INF)	Qr	Qw	NO3 mg/l RAS	Qe	NO3 (Eff)	N-Removal in Sludge kg/d
05/10/00	9.29	12.79	3.06	0.14	9.53	9.29	13.25	334
05/12/00	9.24	15.28	3.04	0.14	8.02	9.24	14.61	437
05/17/00	9.53	13.70	3.10	0.15	5.60	9.53	12.07	425
05/19/00	9.49	12.39	3.08	0.15	5.79	9.49	11.40	374
05/24/00	9.45	12.73	3.08	0.15	3.98	9.45	11.55	406
05/26/00	9.53	12.94	3.00	0.14	4.39	9.53	11.51	414
05/31/00	9.45	12.96	2.98	0.14	1.04	9.45	11.21	451
06/02/00	9.31	13.64	2.96	0.14	5.09	9.31	11.81	421
06/07/00	9.34	13.21	2.97	0.14	3.81	9.34	11.19	422
06/09/00	9.54	13.14	3.00	0.14	5.02	9.54	11.73	414
06/14/00	9.19	14.99	2.94	0.14	5.70	9.19	12.41	454
06/16/00	9.61	12.79	3.02	0.14	5.57	9.61	12.29	398

Table 2: Nitrate Mass Balance on the Clarifier for Data Set 3

Date	Q_i	NO_{3in}	Q_r	Q_w	$NO_3(RAS)$	Q_e	$NO_3(Eff)$	Nitrate removed in Sludge kg/d
08/04/99	10.86	16.00	3.3	0.152	0.6	10.86	14.31	649
08/11/99	10.33	14.36	3.26	0.150	0.5	10.33	14.65	554
08/25/99	10.45	14.41	3.28	0.151	1.7	10.45	14.82	547
09/01/99	10.33	14.23	3.19	0.146	2.2	10.33	12.01	528
09/08/99	10.21	12.91	3.15	0.145	0.4	10.21	14.41	493
09/15/99	10.25	13.41	3.15	0.145	0.7	10.25	14.58	511
09/22/99	10.6	14.77	3.27	0.150	0.5	10.6	14.57	585
09/29/99	10.4	15.60	3.2	0.147	3	10.4	14.35	575
10/06/99	10.29	13.86	3.71	0.170	0.8	10.29	14.31	528
10/13/99	11.08	14.12	3.63	0.167	2.9	11.08	14.49	550
10/20/99	11.59	13.17	3.44	0.158	1.3	11.59	12.74	559
10/27/99	11.18	13.24	3.52	0.162	0.1	11.18	13.97	558
11/10/99	9.29	14.35	2.89	0.133	1.7	9.29	15.39	485
11/17/99	9.95	14.20	3.08	0.141	1.5	9.95	15.05	516
11/24/99	9.46	13.71	3.26	0.157	2.4	9.46	14.13	459
12/01/99	9.37	12.76	3.45	0.166	2.2	9.37	14.31	422
12/15/99	9.87	12.45	3.33	0.153	0.7	9.87	13.92	455
12/22/99	9.65	13.02	3.42	0.157	2.7	9.65	14.68	439
12/29/99	9.66	13.28	3.31	0.152	2.3	9.66	14.40	455
01/05/00	9.35	13.24	2.97	0.136	1.6	9.35	12.86	449
01/11/00	9.33	13.62	2.97	0.136	0.8	9.33	12.00	471
01/18/00	10.46	13.62	3.23	0.148	0.3	10.46	9.40	535
01/25/00	10.16	12.59	3.16	0.145	0.4	10.16	11.47	479
02/01/00	10.08	12.70	3.3	0.152	1.1	10.08	12.66	470
02/08/00	10.45	14.32	3.22	0.148	1.1	10.45	14.21	552
02/22/00	10.8	12.90	3.31	0.152	0.2	10.8	10.38	524
02/29/00	10.94	13.28	3.84	0.176	0.5	10.94	12.29	542
03/06/00	11.07	13.29	3.88	0.178	1.2	11.07	12.25	538
03/13/00	11	13.93	4.04	0.185	1.3	11	11.42	558
03/21/00	10.91	13.62	3.83	0.176	1.1	10.91	14.01	545
03/28/00	10.64	15.25	3.79	0.174	0.5	10.64	14.00	606
04/05/00	10.38	16.05	3.72	0.171	1.4	10.38	13.64	609
04/12/00	9.87	15.54	3.44	0.158	1.1	9.87	14.85	565
04/19/00	9.75	14.96	3.55	0.163	0.8	9.75	15.69	540
04/26/00	9.44	15.56	3.44	0.158	0.2	9.44	16.20	553
05/03/00	9.48	15.26	3.43	0.157	1.4	9.48	14.87	528
05/31/00	9.45	14.73	2.98	0.137	0.2	9.45	15.56	524
06/07/00	9.44	13.59	2.97	0.136	4.3	9.44	14.83	434
06/14/00	9.19	14.17	2.94	0.135	1.3	9.19	17.04	477
06/21/00	9.88	13.54	3.04	0.140	1.4	9.88	14.76	489
06/28/00	9.77	14.21	3.06	0.140	0.7	9.77	14.92	516
07/05/00	9.93	13.23	3.08	0.141	0.4	9.93	13.86	492
07/19/00	9.69	12.98	2.91	0.134	2.1	9.69	14.42	451
07/26/00	9.8	12.72	2.94	0.135	0.3	9.8	15.84	468
10/04/00	9.47	14.32	3.87	0.178	0.2	9.47	14.07	510

Date	Q _i	NO _{3in}	Q _r	Q _w	NO ₃ (RAS)	Q _e	NO ₃ (Eff)	Nitrate removed in Sludge kg/d
10/25/00	10.03	13.88	4.06	0.186	0.5	10.03	13.99	518
01/03/01	9.12	14.84	3	0.138	1.3	9.12	11.92	496
01/10/01	9.22	15.08	3	0.138	1.8	9.22	14.17	504
01/17/01	11.13	13.18	3.83	0.176	0.8	11.13	11.91	542
01/24/01	10.36	13.37	3.19	0.146	0.8	10.36	13.32	514
01/31/01	10.42	13.22	3.21	0.147	2.7	10.42	14.21	486
07/04/01	10.34	16.32	3.45	0.158	7.4	10.34	13.00	537
07/11/01	9.98	14.55	3.41	0.157	4	9.98	11.75	495
07/18/01	9.73	13.74	3.33	0.153	5.1	9.73	13.24	438
07/25/01	9.88	15.54	3.65	0.168	2	9.88	12.23	552
08/01/01	11.21	16.28	3.04	0.140	1.1	11.21	12.32	677
08/08/01	9.9	13.85	3.53	0.162	8.5	9.9	12.50	400
08/15/01	10.13	13.94	3.2	0.147	8.4	10.13	12.88	427
08/22/01	8.88	14.87	2.85	0.131	8.7	8.88	12.67	401
08/29/01	12.31	13.66	3.69	0.169	7.42	12.31	12.98	527
09/05/01	10.47	13.00	3.22	0.148	5.9	10.47	13.45	440
09/12/01	10.5	14.12	3.25	0.149	9.1	10.5	12.82	443
09/19/01	9.91	12.42	3.1	0.142	6.5	9.91	12.83	386
09/26/01	10.13	13.26	3.14	0.144	7.4	10.13	12.48	416
10/03/01	10.07	13.91	3.13	0.144	9	10.07	11.20	418
10/10/01	10.3	14.55	3.19	0.146	8.5	10.3	13.16	459
10/17/01	10.87	13.82	3.26	0.150	9.6	10.87	13.25	444
10/24/01	10.76	15.73	3.31	0.152	7.8	10.76	16.26	538
10/31/01	10.54	13.63	3.3	0.152	8.5	10.54	13.97	432
11/07/01	10.9	13.90	3.51	0.161	6.5	10.9	16.94	483
11/14/01	12.17	14.55	3.73	0.171	8.7	12.17	15.45	541
11/21/01	10.09	14.30	3.38	0.155	9.8	10.09	15.19	414
11/28/01	8.59	15.52	2.83	0.130	9.8	8.59	15.37	394
12/05/01	10.69	14.32	3.3	0.152	9.8	10.69	15.77	451
12/12/01	10.69	14.06	3.29	0.151	8.9	10.69	15.19	453
12/19/01	10.12	13.10	3.41	0.157	12.21	10.12	14.13	337
12/26/01	10.81	13.42	3.41	0.157	9.2	10.81	14.36	424
01/02/02	11.15	13.33	3.58	0.164	7.1	11.15	15.33	461
01/09/02	11.18	15.82	3.49	0.160	8.3	11.18	15.31	554
01/23/02	11.21	13.69	3.25	0.149	9.2	11.21	16.14	462
01/30/02	8.92	14.96	2.88	0.132	7.3	8.92	15.95	421
02/06/02	9.04	16.65	2.92	0.134	16.3	9.04	15.18	381
02/13/02	10.07	14.48	3.14	0.144	7.7	10.07	13.54	455
02/20/02	9.42	14.91	3.02	0.139	6.9	9.42	16.00	449
02/27/02	8.75	15.34	2.83	0.130	9	8.75	15.09	407
03/06/02	10.66	15.22	3.69	0.169	8.7	10.66	14.83	486
03/13/02	9.33	15.41	3.36	0.154	6.4	9.33	16.52	458
03/20/02	9.36	15.72	3.39	0.156	9.5	9.36	15.45	429
03/27/02	9.78	16.02	3.5	0.161	8.4	9.78	15.49	476
04/03/02	9.52	14.89	3.43	0.157	5.8	9.52	16.75	457
04/10/02	9.19	16.97	3.32	0.152	8.4	9.19	17.97	479
04/17/02	8.01	16.35	2.63	0.121	9.7	8.01	16.90	394

Table 4: Comparison Between Actual and Theoretical Values for OP Concentrations Corresponding to Required SS in the CCSD Clarifier at Various P-content

% P	Required ESS, mg/L	Corresponding	
		Actual EOP, mg/L	Theoretical EOP, mg/L
1.5	6	0.109	-
2.5	6	0.145	0.150
3.5	6	0.200	0.210
4.5	6	0.259	0.270

APPENDIX D

MASS BALANCE ON P-RELEASE

Table 1: Ortho-P Mass Balance on the Clarifier for Data Set 1

Date	Q _i	OP (INF)	Q _r	Q _e	OP (RAS)	Q _e	OP (EFF)	P-Release kg/d
10/03/01	10.07	0.12	3.13	0.161	2.4	10.07	0.16	31.4
10/05/01	10.45	0.35	3.24	0.163	1.96	10.45	0.29	22.8
10/10/01	10.30	0.14	3.19	0.174	3.96	10.30	0.962	69.0
10/12/01	10.61	0.19	3.28	0.152	0.35	10.61	0.2	4.9
10/17/01	10.57	0.14	3.26	0.159	1.13	10.57	0.16	15.4
10/19/01	10.65	0.15	3.25	0.131	0.12	10.65	0.17	2.3
10/24/01	10.76	0.15	3.31	0.172	1.3	10.76	0.16	17.5
10/26/01	11.01	0.22	3.38	0.168	0.24	11.01	0.13	-0.5
10/31/01	10.74	0.08	3.30	0.163	0.07	10.74	0.11	2.1
11/02/01	10.54	0.05	3.26	0.164	0.9	10.54	0.8	41.5
11/09/01	10.31	0.8	3.22	0.163	3.5	10.31	0.09	17.1
11/14/01	9.91	0.17	3.09	0.172	1.82	9.91	0.13	20.9
11/16/01	10.23	0.04	3.25	0.181	2.26	10.23	0.06	30.1
11/21/01	10.69	0.07	3.29	0.157	0.21	10.69	0.04	1.5
11/23/01	10.40	0.06	3.29	0.160	0.94	10.40	0.1	13.8
12/12/01	10.52	0.45	1.39	0.144	0.6	10.52	0.3	-2.5
12/14/01	10.53	0.05	3.24	0.149	0.2	10.53	0.13	5.7
12/19/01	11.08	2.74	3.41	0.154	0.96	11.08	0.06	-99.3
12/21/01	11.37	0.13	3.48	0.150	1.76	11.37	0.19	26.7
12/26/01	11.85	0.07	3.58	0.154	0.21	11.85	0.06	2.5
12/28/01	11.52	0.11	3.49	0.158	1.34	11.52	0.13	19.4
01/02/02	11.18	1.30	3.45	0.159	4.12	11.18	0.06	3.8
01/04/02	11.23	0.06	3.46	0.156	2.08	11.23	0.08	29.3
01/09/02	10.70	0.04	3.29	0.159	3.39	10.70	0.08	45.8
01/11/02	11.11	0.06	3.40	0.147	5.43	11.11	0.09	74.1
01/16/02	11.21	0.12	3.25	0.147	4.13	11.21	0.11	52.6
01/18/02	8.92	0.06	2.88	0.139	0.95	8.92	0.06	40.8
01/23/02	9.13	0.07	2.94	0.133	0.69	9.13	0.1	9.0
01/30/02	9.04	0.09	2.92	0.136	0.08	9.04	0.09	0.9
02/01/02	9.64	0.09	2.93	0.130	0.14	9.64	0.16	4.2
02/06/02	10.07	0.07	3.14	0.133	0.41	10.07	0.12	7.0
02/08/02	10.07	-	3.00	0.136	0.09	10.07	-	-
02/13/02	9.34	0.09	2.99	0.114	2.62	9.34	0.18	33.9
02/15/02	8.75	0.09	2.83	0.122	0.44	8.75	0.09	4.9
02/22/02	9.10	0.08	2.93	0.135	0.3	9.10	0.13	5.2
02/27/02	8.75	0.14	3.29	0.128	0.44	8.75	0.13	5.2
03/01/02	9.10	0.02	3.33	0.144	0.43	9.10	0.15	9.9
03/06/02	10.66	0.06	3.36	0.144	1.30	10.66	0.12	19.6
03/13/02	9.33	0.04	3.42	0.149	0.39	9.33	0.11	7.5
03/15/02	9.46	0.06	3.50	0.150	0.58	9.46	0.07	8.4
03/22/02	9.47	0.07	3.41	0.149	1.75	9.47	0.11	25.0
03/27/02	9.78	0.05	3.50	0.15	0.15	9.78	0.08	3.3
03/29/02	9.46	0.01	3.41	0.15	1.44	9.46	0.03	20.0
04/03/02	9.52	0.05	3.43	0.15	0.04	9.52	0.06	1.0
04/05/02	9.61	0.04	3.45	0.15	0.06	9.61	0.08	2.2
04/10/02	9.19	0.05	3.32	0.15	0.13	9.19	0.12	4.1

Date	Q _i	OP (INF)	Q _r	Q _e	OP (RAS)	Q _e	OP (EFF)	P-Release kg/d
04/12/02	9.24	0.09	3.34	0.15	0.23	9.24	0.11	3.8
04/24/02	9.26	0.31	3.40	0.15	1.06	9.26	0.10	7.0
04/26/02	9.80	0.02	3.35	0.16	2.05	9.80	0.13	31.3
05/01/02	9.73	0.04	3.30	0.15	0.63	9.73	0.09	9.8
05/03/02	10.33	0.13	3.30	0.15	1.62	10.33	0.11	20.4
05/08/02	10.12	0.04	3.30	0.15	0.03	10.12	0.06	1.1
05/10/02	9.99	0.05	3.40	0.15	1.30	9.99	0.21	23.5
05/15/02	10.91	0.09	3.35	0.15	1.31	10.91	0.10	18.2
05/17/02	11.17	0.08	3.32	0.15	0.07	11.17	0.09	1.3
05/22/02	10.48	0.31	3.39	0.15	2.71	10.48	0.25	34.2
05/24/02	10.94	0.52	3.30	0.15	1.03	10.94	0.33	5.5
05/29/02	10.55	0.09	3.30	0.15	0.43	10.55	0.41	18.5

Table 2: Ortho-P Mass Balance on the Clarifier for Data Set 2

DATE	Q _{in}	OP _i	Q _e	OP (Eff)	Q _r	Q _w	OP (RAS)	P-Release kg/d
09/01/99	10.33	0.23	10.33	0.10	3.19	0.15	0.58	2.35
09/03/99	9.54	-	9.54	0.15	3.23	0.15	14.17	-
09/08/99	10.97	0.07	10.97	0.08	3.10	0.15	0.36	4.78
09/10/99	10.27	0.08	10.27	0.09	3.16	0.15	0.41	5.58
09/15/99	10.25	0.06	10.25	0.09	3.15	0.15	0.43	6.54
09/17/99	10.33	0.13	10.33	0.11	3.18	0.15	1.21	14.34
09/22/99	10.6	0.08	10.60	0.10	3.27	0.15	1.72	22.77
09/24/99	10.63	0.10	10.63	0.12	3.25	0.15	2.21	29.08
09/29/99	10.4	0.12	10.40	0.10	3.20	0.15	2.19	26.95
10/01/99	10.25	0.43	10.25	0.24	3.16	0.15	2.19	20.27
10/06/99	10.29	0.33	10.29	0.11	3.38	0.15	2.95	30.78
10/08/99	10.36	0.21	10.36	0.29	3.19	0.15	2.15	30.33
10/13/99	11.08	0.66	11.08	0.22	3.39	0.16	1.97	8.21
10/15/99	11.34	0.62	11.34	0.21	3.42	0.16	2.03	9.73
10/20/99	11.59	0.80	11.59	0.26	3.51	0.17	1.93	3.14
10/22/99	11.3	0.36	11.30	0.08	3.42	0.16	1.79	12.55
10/27/99	11.18	0.79	11.18	0.36	3.39	0.16	2.27	12.52
10/29/99	10.87	0.86	10.87	0.58	3.32	0.16	2.15	16.82
11/03/99	11.66	0.90	11.66	0.67	3.51	0.17	2.12	19.37
11/05/99	11.24	0.78	11.24	0.67	3.40	0.16	1.83	19.85
11/10/99	10.29	0.59	10.29	0.47	2.89	0.14	1.46	12.22
11/12/99	10.01	1.10	10.01	0.91	3.04	0.14	1.02	5.23
11/17/99	10.95	1.06	10.95	0.93	3.08	0.15	1.91	17.65
11/19/99	10.75	1.08	10.75	0.91	3.05	0.14	1.82	15.03
11/24/99	9.76	0.64	9.76	0.47	3.06	0.14	0.63	1.60
11/26/99	10.15	0.72	10.15	0.38	3.17	0.15	1.32	3.72
12/01/99	10.25	0.22	10.25	0.21	3.16	0.15	0.38	4.04
12/03/99	10.23	0.49	10.23	0.27	3.18	0.15	1.02	4.46
12/08/99	10.54	0.36	10.54	0.18	3.20	0.15	1.06	6.11
12/10/99	10.45	1.64	10.45	-	3.26	0.15	1.37	-
12/15/99	10.21	0.21	10.21	0.13	3.32	0.16	0.42	2.58
12/17/99	10.19	0.22	10.19	0.22	3.14	0.15	1.02	12.56
01/21/00	10.49	0.04	10.49	0.09	3.22	0.15	1.16	16.69
01/26/00	10.32	0.02	10.32	0.06	3.19	0.15	1.51	20.77
01/28/00	10.4	0.03	10.40	0.11	3.21	0.15	0.64	11.07
02/02/00	10.26	0.10	10.26	0.10	3.17	0.15	0.85	10.74
02/04/00	10.45	0.03	10.45	0.07	3.22	0.15	0.87	12.53
02/09/00	10.31	0.03	10.31	0.10	3.18	0.15	0.86	13.47
02/11/00	10.3	0.05	10.30	0.21	3.18	0.15	0.43	11.66
02/16/00	8.97	0.06	8.97	0.31	2.64	0.12	0.48	13.76
02/18/00	10.55	0.06	10.55	0.18	3.25	0.15	0.62	12.93
02/23/00	10.93	0.05	10.93	0.28	3.35	0.16	0.36	14.02
04/28/00	10.45	0.07	10.45	0.19	3.52	0.17	1.28	22.55
05/03/00	10.18	0.06	10.18	0.28	3.43	0.16	1.09	23.15
05/05/00	9.51	0.10	9.51	0.08	3.47	0.16	1.39	18.47
05/10/00	9.29	0.07	9.29	0.10	3.06	0.14	0.09	2.10

DATE	Q _{in}	OP _i	Q _e	OP (Eff)	Q _r	Q _w	OP (RAS)	P-Release kg/d
05/12/00	9.24	0.07	9.24	0.11	3.04	0.14	0.20	3.92
05/17/00	9.53	0.07	9.53	0.07	3.10	0.15	0.17	2.29
05/19/00	9.49	0.09	9.49	0.08	3.08	0.15	0.10	0.72
05/24/00	9.45	0.02	9.45	0.14	3.08	0.15	0.12	5.88
05/26/00	9.53	0.14	9.53	-	3.00	0.14	0.08	-
05/31/00	9.45	0.04	9.45	0.10	2.98	0.14	0.10	3.14
06/02/00	9.31	-	9.31	0.06	2.96	0.14	0.07	-
06/07/00	9.34	0.05	9.34	0.06	2.97	0.14	0.11	1.65
06/09/00	9.54	-0.01	9.54	0.08	3.00	0.14	0.15	4.81
06/14/00	9.19	0.05	9.19	0.08	2.94	0.14	0.06	1.75
06/16/00	9.61	0.05	9.61	0.08	3.02	0.14	0.19	3.26

APPENDIX E

MASS BALANCE ON ALKALINITY RECOVER

Table 1: Alkalinity Recovered within the Clarifier for Data Set 1

Date	CABI ALK, mg/l	CABI NH ₄ , mg/l	ABE ALK, mg/l	RAS ALK, mg/l	Alkalinity Recover, mg/l
10/03/01	246.5	22.68	86.62	100.5	13.86
10/05/01	240.5	21.60	88.25	102.4	14.12
10/10/01	250.5	20.74	104.34	123.1	18.78
10/12/01	240.2	20.24	97.52	107.3	9.75
10/17/01	243.5	18.66	111.90	126.4	14.55
10/19/01	247.3	20.15	105.21	115.1	9.89
10/24/01	246.2	23.06	83.61	93.4	9.78
10/26/01	241.1	22.86	79.88	89.9	9.99
10/31/01	245.4	21.52	93.63	104.5	10.91
11/02/01	251.4	24.37	79.57	94.4	14.80
11/09/01	239.9	22.92	78.27	90.8	12.52
11/14/01	240.0	21.33	89.60	103.8	14.25
11/16/01	241.4	22.20	84.86	97.3	12.47
11/21/01	241.5	24.07	71.74	84.1	12.34
11/23/01	247.4	27.18	55.77	65.8	10.04
12/12/01	235.7	23.30	71.45	81.4	9.93
12/14/01	229.8	23.42	64.65	75.0	10.34
12/19/01	231.1	21.02	82.88	95.3	12.43
12/21/01	229.7	23.19	66.21	77.5	11.26
12/26/01	242.7	25.54	62.61	68.9	6.26
12/28/01	242.9	28.61	41.24	56.0	14.76
01/02/02	231.4	26.34	45.67	65.4	19.76
01/04/02	244.8	25.34	66.17	85.4	19.19
01/09/02	241.7	25.00	65.52	87.1	21.62
01/11/02	241.8	24.82	66.85	81.9	15.04
01/16/02	229.8	27.10	38.71	58.1	19.36
01/18/02	245.4	25.07	68.66	79.7	10.99
01/23/02	228.9	22.32	71.55	83.0	11.45
01/30/02	235.1	25.19	57.51	66.7	9.20
02/01/02	231.3	25.67	50.25	59.8	9.55
02/06/02	241.2	25.14	64.01	74.2	10.24
02/08/02	229.4	23.54	63.43	73.6	10.15
02/13/02	252.0	24.78	77.25	95.4	18.15
02/15/02	228.5	24.95	52.67	62.7	10.01
02/22/02	227.7	23.19	64.16	71.2	7.06
02/27/02	247.7	22.49	89.07	98.0	8.91
03/01/02	249.6	23.73	82.29	93.0	10.70
03/06/02	248.0	23.68	81.06	94.4	13.38
03/08/02	250.3	24.74	75.90	86.1	10.25
03/13/02	247.6	22.60	88.27	99.7	11.47
03/15/02	248.4	24.12	78.33	90.9	12.53
03/22/02	248.1	25.27	69.99	80.6	10.57
03/27/02	240.6	23.50	74.92	86.9	11.99
03/29/02	243.1	24.14	72.94	81.7	8.75
04/03/02	239.63	21.84	85.67	94.6	8.91

Date	CABI ALK, mg/l	CABI NH ₄ , mg/l	ABE ALK, mg/l	RAS ALK, mg/l	Alkalinity Recover, mg/l
04/10/02	241.17	24.88	65.73	75.6	9.86
04/12/02	249.70	23.69	82.71	95.9	13.23
04/24/02	238.68	22.57	79.56	95.1	15.59
04/26/02	245.38	23.12	82.36	95.5	13.18
05/01/02	238.5	24.33	66.98	77.7	10.72
05/03/02	249.6	23.80	66.98	71.7	4.69
05/08/02	244.0	23.15	81.82	103.1	21.27
05/10/02	243.7	22.65	80.81	93.7	12.93
05/15/02	260.3	26.26	84.00	97.9	13.86
05/17/02	252.3	21.85	75.11	94.6	19.53
05/22/02	253.5	22.23	98.26	114.0	15.72
05/24/02	248.6	22.53	96.77	112.3	15.48
05/29/02	249.6	25.32	89.77	104.1	14.36

Table 2: Alkalinity Recovered within the Clarifier for Data Set 2

Date	ABE ALK, mg/l	RAS LK, mg/l	Alkalinity Recover, mg/l
09/01/99	129	154	25.27
09/03/99	131	158	26.93
09/08/99	133	158	25.01
09/10/99	131	147	15.92
09/15/99	133	156	23.18
09/17/99	133	157	23.70
09/22/99	159	188	29.07
09/24/99	97	130	32.70
09/29/99	129	162	33.31
10/01/99	128	161	33.68
10/06/99	130	188	58.25
10/08/99	124	164	40.12
10/13/99	127	151	24.20
10/15/99	125	150	24.56
10/20/99	123	152	28.57
10/22/99	128	151	22.86
10/27/99	128	150	21.99
10/29/99	128	149	21.48
11/03/99	127	153	25.90
11/05/99	126	157	30.60
11/10/99	128	148	20.23
11/12/99	127	139	11.65
11/17/99	-	77	-
11/19/99	127	145	17.83
11/24/99	115	126	11.05
11/26/99	124	137	13.13
12/01/99	128	139	10.72
12/03/99	130	140	9.93
12/08/99	128	139	11.11
12/10/99	-	119	-
12/15/99	130	140	10.37
12/17/99	123	135	12.46
01/21/00	124	148	23.74
01/26/00	110	135	25.13
01/28/00	114	137	23.32
02/02/00	122	145	22.79
02/04/00	121	148	27.28
02/09/00	118	142	24.09
02/11/00	115	141	26.22
02/16/00	113	134	21.31
02/18/00	111	137	25.51
02/23/00	112	139	27.33
04/28/00	128	159	31.15
05/03/00	131	164	32.72
05/05/00	126	168	41.66
05/10/00	133	144	11.47

Date	ABE ALK, mg/l	RAS LK, mg/l	Alkalinity Recover, mg/l
05/12/00	127	148	21.24
05/17/00	123	145	21.86
05/19/00	129	145	15.79
05/24/00	130	152	22.16
05/26/00	127	149	21.64
05/31/00	130	153	22.96
06/02/00	125	147	22.43
06/07/00	126	148	22.44
06/09/00	125	147	22.29
06/14/00	124	150	26.24
06/16/00	131	146	15.36

Table 3: Alkalinity Recovered within the Clarifier for Data Set 3

Date	CABI ALK, mg/l	CABI NH ₄ , mg/l	ABE ALK, mg/l	RAS ALK, mg/l	Alkalinity Recover, mg/l
08/04/99	243	21.6	90.3	130.1	39.7
08/11/99	245	23.0	82.6	111.3	28.7
08/25/99	238	21.8	84.7	111.4	26.7
09/01/99	233	20.3	90.2	115.0	24.8
09/08/99	233	18.4	103.6	123.2	19.6
09/15/99	239	19.1	104.6	128.2	23.6
09/22/99	250	20.5	105.4	138.7	33.3
09/29/99	245	21.1	96.1	126.4	30.3
10/06/99	302	18.7	170.1	194.9	24.7
10/13/99	246	20.7	100.4	131.0	30.7
10/20/99	243	22.2	87.0	119.1	32.1
10/27/99	240	22.2	84.2	114.1	29.9
11/10/99	244	21.1	95.7	115.4	19.7
11/17/99	248	23.1	85.0	109.2	24.2
11/24/99	246	23.1	82.9	101.6	18.7
12/01/99	248	23.8	79.9	96.3	16.4
12/15/99	244	21.7	91.1	109.8	18.7
12/22/99	255	22.7	94.8	114.3	19.5
12/29/99	246	23.5	79.7	100.1	20.4
01/05/00	249	22.3	92.0	110.8	18.9
01/11/00	245	22.9	83.3	103.7	20.4
01/18/00	247	22.1	91.5	120.4	28.9
01/25/00	259	21.1	110.1	129.4	19.3
02/01/00	245	23.3	80.8	97.4	16.6
02/08/00	244	22.6	84.1	111.9	27.7
02/22/00	239	21.0	90.9	115.1	24.1
02/29/00	244	23.9	74.9	100.1	25.1
03/06/00	242	20.6	96.7	121.4	24.7
03/13/00	247	24.3	76.2	106.4	30.1
03/21/00	248	23.7	80.8	108.8	27.9
03/28/00	248	22.4	90.3	125.5	35.2
04/05/00	250	23.5	83.6	121.6	38.0
04/12/00	243	22.8	81.8	107.6	25.8
04/19/00	237	21.9	82.4	108.4	26.0
04/26/00	247	22.8	86.5	113.8	27.3
05/03/00	241	21.8	88.0	112.2	24.2
05/31/00	237	21.6	85.1	108.6	23.4
06/07/00	237	18.4	107.5	126.4	18.9
06/14/00	237	20.8	90.9	110.5	19.6
06/21/00	234	19.9	93.7	113.9	20.2
06/28/00	240	20.8	92.8	117.4	24.6
07/05/00	230	19.4	93.0	112.1	19.1
07/19/00	235	19.0	100.6	119.3	18.7
07/26/00	251	18.7	119.2	138.1	18.9
10/04/00	249	19.3	113.1	137.4	24.4

Date	CABI ALK, mg/l	CABI NH ₄ , mg/l	ABE ALK, mg/l	RAS ALK, mg/l	Alkalinity Recover, mg/l
10/11/00	260	22.6	100.9	122.6	21.7
10/18/00	247	20.1	104.8	129.5	24.7
10/25/00	252	23.0	90.1	114.9	24.8
01/03/01	252	24.2	81.4	102.4	21.0
01/10/01	249	24.6	76.0	100.0	24.0
01/17/01	248	21.5	96.8	124.5	27.6
01/24/01	257	22.1	101.3	126.1	24.9
01/31/01	248	21.9	93.4	114.0	20.6
07/04/01	240	21.5	88.9	115.6	26.7
07/11/01	240	21.3	89.3	110.8	21.5
07/18/01	232	22.4	73.6	90.6	17.0
07/25/01	243	22.8	82.7	108.8	26.1
08/01/01	236	19.4	99.4	142.7	43.3
08/08/01	235	20.3	91.9	111.7	19.8
08/15/01	244	23.1	81.3	97.6	16.4
08/22/01	242	21.8	88.1	104.9	16.8
08/29/01	237	19.5	100.0	127.5	27.5
09/05/01	236	19.1	101.9	120.8	18.9
09/12/01	246	20.7	99.6	119.1	19.5
09/19/01	223	18.2	94.2	108.9	14.6
09/26/01	225	19.4	88.2	108.9	20.8
10/03/01	247	22.7	87.4	108.4	20.9
10/10/01	242	20.7	95.3	117.8	22.4
10/17/01	241	18.7	109.5	129.8	20.3
10/24/01	254	23.1	91.9	116.2	24.3
10/31/01	247	21.5	94.8	115.1	20.3
11/07/01	242	22.3	84.3	105.8	21.5
11/14/01	239	21.3	88.9	114.2	25.4
11/21/01	241	24.1	71.7	90.8	19.0
11/28/01	232	22.8	71.7	86.4	14.7
12/05/01	229	22.6	69.8	87.6	17.8
12/12/01	234	23.3	70.0	87.9	17.9
12/19/01	231	21.0	82.9	95.2	12.3
12/26/01	243	25.5	62.6	79.0	16.4
01/02/02	231	26.3	45.7	63.3	17.6
01/09/02	232	25.0	55.5	79.7	24.2
01/16/02	230	27.1	38.7	53.9	15.2
01/23/02	229	22.3	71.6	91.3	19.7
01/30/02	235	25.2	57.5	75.6	18.1
02/06/02	241	25.1	64.0	77.4	13.4
02/13/02	252	24.8	77.3	97.8	20.5
02/20/02	228	23.2	64.1	84.3	20.2
02/27/02	248	22.5	89.1	106.5	17.4
03/06/02	248	23.7	81.1	102.6	21.5
03/13/02	248	22.6	88.3	108.2	19.9
03/20/02	243	26.5	56.9	74.8	17.9
03/27/02	241	23.5	74.9	95.6	20.6
04/03/02	240	21.8	85.7	104.1	18.5

APPENDIX F

SLUDGE BLANKET HEIGHT

Table 1: Sludge Blanket Height within the Clarifier for Data Set 1

Date	Sludge Blanket Height, ft	Date	Sludge Blanket Height, ft
10/03/01	4.50	02/01/02	4.50
10/05/01	4.50	02/06/02	4.50
10/10/01	5.25	02/08/02	4.00
10/12/01	4.00	02/13/02	5.25
10/17/01	5.00	02/15/02	4.50
10/19/01	4.00	02/22/02	4.00
10/24/01	4.00	02/27/02	4.00
10/26/01	4.00	03/01/02	4.25
10/31/01	4.25	03/06/02	4.75
11/02/01	4.75	03/13/02	4.50
11/09/01	4.50	03/15/02	4.50
11/14/01	4.75	03/22/02	4.50
11/16/01	4.50	03/27/02	4.25
11/21/01	4.50	03/29/02	4.50
11/23/01	4.50	04/03/02	4.00
12/12/01	4.25	04/05/02	3.75
12/14/01	4.50	04/10/02	4.00
12/19/01	4.50	04/12/02	4.00
12/21/01	4.50	04/24/02	4.50
12/26/01	3.50	04/26/02	5.25
12/28/01	4.75	05/01/02	4.50
01/02/02	5.50	05/03/02	5.25
01/04/02	5.25	05/08/02	3.25
01/09/02	5.50	05/10/02	5.50
01/11/02	5.25	05/15/02	4.75
01/18/02	5.00	05/17/02	4.50
01/23/02	5.00	05/22/02	5.25
01/23/02	5.00	05/24/02	4.50
01/30/02	4.00	05/29/02	4.50

Table 2: Sludge Blanket Height and its Corresponding DO, mg/L for Data Set 1

Sludge Blanket Height, ft	Corresponding DO, mg/L
3.5	0.249
4.0	0.200
4.5	0.151
5.0	0.101
5.5	0.052
6.0	0.003

Table 3: Sludge Blanket Height and its Corresponding SCOD, mg/L for Data Set 1

Sludge Blanket Height, ft	Corresponding SCOD, mg/L
3.5	50
4.0	78
4.5	105
5.0	133
5.5	160
6.0	188

Table 4: Sludge Blanket Height and its Corresponding ESS, mg/L for Data Set 1

Sludge Blanket Height, ft	Corresponding ESS, mg/L
3.5	1
4.0	4
4.5	8
5.0	11
5.5	14
6.0	18

Table 5: Sludge Blanket Height and its Corresponding ESS, mg/L for Data Set 1

Sludge Blanket Height, ft	Corresponding ETP, mg/L
3.5	0.01
4.0	0.12
4.5	0.24
5.0	0.35
5.5	0.46
6.0	0.58

APPENDIX G

COLUMN SETTLING TEST

Results of Column Settling Test for CCSD Plant

Solids Concentration (11721, mg/L)

Time, min	height, cm	V_s , m/s
0	0	0
5	0.15	0.018
10	0.35	0.021
15	0.475	0.019
20	0.55	0.017
25	0.6	0.014
30	0.65	0.013
V_s , m/s =		0.017

Solids Concentration (9960, mg/L)

Time, min	height, cm	V_s , m/s
0	0	0
5	0.2	0.024
10	0.4	0.024
15	0.5	0.020
20	0.6	0.018
25	0.65	0.016
30	0.7	0.014
V_s , m/s =		0.024

Solids Concentration (7655, mg/L)

Time, min	height, cm	V_s , m/s
0	0	0
5	0.3	0.036
10	0.8	0.048
15	1.3	0.052
20	1.7	0.051
25	2	0.048
30	2.2	0.044
V_s , m/s =		0.052

Solids Concentration (6820, mg/L)

Time, min	height, cm	V_s , m/s
0	0	0
5	1.2	0.144
10	1.9	0.114
15	2.5	0.100
20	2.8	0.084
25	3	0.072
30	3.1	0.062
V_s , m/s =		0.111

Solids Concentration (5916, mg/L)

Time, min	height, cm	V_s , m/s
0	0	0
5	1.3	0.156
10	4	0.24
15	9	0.36
20	20	0.6
25	32	0.768
30	38	0.76
V_s , m/s =		0.252

Solids Concentration (4547, mg/L)

Time, min	height, cm	V_s , m/s
0	0	0
5	5	0.60
10	13	0.78
15	25	1.00
20	37.5	1.13
25	47	1.13
30	56	1.12
V_s , m/s =		0.96

Results of Column Settling Test for CCSD Plant

Solids Concentration (4012, mg/L)

Time, min	height, cm	V_s , m/s
0	0	0
5	7	0.84
10	27.5	1.65
15	47.5	1.90
20	65	1.95
25	72.5	1.74
30	81.5	1.63

V_s , m/s = 1.25

Solids Concentration (3410, mg/L)

Time, min	height, cm	V_s , m/s
0	0	0
5	9	1.08
10	29	1.74
15	51.5	2.06
20	69	2.07
25	78.5	1.88
30	86	1.72

V_s , m/s = 1.96

Solids Concentration (2728, mg/L)

Time, min	height, cm	V_s , m/s
0	0	0
5	16	1.92
10	42	2.52
15	70	2.80
21	91	2.60
24	97	2.43
30	107	2.14

V_s , m/s = 2.40

Solids Concentration (2173, mg/L)

Time, min	height, cm	V_s , m/s
0	0	0
5	24	2.88
10	60	3.60
15	91	3.64
20	107	3.21
25	116	2.78
30	122	2.44

V_s , m/s = 3.24

APPENDIX H

SOLID FLUX

Table 1: Solid Flux and Operating Conditions of the CCSD Clarifier

Date	Inflow rate Qi, MGD	RAS flow rate QR, MGD	WAS flow rate Qw, MGD	Surface Area A, m ²	Underflow Conc. Xu, mg/L	Underflow Velocity, Uc= Qu/A, m/d	Overflow rate OFR=(Qe/A), m/d	Flux , Kg/m ² .d	Operating Condition
10/3/2001	10.07	3.13	0.161	1431	10231	8.69	26.6	66	Underloaded
10/5/2001	10.45	3.24	0.163	1431	9213	8.99	27.61	68	Underloaded
10/10/2001	10.3	3.19	0.174	1431	11600	8.89	27.21	78	Overloaded
10/12/2001	10.61	3.28	0.152	1431	4900	9.06	28.03	64	Underloaded
10/17/2001	10.57	3.26	0.159	1431	8541	9.03	27.92	63	Underloaded
10/19/2001	10.65	3.25	0.131	1431	8421	8.93	28.13	64	Underloaded
10/24/2001	10.76	3.31	0.172	1431	9900	9.2	28.42	67	Underloaded
10/26/2001	11.01	3.38	0.168	1431	9423	9.37	29.08	61	Underloaded
10/31/2001	10.74	3.3	0.163	1431	6042	9.15	28.37	56	Underloaded
11/2/2001	10.54	3.26	0.164	1431	9500	9.04	27.84	64	Underloaded
11/9/2001	10.31	3.22	0.163	1431	7900	8.94	27.24	68	Underloaded
11/14/2001	9.91	3.09	0.172	1431	8965	8.62	26.18	65	Underloaded
11/16/2001	10.23	3.25	0.181	1431	8754	9.06	27.02	42	Underloaded
11/21/2001	10.69	3.29	0.157	1431	5800	9.1	28.24	42	Underloaded
11/23/2001	10.4	3.29	0.16	1431	7542	9.11	27.47	47	Underloaded
12/12/2001	10.52	3.29	0.157	1431	5450	9.1	27.79	49	Underloaded
12/14/2001	10.53	3.29	0.16	1431	6658	9.11	27.82	45	Underloaded
12/19/2001	11.08	1.39	0.144	1431	3740	4.05	29.27	22	Underloaded
12/21/2001	11.37	3.24	0.149	1431	2525	8.95	30.04	52	Underloaded
12/26/2001	11.85	3.41	0.154	1431	7725	9.41	31.3	61	Underloaded
12/28/2001	11.52	3.48	0.15	1431	10880	9.59	30.43	63	Underloaded
1/2/2002	11.18	3.58	0.154	1431	7600	9.86	29.53	82	Overloaded
1/4/2002	11.23	3.49	0.158	1431	11999	9.64	29.67	81	Overloaded
1/9/2002	10.7	3.45	0.159	1431	9940	9.53	28.27	83	Overloaded
1/11/2002	11.11	3.46	0.156	1431	10965	9.55	29.35	83	Overloaded
1/16/2002	11.21	3.29	0.159	1431	12800	9.11	29.61	82	Overloaded
1/18/2002	8.92	3.4	0.147	1431	9980	9.37	23.56	88	Overloaded
1/23/2002	9.13	3.25	0.147	1431	5960	8.97	24.12	84	Overloaded
1/30/2002	9.04	2.88	0.139	1431	6840	7.98	23.88	61	Underloaded
2/1/2002	9.64	2.94	0.133	1431	6420	8.12	25.47	52	Underloaded
2/6/2002	10.07	2.92	0.136	1431	3980	8.07	26.6	51	Underloaded
2/8/2002	10.07	2.93	0.13	1431	7220	8.08	26.6	51	Underloaded
2/13/2002	9.34	3.14	0.133	1431	7600	8.65	24.67	59	Underloaded
2/15/2002	8.75	3	0.136	1431	7620	8.28	23.11	55	Underloaded
2/22/2002	9.1	2.99	0.114	1431	8160	8.2	24.04	56	Underloaded
2/27/2002	10.66	2.83	0.122	1431	5620	7.8	28.16	53	Underloaded
3/1/2002	9.19	2.93	0.135	1431	9320	8.1	24.28	55	Underloaded
3/6/2002	9.33	3.69	0.128	1431	4640	10.08	24.65	72	Underloaded
3/13/2002	9.47	3.36	0.144	1431	9480	9.26	25.02	59	Underloaded
3/15/2002	9.78	3.41	0.149	1431	6213	9.4	25.34	58	Underloaded
3/22/2002	9.46	3.42	0.149	1431	6000	9.43	24.99	61	Underloaded
3/27/2002	9.78	3.5	0.15	1431	6,781	9.64	25.84	65	Underloaded
3/29/2002	9.46	3.41	0.149	1431	6,711	9.4	24.99	63	Underloaded
4/3/2002	9.52	3.43	0.149	1431	6,771	9.45	25.15	64	Underloaded

Date	Inflow rate Q_i , MGD	RAS flow rate Q_R , MGD	WAS flow rate Q_w , MGD	Surface Area A , m ²	Underflow Conc. X_u , mg/L	Underflow Velocity, $U_c = Q_u/A$, m/d	Overflow rate $OFR = (Q_e/A)$, m/d	Flux , Kg/m ² .d	Operating Condition
4/12/2002	9.24	3.34	0.149	1431	6,566	9.22	24.41	61	Underloaded
4/24/2002	9.26	3.4	0.2	1431	6,590	9.38	24.46	62	Underloaded
4/26/2002	9.8	3.35	0.2	1431	8,949	9.27	25.89	83	Overloaded
5/1/2002	9.73	3.3	0.2	1431	6,756	9.12	25.69	62	Underloaded
5/3/2002	10.33	3.3	0.2	1431	6,854	9.12	27.3	62	Underloaded
5/8/2002	10.12	3.3	0.2	1431	4,251	9.12	26.74	39	Underloaded
5/10/2002	9.99	3.4	0.2	1431	8,903	9.41	26.4	84	Overloaded
5/15/2002	10.91	3.35	0.2	1431	6,849	9.26	28.81	63	Underloaded
5/17/2002	11.17	3.32	0.2	1431	6,679	9.17	29.51	61	Underloaded
5/22/2002	10.48	3.39	0.2	1431	8,654	9.36	27.68	81	Overloaded
5/24/2002	10.94	3.3	0.2	1431	6,907	9.12	28.9	63	Underloaded
5/29/2002	10.55	3.3	0.2	1431	6,689	9.12	27.86	61	Underloaded

APPENDIX I
TWO-SAMPLE T-TEST FOR CHAPTER 5

Two Sample T-Test data used in Regression Analysis for Chapter 5 - 95% Confidence Interval

Two Sample T-Test and Confidence Interval

Two sample T for SBH, ft vs Denitrification, kg/d

	N	Mean	StDev	SE Mean
SBH, ft	41	4.591	0.487	0.076
Denitrif	41	473.0	76.0	12

95% CI for μ SBH, ft - μ Denitrif: (-492.405, -444)

T-Test μ SBH, ft = μ Denitrif (vs not =): T = -39.45 P = 0.0002
DF = 40

Slope is positive

Two Sample T-Test and Confidence Interval

Two sample T for SBH, ft vs P-release, kg/d

	N	Mean	StDev	SE Mean
SBH, ft	41	4.591	0.487	0.076
P-releas	41	17.4	18.1	2.8

95% CI for μ SBH, ft - μ P-releas: (-18.531, -7.1)

T-Test μ SBH, ft = μ P-releas (vs not =): T = -4.53 P = 0.0009
DF = 40

Slope is positive

Two Sample T-Test and Confidence Interval

Two sample T for SBH, ft vs ESS mg/l

	N	Mean	StDev	SE Mean
SBH, ft	41	4.591	0.487	0.076
ESS mg/l	41	9.80	3.96	0.62

95% CI for μ SBH, ft - μ ESS mg/l: (-6.473, -3.95)

T-Test μ SBH, ft = μ ESS mg/l (vs not =): T = -8.36 P = 0.0050
DF = 41

Slope is positive

Two Sample T-Test and Confidence Interval

Two sample T for SBH, ft vs ETP, mg/L

	N	Mean	StDev	SE Mean
SBH, ft	41	4.591	0.487	0.076
ETP, mg/	41	0.403	0.179	0.028

95% CI for μ SBH, ft - μ ETP, mg/: (4.026, 4.351)

T-Test μ SBH, ft = μ ETP, mg/ (vs not =): T = 51.74 P = 0.0070
DF = 50

Slope is positive

Two Sample T-Test and Confidence Interval

Two sample T for SBH, ft vs pH increase

	N	Mean	StDev	SE Mean
SBH, ft	41	4.591	0.487	0.076
pH incre	41	0.1022	0.0337	0.0053

95% CI for μ SBH, ft - μ pH incre: (4.335, 4.6432)

T-Test μ SBH, ft = μ pH incre (vs not =): T = 58.94 P = 0.0050
DF = 40

Slope is positive

Two Sample T-Test and Confidence Interval

Two sample T for SBH, ft vs DO, mg/L

	N	Mean	StDev	SE Mean
SBH, ft	41	4.591	0.487	0.076
DO, mg/L	41	0.1321	0.0302	0.0047

95% CI for μ SBH, ft - μ DO, mg/L: (4.305, 4.6132)

T-Test μ SBH, ft = μ DO, mg/L (vs not =): T = 58.57 P = 0.0020
DF = 40

Slope is negative

Two Sample T-Test and Confidence Interval

Two sample T for SBH, ft vs SS, mg/L

	N	Mean	StDev	SE Mean
SBH, ft	41	4.591	0.487	0.076
SS, mg/L	41	8345	1811	283

95% CI for mu SBH, ft - mu SS, mg/L: (-8911.770, -7769)
 T-Test mu SBH, ft = mu SS, mg/L (vs not =): T = -29.49 P = 0.0090
 DF = 40

Slope is positive

Two Sample T-Test and Confidence Interval

Two sample T for SBH, ft vs SCOD, mg/L

	N	Mean	StDev	SE Mean
SBH, ft	41	4.591	0.487	0.076
SCOD, mg	41	107.7	21.3	3.3

95% CI for mu SBH, ft - mu SCOD, mg: (-109.810, -96.4)
 T-Test mu SBH, ft = mu SCOD, mg (vs not =): T = -31.01 P = 0.0030
 DF = 40

Slope is positive

APPENDIX J

TWO-SAMPLE T-TEST FOR CHAPTER 6

Two Sample T-Test data used in Regression Analysis for Chapter 6 - 95% Confidence Interval

Two Sample T-Test and Confidence Interval

Two sample T for Flux Kg/m².d vs SBH, ft

	N	Mean	StDev	SE Mean
Flux Kg/	41	65.7	10.3	1.6
SBH, ft	41	4.591	0.487	0.076

95% CI for mu Flux Kg/ - mu SBH, ft: (57.9, 64.394)

T-Test mu Flux Kg/ = mu SBH, ft (vs not =): T = 37.97 P = 0.0003
DF = 40

Slope is positive

Two Sample T-Test and Confidence Interval

Two sample T for Flux Kg/m².d vs Denitrification, kg/d

	N	Mean	StDev	SE Mean
Flux Kg/	41	65.7	10.3	1.6
Denitrif	41	473.0	76.0	12

95% CI for mu Flux Kg/ - mu Denitrif: (-431.5, -383)

T-Test mu Flux Kg/ = mu Denitrif (vs not =): T = -33.99 P = 0.0008
DF = 41

Slope is positive

Two Sample T-Test and Confidence Interval

Two sample T for Flux Kg/m².d vs P-release, kg/d

	N	Mean	StDev	SE Mean
Flux Kg/	41	65.7	10.3	1.6
P-releas	41	17.4	18.1	2.8

95% CI for mu Flux Kg/ - mu P-releas: (41.8, 54.8)

T-Test mu Flux Kg/ = mu P-releas (vs not =): T = 14.85 P = 0.0008
DF = 63

Slope is positive

Two Sample T-Test and Confidence Interval

Two sample T for Flux Kg/m².d vs ESS mg/l

	N	Mean	StDev	SE Mean
Flux Kg/	41	65.7	10.3	1.6
ESS mg/l	41	9.95	3.87	0.60

95% CI for mu Flux Kg/ - mu ESS mg/l: (52.3, 59.23)

T-Test mu Flux Kg/ = mu ESS mg/l (vs not =): T = 32.46 P = 0.0091
DF = 51

Slope is positive

Two Sample T-Test and Confidence Interval

Two sample T for Flux Kg/m².d vs ETP, mg/L

	N	Mean	StDev	SE Mean
Flux Kg/	41	65.7	10.3	1.6
ETP, mg/	41	0.403	0.179	0.028

95% CI for mu Flux Kg/ - mu ETP, mg/: (62.1, 68.580)

T-Test mu Flux Kg/ = mu ETP, mg/ (vs not =): T = 40.61 P = 0.0080
DF = 40

Slope is positive

Two Sample T-Test and Confidence Interval

Two sample T for Flux Kg/m².d vs DO, mg/L

	N	Mean	StDev	SE Mean
Flux Kg/	41	65.7	10.3	1.6
DO, mg/L	41	0.1321	0.0302	0.0047

95% CI for mu Flux Kg/ - mu DO, mg/L: (62.3, 68.8501)

T-Test mu Flux Kg/ = mu DO, mg/L (vs not =): T = 40.79 P = 0.0070
DF = 40

Slope is negative

Two Sample T-Test and Confidence Interval

Two sample T for Flux Kg/m².d vs SS, mg/L

	N	Mean	StDev	SE Mean
Flux Kg/	41	65.7	10.3	1.6
SS, mg/L	41	8369	1731	270

95% CI for mu Flux Kg/ - mu SS, mg/L: (-8849.9, -7757)
 T-Test mu Flux Kg/ = mu SS, mg/L (vs not =): T = -30.71 P =
 0.0099 DF = 40

Slope is positive

Two Sample T-Test and Confidence Interval

Two sample T for Flux Kg/m².d vs SCOD, mg/L

	N	Mean	StDev	SE Mean
Flux Kg/	41	65.7	10.3	1.6
SCOD, mg	41	108.5	21.2	3.3

95% CI for mu Flux Kg/ - mu SCOD, mg: (-50.2, -35.4)
 T-Test mu Flux Kg/ = mu SCOD, mg (vs not =): T = -11.64 P = 0.0083
 DF = 57

Slope is positive

REFERENCE

- Albertson, O. E. (1963). Dorr Oliver Internal Report, Reduction of Clarifier Operating Data.
- Anderson, N.E. (1945). "Design of Final Clarifiers for Activated Sludge." *Sewage Works J.*, Vol. 17, No. 1, pp. 1-17.
- Anthonisen, A.C., Loehr, R.C., Prakasam, T.B.S., and Srinath, E.G. (1976). "Inhibition of nitrification by ammonia and nitrous acid." *J. Water Pollut. Control Fed.* 48: pp. 835-852.
- APHA (1990). "Standard Methods for Examination of Water and Wastewater." 19th Edition. American Public Health Association, Washington D.C.
- Aravinthan, V., Mino, T., Takizawa, S., Satoh, H., Matsuo, T. (1999). "Sludge Hydrolysate as a Carbon Source for Denitrification." *Wat. Sci. Tech.* Vol. 40, pp.191-199
- Balakrishnan, S. (1968). "Kinetics of Biochemical Nitrification and Denitrification." Thesis, Univ. of Texas.
- Balakrishnan, S. and Erckenfelder, W. W. (1969). "Nitrogen Relationship in Biological Treatment Processes." *Wat. Res.* Vol. 3, pp. 177-188.
- Barnard, J. L. (1974). "Cut O and N without Chemicals." *Wat. and Wastes Eng.* 7, pp. 33-36.
- Barnard, J. L., (1976). "A review of biological phosphorous removal in the activated sludge process" *Water SA*, 2: 136-144.
- Barnes, D. and Bliss, P. J. (1983). "Biological Control of Nitrogen in Wastewater Treatment." E. & F. N. Spon, London.
- Barrith, N. W. (1933). "The Nitrification Process in Soils and Biological Filters." *Ann. Appl. Biol.* Vol. 20, pp. 165-184.

- Beccari, M., di Pinto, A. C., Ramadori, R., Tomei, M. C. (1992). "Effects of Dissolved Oxygen and Diffusion Resistances on Nitrification Kinetics." *Wat. Res.* 26, No. 8, pp. 1099-1104.
- Bender, J. H. (1987). "Assessment of Design Tradeoffs When Using Interchannel Clarifiers." *J. Wat. Poll. Con. Fed.*, Vol. 59, No.10, pp.871-876.
- Borchardt, J. A. (1966). "Nitrification in the Activated Sludge Process." Univ. of Michigan. Ann Arbor.
- Bowker, R. P. G., Stensel, H. D. (1990). "Phosphorus Removal from Wastewater." *Pollution Technology Review* No. 189, Noyes Data Corporation, Park Ridge, New Jersey.
- Bremner, J. M. and Shaw, K. (1958). "Denitrification in Soil II. Factors Affecting Denitrification." *J. Agric. Sci.*, Vol. 51, pp. 39.
- Bryant, J. O.(1972) "Continuous time simulation of the conventional activated sludge wastewater renovation system", PhD dissertation, Clemson University, Clemson, S. C.
- Buchheister, F., Schuch., F., Winter, J., (2000). "Biological nitrogen removal from wastewater of the metal-working industry." *Chemical Engineering and Technology*, v23, n 11, pp, 967-971.
- Camp, T.R. (1946). "Sedimentation and Design of Setting Tanks." *Trans., ASCE*, Vol. 111, pp. 895-936.
- Cech, J. S. and Hartman, P. (1993). "Competition Between Polyphosphate and Polysaccharide Accumulating Bacteria in Enhanced Biological Phosphate Removal Systems." *Wat. Res.*, Vol. 7, pp. 1219-1225.
- Choi E., Lee H. S., Lee J. W. and Oa S. W. (1998). "Another Carbon Source for BNR System." *Water Sci. Technol.* Vol. 34(1-2), pp. 363-369.
- Christensen, M. H. and Harremoes, P. (1978). "Nitrification and Denitrification in Wastewater Treatment." Chapter 15 in R. Mitchell (ed.), *Water Pollution Microbiology*, Vol. 2, pp. 391-414.
- Chuang, S. H., Ouyang, C.F., Yuang, H. C. (1997). "Effects of SRT and DO on Nutrient Removal in a Combined as-Biofilm Process." *Wat. Sci. Tech.*, Vol. 36, No. 12, pp. 19-27
- Clayfield, (1974). "Respiration and Denitrification Studies on Laboratory and Works Activated Sludge." *Wat. Poll. Contr.* Vol. 73, pp. 51-76.
- Coe, H. S., Clevenger, G. H., (1916). "Methods for Determining the Capacity of Slime Settling Tanks." *Trans. Am. Inst. Mining Engrs*, Vol. 55, pp. 356-383.

Cole, R.F. (1979). "Experimental Evaluation of the Kynch Theory." Ph.D. Dissertation, University of North Carolina, Chapel Hill, N. C.

Colt I. and Armstrong D. (1979). "Nitrogen Toxicity to Fish, Crustaceans and Molluscs." Department of Civil Engineering University, University of California, Davis, California.

Comeau, Y., Oldham, W. K. and Hall, K. J. (1987). "Dynamics of Carbon Reserves in Biological Dephosphatation of Wastewater." Proceedings of an IAWPRC specialized conference in Rome on Biological Phosphate Removal from Wastewaters, pp. 39-55.

Crosby, R. M. (1984). "Hydraulic Characteristics of Activated Sludge Secondary Clarifiers." EPA-600/2-84-131, U.S. Envir. Protection Agency, Cincinnati, Ohio.

Csiti, A. (1991). "Factors Affecting the Biological Phosphorus Removal Efficiency." Periodica Polytechnica Se. Civil Eng., Vol. 35, No. 1-2, pp. 97-106.

Daigger, C. T. and Roper, R. E. (1985). "The Relationship Between SVI and Activated Sludge Settling Characteristics." J. Water Pollut. Control Fed., Vol. 57, pp. 859.

Daigger, G. T. (1995). "Development of Refined Clarifier Operating Diagrams Using an Updated Settling Characteristics Database." Water Environ. Res., Vol. 67, No. 21, pp. 95-100.

Dawes, E.A. and Senior, P.J. (1973). "The role and regulation of energy reserve polymers in microorganisms." Adv. Microbial. Physiol., 10, pp. 135.

Dawson and Murphy (1972). "The Temperature Dependency of Biological Denitrification." Wat. Res. Vol. 6, pp. 71-83.

Deakyne, C. W., Patel, M.A., and Krichen, D. J. (1984). "Pilot Plant Demonstration of Biological Phosphorus Removal." JWPCF., Vol. 56, pp. 867.

Deininger, A., Holthausen, E. and Wilderer, P. A. (1998). "Velocity and Solids Distribution in Circular Secondary Clarifiers: Full Scale Measurements and Numerical Modeling." Wat. Res. Vol. 32, pp. 2951.

Devantier, B.A. and Larock B.E., (1987). "Modeling Sediment-Induced Density Current in Sedimentation Basin." J. Hydraulic Engin., American Society of Civil Eng., 113, 80-94.

Dick, R. I. And Ewing, B. B. (1967). "Evaluation of Activated Sludge Thickening Theories." J. Sanit. Eng. Div., ASCE, Vol. 93 (SA4), pp. 9-29.

Dick, R.I. and Young, K. W. (1972). "Analysis of Thickener Performance of Final Settling Tanks." Paper presented at 27th Purdue Industrial Waste Conference, Lafayette, Indiana.

Downing, A. L. (1968) "Factors to be Considered in the Design of Activated Sludge Plants." in E. F. Gloyna and W. W. Eckenfelder, Jr. (eds.), *Advances in Water Quality Improvement*, University of Texas Press, Austin, pp. 190.

Downing, A. L. and Knowles, G. (1966). *Population Dynamics in Biological Treatment Plants.* in Proc. 3rd Int. Conf. Wat. Poll. Res., Series 2, pp. 117-137.

Drews, R. J. L. C., and A. M. Greef. (1973). "Nitrogen Elimination by Rapid Alternation of Aerobic/Anoxic Conditions in Orbal Activated Sludge Plants." *Water Research.*, v. 7, pp. 1183

Dupont R. and Dahl C. (1995) "A one-dimensional model for a secondary settling tank including density current and short-circuiting" *Wat. Sci. Technol.* 31(2), 215-224.

Ekama G. A., Barnard J. L., Gunthert F. W., Krebs P., McCorquodale J. A., Parker D. S. Wahlberg E. J. (1997). "Secondary Settling Tanks; Theory, Modelling, Design and Operation." Scientific and technical Report No. 6

Engeler, Moser R., Udert, K m., Wild, D., Siegrist, H. (1998). "Products from Primary Sludge Fermentation and their Suitability for Nutrient Removal." *Water Science and Technology*, v 38, n 1 pt 1, 1998, Wastewater: Nutrient Removal, Proceedings of the 1998 19th Biennial Conference of the International Association on Water Quality. Part 1 (of 9), Jun 21-26 1998, Vancouver, Can, pp 265-273.

EPA (1975). "Process Design Manual for Nitrogen Control." Office of Technology Transfer, Washington DC.

EPA (1993). "Manual for Nitrogen Control." Office of Technology Transfer, Washington DC.

Eylar, O. r. and Schmidt. (1959). "A Survey of Heterotrophic Microorganisms From Soil for Ability to Form Nitrite and Nitrate." *J. Gen. Microbial.*, Vol. 20, pp. 631

Filipe, C. D. M. (1999). "Competition Between Phosphorus and Glycogen Accumulation Bacteria: Stoichiometry, Kinetics, and the Effects of pH." Ph.D. Dissertation, Clemson University, Clemson, SC, USA.

Filipe, C. D. M. and Grady, C. P. L. Jr. (2000). "Ecological Engineering of Bioreactors for Wastewater Treatment." *Water, Air, Soil Pollution*, Vol. 123, pp. 117-132.

Fillos, J., Diyamandoglu, V., Carrio, L. A., Robinson, L. (1996). "Full-Scale Evaluation of Biological Nitrogen Removal in the Step-Feed Activated Sludge Process." *Water Environ. Res.*, Vol. 68, No. 2., pp. 132-142.

Finnson A. (1994) *Computer Simulations of Full-Scale Activated Sludge Processes.*, Licentiate Thes., Dep. Water Resou. Eng., Royal Institute Technology, Stockholm, Sweden.

- Focht, D. D. and Chang, A.C. (1975). "Nitrification and Denitrification Processes Related to Wastewater Treatment." *Adv. Appl. Microbiol.*, Vol. 20, pp. 631.
- Foster, J. R. M. (1974). "Studies on Nitrification in Marine Biological Filters." *Aquaculture* Vol. 4, pp. 387-397
- Fuhs, G. W. and Chen, M. (1975). "Microbiological Basis of Phosphate Removal in the Activated Sludge Process for Treatment of Wastewater." *Microbial. Ecol.*, Vol. 2, No. 2, pp. 119-138
- Fukase, T., Shibata, M. and Mayaji, Y. (1984). "Factors Affecting Biological Removal of Phosphorus." *Phosphorus Removal from Wastewater*, Vol. I, IAWPRC Post Conference Seminar, Set. 24, Paris, France.
- Gayle, B. P. *et. al.* (1989). "Biological Denitrification of Water." *J. of Env. Engr. Amer. Soc. of Civil Engr.*, Vol. 115, pp. 930.
- Gayon, U., and G. Dupetit. (1883). "La fermentation des nitrates." *Mem. Sot. Sci. Phys. Nat. Bordeaux Ser. 2.* pp, 5:35-36.
(<http://www.asmus.org/mbrsrc/archive/pdfs/521286p627.pdf>)
- Gerber, A., Mostert, E. S., Winter, C. T. and De Villiers, R. H. (1987). "Interactions Between Phosphate, Nitrate and Organic Substrate in Biological Nutrient Removal Process." *Wat. Sci. Tech.*, Vol. 19, pp. 183-194.
- Ghekiere, S., Bruynooghe, H., van Steenberghe, K., Vriens, L., van Haute, A., Verachtert, H. (1991). "The Effects of Nitrate and Carbon Compounds on Enhanced Biological Phosphorus Removal from Wastewaters." *European Water Pollution Control*, Vol. 1, No. 4, pp. 15-24.
- Greenburg, A. E., Levin, G. T., and Kauffman, W. J. (1955). "Effect of Phosphorus Removal on Activated Sludge Process." *Sewage and Industrial Wastes*, Vol. 27, pp. 227.
- Gunthert, F.W. (1984). "Thickening zone and sludge removal in circular final settling," *Water Sci. and Technol.*, 16(10/11), pp. 303-316.
- Hall, I. R. (1974). "Some Studies on Nitrification in the Activated Sludge Process." *J. Wat. Poll. Con. Fed.*, Vol.73, pp. 538.
- Hamilton, J., Jain, R., Antoniou, P., Svoronos, S. A., Koopman, B., and Lyberatos, G. (1992). "Modeling and Pilot-Scale Experimental Verification for Predenitrification Process." *J. Envir. Engrg.*, Vol. 118, No. 1, pp. 38-55.
- Hamm (1970). "Simultane N- and P- Elimination." *Z. Wasser- and Abwasserforsch.* Vol. 3, pp. 102-107.

- Harandy Taebi, A. and Schroeder, E. D. (1995). "Analysis of Structural Features on Performance of Secondary Clarifiers." *Journal of Environmental Engineering*, Vol. 121, No. 12, pp. 911-919.
- Harandy Taebi, A. and Schroeder, E. D. (2000). "Formation of Density Currents in Secondary Clarifier." *Wat. Res.*, Vol. 34, No. 4, pp. 1225-1232.
- Harremoes, P. and Riemer, M. (1975). "Pilot Experiments on Down Filter Denitrification." *Conf. on Nitrogen as a Water Pollutant*, Copenhagen.
- Härtel, L. and Pöpel, H. J. (1992). "A Dynamic Secondary Clarifier Model Including Processes of Sludge Thickening." *Wat. Sci. Tech.*, Vol. 25, No. 6, pp. 267-284.
- Hascoet, M. C. and Florentz, M. (1985). "Influence of Nitrates on Biological Phosphorus Removal from Wastewater." *Water SA*, Vol. 11, No. 1, pp. 1-8.
- Hasselblad, S. and Xu, S. (1998). "Solids Separation for Secondary Clarifiers." *Water Environ. Res.*, Vol. 70, No. 7, pp. 1290-1294.
- Hasselblad, S., Hallin, S. (1998). "Intermittent Addition of External Carbon to Enhance Denitrification in Activated Sludge." *Wat. Sci. Tech.*, Vol. 37, No. 9, pp. 227-233.
- Haug, R. T. and McCarty, P. L. (1972). "Nitrification with Submerged Filter." *J. Wat. Poll. Contr. Fed.*, Vol. 44, pp. 2086-2102.
- Henze, M. and Harremoes, P. (1977). "Biological Denitrification of Sewage." *A literature Review. Prog. Wat. Tech.*, Vol. 8, pp. 509-555.
- Henze, M. and Harremoes, P. and Roed Jensen, O. (1977). "Combined Sludge Denitrification of Sewage Utilizing Internal Carbon Sources." *Prog. Wat. Tech.* Vol. 8, pp. 589-599.
- Henze, M., Dupont, R., Grau, P., and de la Sota, A. (1993). "Rising Sludge in Secondary Settlers Due to Denitrification." *Wat. Res.*, Vol. 27, No. 2, pp. 231-236.
- Hermann (1962). "Stabilization Pond as a Nitrate-Reducing Reactor." *Proc ASCE J. San. Engg. Div.*, Vol. 88, pp. 1-20.
- Horan, N. J. (1990). "Biological Wastewater Treatment Systems: Theory and Operation." John Wiley & Sons Ltd., West Sussex, England.
- Ide, Tohya, Suzuki, Matsuo and Osanai (1972): "Removal of Nitrogen and Phosphorus." In wastewater treatment. Pachec, 72, Session 16-3.

Isaacs, S. H., Henze, M., Seberg, H., and Kümmel, M. (1994). "External Carbon Source Addition as a Means to Control an Activated Sludge Nutrient Removal Process." *Wat. Res.*, Vol. 28, pp. 511-520.

Iwema, A., Meunier, A. (1985). "Influence of Nitrate on Acetic Induced Biological Phosphate Removal." *Wat. Sci. Tech.*, Vol. 17, pp. 289-294.

Jenkins, D. (1993). "Manual on the Causes and Control of Activated Sludge Bulking and Foaming," 2nd ed., Lewis Publishers, MI.

Jespersen, J. P. and Henze, M. (1993). "Biological Phosphorus Uptake Under Anoxic and Aerobic Conditions." *Wat. res.*, Vol. 27, No. 4, pp. 617-624.

Kang, S J., Bailey, W.F., Jenkins, D., (1992). "Biological nutrient removal at the Blue Plains Wastewater Treatment Plant in Washington, D.C." *Water Science and Technology, Proceedings of the 16th Biennial Conference of the International Association on Water Pollution Research and Control- Water Quality International v 26, n 9-11, pp, 2233-2236.*

Kao, T. W. (1977). "Density Currents and their Applications." *J. of the Hydraulic Division*, Vol. 103 (HY5), pp. 543-555.

Keinath, T. M. (1985). *Operational Dynamics of Secondary Clarifiers.*" *J. Wat. Pollut. Control Fed.*, Vol. 57, No. 7, pp. 770-776.

Keinath, T. M. (1990). "Diagram for Designing and Operating Secondary Clarifiers According to the Thickening Criterion." *J. Wat. Poll. Con. Fed.*, Vol.60, No. 3, pp. 254-258.

Keinath, T.M. (1981). "Solids Inventory Control in the Activated Sludge Process." *Wat. Sci. Tech.*, Vol. 13, pp. 413-419.

Koch, G. and Siegrist, H. (1997). "Denitrification with Methanol in Tertiary Filtration." *Wat. Res.*, Vol. 31, No. 12, pp. 3029-3038.

Koch, G., Pianta, R., Krebs, P. (1999). "Potential of Denitrification and Solids Removal in the Rectangular Clarifier." *Wat. Res.*, Vol. 33, No. 2, pp. 309-318.

Koen, G., Bogaert, H., Verstraete, W. (1996). "Design and verification of a model secondary clarifier for activated sludge." *Journal of Chemical Technology and Biotechnology*, v 67, n 4, pp, 404-412.

Krebs, P. (1991). "Density Currents in Final Setting Tanks." *Proc.*, 24th IAHR Congr., Madrid, Spain, C163-C170.

- Krebs, P., Vischer, D., Gujer, W. (1992). "Improvement of Secondary Clarifiers by Porous Walls." *Wat. Sci. Tech.*, Vol. 26, No. 5-6, pp. 1147-1156.
- Krebs, P., Vischer, D., Gujer, W. (1995). "Inlet-Structure Design for Final Clarifiers." *J. Envir. Engrg.*, Vol. 121, No. 8, pp. 558-564.
- Kuba, T., Murnleitner, E., van Loosdrecht, M. C. M., and Heijnen, J. J. (1996a). "A Metabolic Model for Biological Phosphorus Removal by Denitrifying Organisms." *Biotechnology and Bioengineering*, Vol. 52, pp. 685-695.
- Kuba, T., Smolders, G., Loosdrecht, M. and Heijnen, J. J. (1993) "Biological Phosphorus Removal from Wastewater by Anaerobic-Anoxic Sequencing Batch Reactor." *Wat. Sci. Tech.*, Vol. 27, No. 5/6, pp. 241-252.
- Kuba, T., van Loosdrecht, M. C. M. and Heijnen, J. J. (1996b). "Phosphorus and Nitrogen Removal with Minimal COD Requirement by Integration of Denitrifying Dephosphatation and Nitrification in a Two Sludge System." *Water. Res.*, Vol. 30, No. 7, pp. 1702-1710.
- Kuba, T., van Loosdrecht, M. C. M., Brandse, F. A. and Heijnen, J. J. (1997). "Occurrence of Denitrifying Phosphorus Removing Bacteria in Modified UCT-Type Wastewater Treatment Plants." *Wat. Res.*, Vol. 31, No. 4, pp. 777-786.
- Kuba, T., van Loosdrecht, M. C. M., Murnleitner, E., Heijnen, J. J. (1997). "Kinetics and Stoichiometry in the Biological Phosphorus Removal Process with Short Cycle Times." *Wat. Res.*, Vol. 31, No. 4, pp. 918-928.
- Kuba, T., Wachtmeister, A., van Loosdrecht, M. C. M., and Heijnen, J. J. (1994). "Effect of Nitrate on Phosphorus Release in Biological Phosphorus Removal Systems." *Wat. Sci. Tech.*, Vol. 30, No. 6, pp. 263-269.
- Kuroda, M., Watanabe, T. and Umedu, Y. (1997). "Simultaneous COD Removal and Denitrification of Wastewater by Bio-Electro Reactors." *Wat. Sci. Tech.*, Vol. 35, No. 8, pp. 161-168.
- Kynch, J. J. (1952). "A Theory of Sedimentation." *Trans Faraday Soc.*, Vol. 148, pp. 166-176.
- Lage, Wallis C. L.; Hunt, D. B. (1994). "Clarifier Enhancements Yield Excellent Performance." *National Conference on Environmental Engineering*, pp. 194-201.
- Larsen, P. (1977). "On the Hydraulics of Rectangular Settling Basins, Experimental and Theoretical Studies." Rep. No. 100, Dept. of Water Resour. Enng., Lund inst. of Tech., Lund Univ., Lund, Sweden.

- Lee, M.W., Yun, J.P., Jong, M.P. and Hee, D.C., (2001). "Control of External Carbon Addition in Biological Nitrogen Removal Process for the Treatment of Coke-Plant Wastewater." *Water Environ. Research*, 73, pp, 415.
- Lees, M and Park. (1998). "Biological Nitrogen Removal from Coke-Plant Wastewater with External Carbon Addition.", *Water Environ. Research*, 70, pp, 1090.
- Lemmer, H., Zaglauer, A., (1997). "Denitrification in a methanol-fed fixed-bed reactor. Part 1: Physicochemical and biological characterization" *Water Research*, v 31, n 8, pp, 1897-1902.
- Lenhard (1969). "The Determination of Nitrotase Activity in Denitrifying Systems." *Hydrobiologia.*, Vol. 33, pp. 186-192
- Lessard P. and Beck M. B. (1993) "Dynamic Modeling of the Activated sludge process: a case study." *Wat. Res.*, 27, 963-978.
- Levin, G. V. and Shapiro, J. (1965). "Metabolic Uptake of Phosphorus by Wastewater organisms." *J. Water Pollut. Cont. Fed.*, Vol. 37, pp. 800-821
- Lewyta, J.; Esler, J. K. (1996). "Optimization Clarifier Performance." *International Environmental Conference*, Vol. 1, pp. 13-138
- Ludzak, F. J. and Ettinger, M. B. (1962). "Controlling Operation to Minimize Activated Sludge Effluent Nitrogen." *J. Wat. Poll. Contr. Fed.* Vol. 34, pp. 920-931
- Marais G. v. R and Ekama G. A.. (1986) "Sludge settleability. Secondary Settling Tank Design Procedures" *Water Pollution Control* 1, 101-114.
- McCarty, P. J. (1969). "Feasibility of the Denitrification Process for Removal of Nitrogen from Agriculture Drainage Waters." Appendix. *Calif. Dept. Wat. Res. Bull.*, pp. 174-3
- McCorquodale, J. A. (1976). "Hydraulic study of the circular settling tanks a the West Windsor pollution control plant." Rep. Submitted to Lafontaine, Cowie, Buratto & Associates, Consulting Engineers, Industrial Research Institute, Univ. of Windsor, Windsor, Ont., Canada.
- McCorquodale, J. A. (1977). "Temperature measurements in primary clarifiers at West Windsor PCP." Rep. Submitted to Lafontaine, Cowie, Buratto & Associates, Consulting Engineers, Industrial Research Institute, Univ. of Windsor, Windsor, Ont., Canada.
- McCorquodale, J. A. (1987). "Density currents in clarifiers. "Proc., Nat. Conf. on Hydr. Engrg., ASCE, Mew Upri, M/U., pp, 56-61.

- McCorquodale, J. A., Yeun, E.M., Vitasovic, Z., and Samstag, R. (1991). "Numerical simulation of unsteady conditions in clarifiers." *Water Poll. Res. J. Can.*, 6(2), pp, 201-222.
- Mechala, A Ilan and Matyskiela (1970). "A Study of Nitrification and Denitrification." *Water Poll. Control Res. Ser. USA*.
- Meinhold J., Arnold, E. and Isaacs, S. (1999). "Effect of Nitrite on Anoxic Phosphate Uptake in Biological Phosphorus Removal Activated Sludge." *Water Res.*, Vol. 33, No. 8, pp. 1871-1883
- Metcalf and Eddy (1991). "Wastewater Engineering: Treatment, Disposal and Reuse." Tata McGraw-Hill, New Delhi, India.
- Metcalf and Eddy Inc. (1973). "Wastewater Engineering, Treatment Disposal and Reuse." 3rd ed., McGraw-Hill, New York.
- Milbury, W. F., McCauley D. and Hawthorne, C. H.. (1971). "Operation of Conventional Activated Sludge for Maximum Phosphorus Removal." *J. Water Pollut. Control Fed.*, Vol. 43, No. 9.
- Mino, T., Satoh, H. and Matsuo, T. (1994). "Metabolism of Different Bacterial Populations in Enhanced Biological Phosphate Removal Processes." *Water Sci. Tech.*, Vol. 29, No. 7, 67-70
- Montieth, H. D., Bridle T. R. and Sutton P. M. (1979) "Evaluation of industrial waste carbon sources for biological denitrification." *Env. Canada WW. Tech. Center Report*, EPS4-WP-79-9.
- Mota Cesar R., (2001), "Evaluation of Factors affecting the performance of Biological Phosphorus Removal in a Full-Scale Wastewater Treatment Plant." Master's Thesis, University of Nevada, Las Vegas.
- Moursi, A. M., McCorquodale, J. A., and Ibrahim S. El-Sebakhy. (1995). "Experimental Studies of Heavy Radial Density Currents." *J. of Environ. Engg*, Vol. 121, No. 12, pp. 920-929
- Murakami, T., Koike, N., Taniguchi, N., and Esumi, H. (1987). "Influence of Return Flow Phosphorus Load on Performance of Biological Phosphorus Removal Process." *Proc. IAWPRC Spec. Conf., Rome, Italy, Ramadori R (ed.) Adv. Pollut. Control*, pp. 237-245. IAWPRC Conf. Series, Pergamon Press, London.
- Narayanan, B., Hough, S. G., Ooten, R. J. (2000). "New Hypothesis for Secondary Clarifier Performance Under Hydraulically Limited Conditions." *Water Environ. Res.*, Vol. 72, No. 1, pp. 116-126

Nelson, L. M. and R Knowles. (1978). "Effect of Oxygen and nitrate on Nitrogen Fixation and Denitrification by *Azospirillum Brasilense* Grown in Continuous Culture." *Canadian Journal of Microbiology*, v. 24(11), pp. 1395-1403

Nicholls, H. A. and Osborn, D. W. (1979). "Bacterial Stress: A Prerequisite for Biological Removal of Phosphorus." *J. Water Pollut. Control. Fed.*, Vol. 51, No. 3, pp. 557

Niel Van, E.W.J., Robertson, L.A., Kuenen, J.G. (1993). "A mathematical description of the behaviour of mixed chemostat cultures of an autotrophic nitrifier and a heterotrophic nitrifier/aerobic denitrifier; a comparison with experimental data." *FEMS Microbiol. Ecol.* 102, pp. 99-108.

Nommik, H. (1956). "Investigations on Denitrification in Soil." *Acta Agric. Scand.*, Vol. 6, pp. 195

Osborn, D. W, Nicholls, H. A., and Pitman, A. R. (1984) "The Readily Biodegradable Fraction of Sewage; its Influence on Phosphorus Removal and Measurement." *Enhanced Biological Phosphorus Removal from Wastewater*, IAWPRC Post Conference Seminar, Paris, France, Vol. 1, pp. 105

Paepcke, B. H. (1983). "Performance and Operational Aspects of Biological Phosphate Removal Plants in South Africa." *Wat. Sci. Tech.*, Vol. 15, pp. 219-232

Painter, H. A. (1970). "A Review of Literature on Inorganic Nitrogen Metabolism in Micro-organisms." *Wat. Res.* Vol. 4, pp. 393-450

Parker, D. S., and Wilson, T. E. (1991). "A debate: Circular clarifiers or rectangular clarifiers." *Water/Engrg. And Mgmt.*, pp. 20-26.

Parker, D., Aberley and Cadwell, (1975). "Development and Implementation of Biological Denitrification for Two Large Plants." Presented at Conf. on nitrogen as a Water Pollut., Copenhagen.

Parker, D., Aberley and Cadwell, (1975). "Development and Implementation of Biological Denitrification for Two Large Plants." Presented at Conf. on nitrogen as a Water Pollut., Copenhagen.

Parker, D.S., Wahiberg, E. J., Gerges, H. Z. (2000). "Improving Secondary Clarifier Performance and Capacity Using a Structure Diagnostic Approach." *Wat. Sci. Tech.*, Vol. 41, No. 9, pp. 201-208

Pasveer, (1965). "Beitrag uber Stickstoffbeseitigung aus Abwassern. Munchner Beitrage zur Abwasser-, Fisherei- und Flussbiologie (ed. Liebmann). Bd. 12, pp. 197-200

Payne, W. J. (1973). "Reduction of Nitrogenous Oxides by Microorganisms." *Bacteriol. Rev.* 37, pp. 409-452

Payne, W. J. (1981). "Denitrification." John Wiley & Sons, New York.

Petr Grau. (1999). "Final Clarifier Design and Operation." <http://web.telecom.cz/aquanoval/>

Pitman, A. R. (1980). "Settling Properties of Extended Aeration Sludge." *JWPCF*, Vol. 52, No. 3, pp. 524-536

Pochana, K. and Keller, J. (1999). "Study of Factors Affecting Simultaneous Nitrification and Denitrification (SND)." *Wat. Sci. Tech.*, Vol. 39, No. 6, pp. 61-68

Pokallus (1963). "Toxicity of Nitrite to *Nitrosomonas europea*." Ph.D. Thesis. Rutgers Univ. New Brauswick, New Jersey.

Prabhata K. Swamee, Aditya Tyagi, (1996). "Design of Class-I Sedimentation Tanks" *Journal of Environmental Engineering*, Vol. 122, No.1, Jan ,1996, pp. 71-73

Praksam, T. B. S. and Loehr, R. C. (1972). "Microbiological Nitrification and Denitrification in Concentrated Wastes." *Water Res.*, Vol. 6, pp. 859-869

Praksam, T. B. S., Joo, Y. D., Srinath, E. G. and Loehr, R. C. (1974). "Nitrogen Removal from a Concentrated Waste by Nitrification and Denitrification." *Proc. 29th Int. Waste Conf. Purdue Univ.* pp. 497-509

Randall C. W., Barnard J. L., Stensel H. D. (1992). "Design and Retrofitting of Wastewater Treatment Plants for Biological Nutrient Removal." *Water Quality Management Library*, Vol. 5, Technomic Publishing Co., Inc., Lancaster, PA.

Rittman, B. E. and Langeland, W. E. (1985). "Simultaneous Denitrification with Nitrification in Single-channel Oxidation Ditches." *J. Wat. Poll. Con. Fed.*, Vol.57, pp. 300

Rittmann Bruce E. (2001). "Environmental Biotechnology: Principles and Applications"

Sakakibara, Y., Flora, J. R., Suidan, M. T. and Kuroda, M. (1994). "Modeling of Electrochemically-Activated Denitrification Biofilms." *Wat. Res.*, Vol. 28, pp. 1077-1086

Schon, George; Geywitz, Susanne; Mertens, Franks. (1993). "Influence of Dissolved Oxygen and Oxidation-reduction Potential on Phosphate Release and Uptake by Activated Sludge from Sewage Plants with Enhanced Biological Phosphorus Removal." *Water Research*, v 27, n 3, Mar, 1993, pp 349-354

Schuler, A. J. (1998). "The Effects of Varying Influent Phosphate and Acetate Concentrations of Enhanced Biological Removal of Phosphate from Wastewater". PhD. Thesis Dissertation, University of California at Berkeley, 256 pages

Schuster (1970). "Zum gegenwärtigen stand der stickstoffelimination aus abwassern." Fortschr. Wasserchem. Grenzgeb. Vol. 12, pp. 124-138

Scott K.J. (1996) "Mathematical models of mechanism of thickening," I. & EC Fundamentals 5, pp. 109-113

Sedlak, R. (Ed) (1991) "Phosphorus and Nitrogen removal from municipal wastewater.", 2nd Edition, Lewis Publishers, New York.

Semon J. (1982). "Private Communication on Installation of First Stamford Baffle", Stanford, CA

Sherman, V. B. D. and MacRae, I. C. (1957). "The Influence of Oxygen Availability on the Degree of Nitrate Reduction by *Pseudomonas denitrifications*." Can. J. of Microbiol., Vol. 3, pp. 505

Siegrist H., Krebs P., Buhler R., Purtschert I., Rock C., and Rufer R. (1995). "Denitrification in Secondary Clarifier." Water Sci. Technol. Vol. 31(2), pp. 205-214

Siegrist, H., Brack, T., Koch, G., Nissbaumer, A., and Gujer, W. (2000). "Optimization of Nutrient Removal in the WWTP Zürich-Werhölzli." Wat. Sci. Tech., Vol. 14, No. 9, pp. 63-71

Siegrist, H., Gujer, W., (1994). "Nitrogen Removal in Activated Sludge Systems including denitrification in Secondary Clarifiers." Water Science and Technology, Nutrient Removal, Proceedings of the 17th Biennial Conference of the International Association on Water Quality, v 30, n 6, pp, 101-111.

Siegrist, H., Krebs, P., Bühler, R., Purtschert, I., Röck, C., and Rufer, R. (1995). "Denitrification in Secondary Clarifiers." Wat. Sci. Tech., Vol. 31, No. 2, pp. 205-214

Siegrist, H., Reithaar, S., Kock, G., Lais, P. (1998). "Nitrogen Loss in a Nitrifying Rotating Contactor Treating Ammonium-Rich Wastewater Without Organic Carbon." Wat. Sci. Tech., Vol. 38, No. 8-9, pp. 241-248

Smolders, G. J. F., Meij J. vd, Loosdrecht, M. C. M. and Heijnen, J. J. (1994) "Model of the Anaerobic Metabolism of the Biological Phosphorus Removal Process: Stoichiometry and pH Influence." Biotech. Bioeng., Vol. 43, pp. 461-470

Soap and Detergent Association (1988). "Principles and Practices of Nutrient Removal from Municipal Wastewater."

Sorensen Halling, B. and Jørgensen, S. E. (1993). "The Removal of Nitrogen Compounds from Wastewater." *Studies in Environmental Science*, Vol. 54, pp. 120-146

Sorensen, Halling B. and Hjuler, H. (1992). "Simultaneous Nitrification and Denitrification with an Upflow Fixed Bed Reactor Applying Clinoptilolite as Media." *Water Treatment* Vol. 7, pp. 77-88

Sperling, M. and Froes, C. M. V. (1999). "Determination of the Required Surface Area for Activated Sludge Final Clarifier Based on a Unified Database." *Wat. Res.*, Vol. 33, No. 8, pp. 1884-1894

Srinath, E. G. (1959). "Rapid Removal of Phosphorus from Sewage by Activated Sludge." *Experientia* (Switzerland), Vol. 15, pp. 339

Stamou, A. I. (1997). "Optimizing the Design of Secondary Clarifiers Using Mathematical Models." *International conference on Water Pollution*, pp. 681-690

Steinbuchel, A. (1991). "Recent Advances in the Knowledge of the Metabolism of Bacterial Polyhydroxyalkanoic Acids and Potential Impacts on the Production of Biodegradable Thermoplastics." *Acta Biotechnol.*, Vol. 11, pp. 419-427

Stensel (1971). "Biological Kinetics of the Suspended Growth Denitrification Process." Ph.D. Thesis, Cornell University.

Stukenberg, J. R., Rodman, L. C., and Touslee, J. E. (1983). "Activated Sludge Clarifier Design Improvements." *J. Water Pollution Control Fed.*, Vol. 55, No. 4, pp. 341-348

Sutton, P. M., Murphy, K. L. and Dawson, R. N. (1974). "Continuous Biological Denitrification of Wastewater." *Wat. Pollut. Control Directorate*, Environment Canada, Ottawa, Ontario, Environmental Protection Service Report NO. EPS-4-WP-74-6

Takacs, I., Patry, G. G. and Nolasco, D. (1991). "A Dynamic Model of the Clarification Thickening Process." *Wat. Res.*, Vol. 25, No.10, pp. 1263-1271

Talmage, W. P. and Fitch, E. B. (1955). "Determining Thickener Unit Areas." *Industrial and Engineering Chemistry*, Vol. 47, No. 1, pp. 38-41

Tam, N. F. Y., Wong, Y. S. and Leung, G. (1992). "Significance of External Carbon Sources on Simultaneous Removal of Nutrients from Wastewater." *Wat. Sci. Tech.*, Vol. 26, No. 5-6, pp. 1047-1055

Tchobanoglous, G. and Burton, F. L. (1991). "Wastewater Engineering: Treatment Disposal and Reuse." 3rd edition, Chap. 11, McGraw-Hill Publishing Company.

Teichgräber, B. (2000). "Acidification of Primary Sludge to Promote Increased Biological Phosphorus Elimination and Denitrification." *Wat. Sci. Tech.*, Vol. 41, No. 9, pp. 163-170

Tetreault, M. J., Benedict, A. H., Kaempter, C., and Barth, E. F. (1986). "Biological Phosphorus Removal – A Technology Evaluation." *JWPCF.*, Vol. 58, No. 3, pp. 823-837

Timmerman, M. W. (1979). "Biological Phosphate Removal from Domestic Wastewater Using Anerobic/Aerobic Treatment." Chapter 26 in *Development in Industrial Microbiology*, pp. 285

Tood and Nuner (1973). "Comparison of Two Techniques for Assessing Denitrification in Terrestrial Ecosystems." *Bull. Ecol. Res. Comm. Stock.* Vol. 17, pp. 277-278

Tracy K. D. and Keinath T. M. (1973) "Dynamic model for thickening of activated sludge.", *AIChE Sympo. Ser.* 70(136), 291-308.

Vacker, D. *et. al.* (1967). "Phosphate Removal Through Municipal Wastewater Treatment at San Antonio, Texas." *JWPCF.*, Vol. 39, pp. 750

Vesilind, P.A., (1968). "The influence of stirring in the thickening of biological sludge." Doctoral Thesis, Univ. Carolina, Chapel Hill, North Carolina.

Vitasovic, Z. C., Zhou, S., McCorquodale, J., Lingre, K. (1997). "Secondary Clarifier Analysis Using Data from the Clarifier Research Technical Committee Protocol." *Water Environ. Res.*, Vol. 69, pp. 999-1007

Vlekke, G. J. F., Comeau, Y. and Oldham, W. K. (1988). "Biological Phosphate Removal from Wastewater with Oxygen or Nitrate in Sequencing Batch Reactors." *Environ. Technol. Lett.*, Vol. 9, pp. 791-796

Wanielista, M. and Eckenfelder, W. W. Jr. (1978). "Advances in Water and Wastewater Treatment Biological Nutrient removal." Ann Arbor Science Publishers, Inc., Ann Arbor, Michigan.

Wanner, J., Čech, J. S. and Kos, M. (1992). "New Progress Design for Biological Nutrient Removal." *Wat. Sci. Tech.*, Vol. 25, No. 4-5, pp. 445-448

Wells, S. A., LaLiberte, D. M. (1998). "Winter Temperature Gradients in Circular Clarifiers." *Water Environ. Res.*, Vol. 70, No. 7, pp. 1274-1279

Wentzel, M. C., Loewenthal, R. E., Ekama, G. A. and Marais, G.v.R. (1988). "Enhanced Polyphosphate Organism Cultures in Activated Sludge-Part I: Enhanced Culture Development." *Water SA*, Vol. 14, No. 2, pp. 81-92

- Wheatland, A. B., Barnett, M. J. and Bruce, A. M. (1959). "Some Observations on Denitrification in Rivers nad Estuaries." *Inst. Sewage Purif. J. Proc.*, pp. 149
- White, K.D. (1995). "Enhancement of Nitrogen Removal in Subsurface Flow Constructed Wetlands Employing a 2-Stage Configuration, an Unsaturated Zone, and Recirculation." *Water Sci. Technol.* Vol. 32, 3, pp. 59
- Wild, H. E., Sawyer, C. N. and McMohan, T. C. (1971). "Factors Affecting Nitrification Kinetics." *J. Wat. Poll. Contr. Fed.* 43, pp. 1845-1854
- Wiljer, J. and Delwiche, C. C. (1954). "Investigations on the Denitrifying Process in Soil." *Plant Soil*, Vol. 5, pp. 155
- Wilson, T. E. (1991). "Rectangular Clarifiers Should be Considered," *Water/Engineering and Management*, Vol. 138, No. 4, pp. 20
- Wilson, T. E. (1991). Rebuttal to "The Case for Circular Clarifiers," *Water/Engineering and Management*, Vol. 138, No. 4, pp. 26
- WPCF (1985) "Clarifier Design." *Water Pollution Control Federation*, Washington, D.C.
- Wuhrmann, K. (1960). "Effect of Oxygen on Biochemical Reactions." *Proc. 3th Conf. Biol. Waste Treatm.*, Manhattan College, N.Y.
- Xu, S. (1996). "Wastewater Characterization for A ctivated S ludge Process Modeling." Licentiate thesis, Dep. Water Resource, Eng., Royal Inst. Technology, Stockholm, Sweden.
- Ying, Lin. F., Jing, S. R. (2001). "Characterization of Denitrification and Nitrification in a Step-Feed Alternating Anoxic-Oxic Sequencing Batch Reactor." *Water Environ. Res.*, Vol. 73, No. 5, pp. 526-533
- Yoshioka, N., Hotta, Y., Tanaka, S., Naito, S. and Tsugami, S. (1957). "Continuous Thickening of Homogenous Flocculated Slurries." *Chem Engg.*, Tokyo (Kagaku Kogaku), Vol. 21, pp. 66-74
- Zhou, S. P., and McCorquodale, J. A. (1992a). "Influence of Density on Circular Clarifiers with Baffles." *J. Envir. Engg.*, ASCE, Vol. 118, No. 6, pp. 829-847
- Zhou, S. P., and McCorquodale, J. A. (1992b). "Influence of Skirt Radius on Performance of Circular Clarifier with Density Stratification." *Int. J. Numer. Methods in Fluids*, Vol.14, pp. 919-934
- Zhou, S. P., and McCorquodale, J. A. (1992c). "Mathematical Modeling of a Circular Clarifier." *Can. J. Civil Engg.*, Vol. 19, pp. 365-374

Zhou, S. P., McCorquodale, J. A. and Godo, A. (1994). "Short Circuiting and Density Interface in Primary Clarifiers." J. Hydr. Engrg., ASCE, Vol. 120, No. 9, pp. 1060-1080

VITA
Graduate College
University of Nevada, Las Vegas

Prithviraj V. Chavan

Home Address:

12 Lane, Nandani Road,
Jaysingpur, MS 416101,
India.

Local Address:

4235, Cottage Cir. #4
Las Vegas, Nevada 89119

Degree:

Bachelor of Engineering, Civil Engineering, 2000
Shivaji University, Kolahapur, MS, India

Thesis Title: The Influence of Denitrification in Secondary Clarifiers on Biological Phosphorus Removal at the Clark County Sanitation District (CCSD) at Las Vegas, Nevada.

Thesis Examination Committee:

Chairperson: Dr. Jacimaria Ramos Batista, Ph.D
Committee Member, Dr. David E. James, Ph.D
Committee Member, Dr. Barbara A. Luke, Ph.D., P.E
Graduate Faculty Representative, Dr. Dr. J. Abiodun Elegbede, Ph.D