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THE BIOLOGICAL REMOVAL OF PHOSPHORUS AT THE CLARK COUNTY SANITATION DISTRICT WASTEWATER TREATMENT PLANT

by

Jon Robert Becker

Bachelor of Science
California State University, Northridge
1974

A thesis submitted in partial fulfillment
of the requirements for the

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

The Graduate College
University of Nevada, Las Vegas
May 2000

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Jon R. Becker

Entitled

The Biological Removal of Phosphorus at the Clark County Sanitation District Wastewater Treatment Plant

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

Master of Science in Engineering

Examination Committee Chair

Dean of the Graduate College

Examination Committee Member

Examination Committee Member

Graduate College Faculty Representative

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ABSTRACT

The Biological Removal Of Phosphorus At The Clark County Sanitation District Wastewater Treatment Plant

by

Jon Robert Becker

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

This research examines the influence of operating parameters on the enhanced biological phosphorus removal (EBPR) from the effluent of the Clark County Sanitation District (CCSD) wastewater treatment plant. Several parameters that influence EBPR were investigated, including wastewater composition: (e.g. BOD, nitrate, nitrite, ammonia, Total P, Ortho-P, alkalinity, pH), dissolved oxygen levels, oxidation reduction potential, microbiology, volatile fatty acid concentrations, fraction of P in wasted sludge, and nitrification levels. Analysis of nitrate and effluent phosphorus levels indicated a strong correlation between the two parameters. Very strong denitrification, evidenced by very low nitrate levels, produced nitrogen gas that lifted microbes into the clarifier effluent. Weak denitrification allowed for the release of Ortho-P from the microbes into the clarifier effluent. Moderate amounts of denitrification stalled phosphorus release and did not lift microbes into the effluent.

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CHAPTER 1

STATEMENT OF THE PROBLEM

This research examines the influence of operating parameters on the biological removal of phosphorus from the effluent of the Clark County Sanitation District (CCSD) wastewater treatment plant.

The CCSD plant currently uses a process known as the Anoxic/Anaerobic/Oxic (A^2/O) to implement enhanced biological phosphorus removal (EBPR). The A^2/O proceeds by initially exposing the (acclimated) return activated sludge (RAS) to the influent wastewater under non-aerated (anoxic/anaerobic) conditions, and subsequently to aerated (oxic) conditions.

In the BOD rich anaerobic stages, OP (ortho-phosphate) is released into the water from polyP stored within the cells of phosphate accumulating organisms (PAOs). The release of polyP provides the energy necessary for the uptake of volatile fatty acids (VFAs), also referred to as short chain fatty acids (SCFAs), and lower fatty acids (LFAs). The VFAs are then taken up and stored as polyhydroxyalkanoates (PHA) under anoxic/anaerobic conditions. Under aerobic conditions, the PAOs alter their metabolism to use the stored PHA for cell growth, polyP synthesis and glycogen formation. The uptake of P to form polyP is commonly referred to as luxury uptake, since the microbes store P in excess of their biological requirement. Stored polyP within the cell is removed from the treatment train as wasted microbial growth, termed waste activated

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sludge (WAS). The treated CCSD wastewater with low P concentration is then channeled into the Las Vegas Wash, from where it flows into Lake Mead.

CCSD records document that the EBPR process has been able to lower the phosphorus to average concentrations around 0.25 mg/L in the effluent. However, the effluent phosphorus concentrations occasionally exceed the NPDES permit target value (0.5 mg/L). It is necessary to operate the plant on a consistent, daily basis with dependably high removal efficiencies. The objective of this research is to determine which operating parameters consistently minimize the mean effluent phosphorus concentration, and identify factors that are associated with occasional destabilization of the EBPR.

The ultimate goal in removing phosphorus from treated wastewater is prevention of eutrophication in Lake Mead and the natural waterways below Hoover Dam through which the Colorado River flows. This work is supportive of the higher water effluent standards being sought by State and Federal Government regulations, as well as public demand.

1.1 Specific Objectives

The specific objectives of this research are:

1. To investigate the effects of solids retention time (SRT) on phosphorus removal and numerous related plant parameters.
2. To evaluate the overall efficiency of phosphorus removal in the plant by chemical and biological means.

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3. To perform a mass balance of phosphorus and identify its fate at the unit processes within the plant treatment train.
4. To study the effects of wastewater composition and several operating parameters on EBPR system at CCSD.
5. To analyze the interactions of denitrification and phosphorus removal in the plant.

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CHAPTER 2

LITERATURE REVIEW

2.1 Phosphorus: Properties and Characteristics

2.1.1 Phosphorus in Eutrophication

The major goal of removing phosphorus from wastewater effluent is to minimize eutrophication of receiving waters. Many descriptions exist for the effects of eutrophication and the level at which it is present in a body of water. Beginning with a standard reference of that description, Webster's Dictionary (1994) defines a eutrophic state as one in which the "concentrations of algae, phytoplankton, and other plant life have diminished the oxygen supplies to the extent that animal life cannot co-exist".

Simpler definitions for eutrophic mean nutrient rich, nutrient referring to a broad complement of organic nitrogen and phosphates that will be found in the water. Once a lake has become visibly green in color, it is generally assumed to have entered the first and easily identifiable stage of eutrophication.

Naturally occurring bodies of water such as the Florida Everglades are assemblies of many forms of animal, plant and pond life in continual competition with each other. By inspection, these living organisms form their own, individual but diversified zones of competition, and each of these has its own eutrophic level. Delicate

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mineral and organic cycles sustain these life forms without allowing any single form to take control. Wetlands such as these are important to maintaining diversity in plant and animal life.

Eutrophication becomes a problem when a large influx of water which is used domestically, is returned to natural waterways. Because this water has received only remedial treatment and not complete cleansing, it is returned with additional solids and nutrients which begin the waterway fouling process.

In the first stages of eutrophication, the water body may have a green tint in its color, but still remains home to thriving fish, plant, and bottom feeder populations such as mollusks and nematodes that flourish in the benthos. Oxygen is generated in the water during carbon fixing cycles by algae and other aquatic plant life. In these fixing cycles, carbon dioxide and water are used in the presence of light and chlorophyll to form carbohydrates and starches, the energy storage molecule. Respiration cycles that build cellular structures require oxygen, and this anabolic process consumes a portion of the daytime oxygen production.

Beyond that of green water, increasing nutrient levels spawn more serious stages of eutrophication, in which the small fish cannot exist because of high turbidity combined with low oxygen levels. Multiplying algae cells at the surface develop overcrowded conditions and diffusion of the cells downward increase the attenuation of light at lower depths. Algae cells in diminished light ultimately use more oxygen then they produce and begin to suffocate. At the surface however, protozoans may still flourish, while amphibians and reptiles forage from the shallow waters.

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The slow build up of dead and decaying cells from the surface continues to reduce the dissolved oxygen level at depth to near zero, but the BOD_i continues to increase. Higher eutrophic levels might permit only protozoans and protists to survive near the surface of the water. At the same time, heavy depositions of decaying biomass have driven the bottom sediments anaerobic, killing all but a few, select species of obligate anaerobes. High levels of dissolved nutrients that continue to flow into the body of water will increase the BOD, eventually building a plethora of decay related toxins, breeding putrefaction and spawning pathogenic organisms often associated with anaerobic conditions. Once the decaying biomass builds such a demand in waterways, it often has to be physically removed because the microbiology is not capable of eliminating this demand in any near term period of time.

Countless numbers of inland lakes and watercourses have been identified as eutrophic and in need of support to reverse this trend, but not just freshwater has been affected. Malakoff (1998) locates a number of oxygen-starved coastal dead zones, the number of which have tripled around the world during the past 30 years. One of these zones, attributed to agricultural fertilizer, is located near Mississippi River delta and is nearly 400 km long and 100 km in width. Much of Louisiana's fishing industry is considered to be in jeopardy, along with the food and nutritional supplements it once provided. The Baltic Sea is another example of very severe eutrophication.

Raw wastewater has such a large oxygen demand from dissolved organic carbon that it can keep oxygen levels at near zero for a long time if not treated. An example of the potential oxygen depletion that might exist without water treatment can be seen in the records of Clark County's raw wastewater, which averaged a BOD_5 of 249 mg/L for

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1998. Since the oxygen saturation level in fresh water at the elevation of Las Vegas is approximately 8.3 mg/L at temperatures of approximately 25^0C, more than thirty times the mass of oxygen required to saturate fresh water would have to be passed into the water.

2.1.2 Phosphorus – The Limiting Nutrient

Phosphorus is often called the limiting nutrient because of its relatively small mass fraction as compared to the remaining biomass that it controls. A quantification of this small mass fraction can be seen from what is know as the Redfield Formula For Protoplasm, cited by Morel and Hering (1993) as:

$$\mathbf{C_{106}\,H_{263}\,O_{110}\,N_{16}\,P} \qquad \text{eq. 2.1}$$

This formula is generalized to cover phytoplankton, algae and single celled animal life forms. The protoplasm of Redfield's formula has an atomic weight of 3550 Da. Therefore, the dry mass fraction of phosphorus, having an atomic weight of 30.9, is 0.00871, or approximately 0.9%. Assuming water content in algae and other single cell organisms to be approximately 90%, the wet fractional weight of phosphorus in simple cells is reduced to ~0.09% or 1 part in 1034. This allows one pound of phosphorus to control the growth of over 1000 pounds of algae or phytoplankton, by its presence or absence.

By first calculating the potential mass of algae that might be grown from the CCSD wastewater effluent, an appreciation of the potential eutrophic impact on Lake Mead can be gained. Using the 1998 average P influent concentration and flow from

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section 2.1.3, it is found that a daily mass of 3062 lbs. P enters the CCSD plant through the sewers and would be passed out into the Las Vegas Wash were it not removed. Using the Redfield formula and assuming adequate nitrogen, carbon, and 100% utilization by the cells, this influent phosphorus represents a growth potential of approximately 3.17 million lbs. of algae per day, or 1.16 billion lbs. per year.

Next is an estimation of the surface area or volume needed to distribute this algae mass. To choose a convenient starting point, a concentration of 1000 mg/L is chosen. This value would leave the water unmistakably green, in the same sense that an MLSS concentration of 1000 mg/L would leave wastewater unmistakably brown. Experience with grab samples in basin #4, shows that the bottle disappears at a depth of 3 to 4 inches while operating at an MLSS concentration between 2000 and 2400 mg/L. Halving these values and allowing all the attenuation to come from simple mass of cells, an MLSS of 1000 mg/L would then hide a bottle at a depth of 6 to 8 inches. Using that perspective, an algae concentration of 1000 mg/L would appear almost solid green at the surface. Volumes derived from other concentrations are easily achieved by scaling.

Mixing one year's algae production to a concentration of 1000 mg/L would require 426,000 acre feet of water. This volume, to a depth of one foot, is equal to 665 square miles or an area 29 miles in diameter, nearly the North-South length of Lake Mead itself. Yet, this volume of water does not include contributions of effluents from the cities of Las Vegas and North Las Vegas. This biomass would have a tremendous impact on Lake Mead and waterways below Hoover Dam, if the effluents were not treated and controlled.

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Before continuing to the next section, it is important to point out the two main features that secure phosphorus the title of limiting nutrient.

These features are:

1. the required mass fraction in cells as described is actually too large for concentrations in most naturally occurring water bodies to support algae growth at eutrophic levels. This prevents environmental sources from contributing nutrient P after it has been taken out of the wastewater.

2. there is no gaseous form of the element that can be fixed by microbial life, similar to the fixing of inorganic carbon, oxygen, or nitrogen for organic usage. Lack of a gaseous form of P prevents uptake by algae from atmospheric sources.

The first feature can be easily understood by considering the same proposition for iron, a necessary and extremely small mass component of chlorophyll. Remove iron completely and algae dies because it cannot convert CO_2 to glucose during sunlight hours and, for that reason, iron becomes a limiting nutrient. Unfortunately, iron concentrations appear to exist in most waterways to ample proportions that support algae at any growth level. For that reason, taking iron out of the wastewater has no effect, but this is not the case for phosphorus.

Lean and Pick (1981) measured carbon uptake in nutrient-deficient (clear) water in Lake Erie and neighboring Kootenay and Jack's lakes. The research sampled water at various depths, and measured the initial phytoplankton populations along with N and P concentrations. Enrichments of N and P were added and carbon uptake measured. P concentrations are often a function of depth and turbulence in the water, but soluble

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reactive phosphorus was measured in concentrations between 0.21 and .92 μg-P/l. Enrichment P concentrations began at 10 μg-P/l. Using the 1:1034 Redfield ratio, natural occurring phytoplankton might be expected at levels of 1.0 mg/L. Measured population biomass from the study cited 1.97 mg/L for diatoms in one case. In another study by Elser et. al. (1990), chlorophyll was found at concentrations in (oligotrophic) Lake St. Clair to measure 0.54 μg/l to 35.0 μg/l in eutrophic Clear Lake.

The second feature is unlike carbon, hydrogen or nitrogen, because are all readily fixed into organic forms by microorganisms of various species. Nitrogen, though not useable in its gaseous form, can be fixed into the organic form by certain species of bacteria into nitrates and ammonia. Griffith (1973) identifies specific species of cyanobacteria such as *Anabaena*, *Gleotrichia*, *Aphanizomenon*, and *Nostoc*, as having the ability to fix nitrogen from atmospheric nitrogen gas (N_2), thereby creating nitrate and ammonia, the only forms of nitrogen usable to plant life. Lim (1998) adds the nitrogen fixing bacteria species of *Azotobacter*, *Klebsiella*, *Clostridium*, and *Rhizobium* to this list of fixing microbes. Thus, even if nitrogen was completely removed from the treated wastewater, blooms of nitrogen fixing algae could again return it to the aquatic environment. Nitrogen is also present in the wash due to drainage from anthropogenic sources such as plant fertilizers and animal feces.

The vast amount of phosphorus inputs to water result from human populations, and not inorganic sources or microbial fixing. Therefore, once taken out of these sources, the water remains nutrient deficient, and the most effective technique of delaying the onset of eutrophication is removal of phosphorus from return flows.

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2.1.3 Natural Characteristics of Phosphorus

Phosphorus is an essential element in all life on Earth, from the virus, through single cell organisms, to plants and animals. It is the tenth most abundant element constituting approximately 0.1% of the earth's crust by weight.

Elemental phosphorus can exist in liquid, solid and vapor states, the vapor consisting of tetrahedral P_4 molecules. Birk (1994) describes phosphorus as highly reactive with a tendency for spontaneous ignition in air. For that reason, it is normally found in nature, existing in the form of phosphate compounds ($-PO_4^{3-}$). Isolated from these natural states, phosphorus has 19 allotropes, the three main varieties being prefixed as black, red and white. White phosphorus can be found in liquid and solid phases, both of which are quite poisonous and burn the skin on contact. Exposure to air will cause it to glow a greenish color, giving off white fumes. Minerals containing phosphorus compounds or phosphors, are visible in the dark when illuminated by black lamps that radiate ultraviolet wavelengths. In some minerals, this illumination can persist a long time after the lamp radiation has been removed. The attribute of phosphorescence, meaning to glow in the dark, provided phosphorus with its name.

The highly reactive, elemental phosphorus began to combine with oxygen to form mineral phosphates while the Earth's crust was still molten, and became bound in the rocks. Phosphate leaching from Precambrian rocks was accelerated by sulfate emissions originating in volcanic activity. When mixed with water vapor in the air, a portion of the sulfate anions will generate sulfuric acid, and return to the Earth as acid in the rain. Phosphorus pentoxide (P_2O_5), a naturally occurring phosphate, readily absorbs moisture from the atmosphere to form phosphoric acid.

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As water bodies began accumulating other salts in solution, the high solubility and chemical reactivity of phosphates combined with acidic rain run-off, further enhanced leaching from early rocks. At some point in time, the phosphates in mineral rich water were accepted as obligate compounds in life, assuming irreplaceable roles in function and evolution of all organisms.

Much of the modern phosphate rock formations had biological origins, having been accumulated in the sediment of prehistoric seas from guano, metabolic wastes, decomposed bodies, urine and the skeletons of animals (Birk, 1994). Phosphate rock beds have also formed after precipitation from water. Further concentration of the phosphate sediments resulted from natural chemical condensations. These sediments ultimately being agglutinated by hydrogeologic and regolith pressure, generated by the convolution and burial of geologic strata, into the modern phosphate bearing rock.

The most abundant source of phosphate according to Butcher et. al., (1992) is found in apatite, a sedimentary rock that accounts for more than 95% of all phosphorus in the Earth's crust. Apatite has many forms, the generic formula being $Ca_{10}(PO_4)_6X_2$ Common substitutes for X are OH^-, (hydroxyapatite or simply apatite), F^- (fluorapatite), and Cl^- (chlorapatite). A partial list for occasional substitutes of Ca^{2+} can be Na^+, K^+, Ag^+, Mn^{2+}, Mg^{2+}, Zn^{2+} and Cd^{2+}.

Basic phosphate rock or calcium phosphate [$Ca_3(PO_4)_2$], reacts with sulfuric acid, forming phosphoric acid according to the following reaction:

$$Ca_3(PO_4)_2(s) + 3H_2SO_4 + 6H_2O \longrightarrow 3CaSO_4.2H_2O(s) + 2H_3PO_4(aq) \quad \text{eq. 2.2}$$

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Phosphoric acid (in the orthophosphate form) readily dissociates in water and has three forms:

$$H_3PO_4(aq) \longrightarrow H^+ + H_2PO_4^-(aq) \qquad \text{eq. 2.3}$$

$$H_2PO_4^-(aq) \longrightarrow H^+ + HPO_4^{2-}(aq) \qquad \text{eq. 2.4}$$

$$HPO_4^{2-}(aq) \longrightarrow H^+ + PO_4^{3-}(aq) \qquad \text{eq. 2.5}$$

By combining all three reactions, the stoichiometry becomes:

$$H_3PO_4(aq) \longrightarrow 3H^+ + PO_4^{3-}(aq) \qquad \text{eq. 2.6}$$

Bolin and Cook (1983) in a SCOPE report (Scientific Committee on Problems of the Environment) proposed a model for the Global Phosphorus Cycle (Figure 2.1). The numbers in the Figure are millions of metric tons, MMT, while fluxes are in MMT/yr.

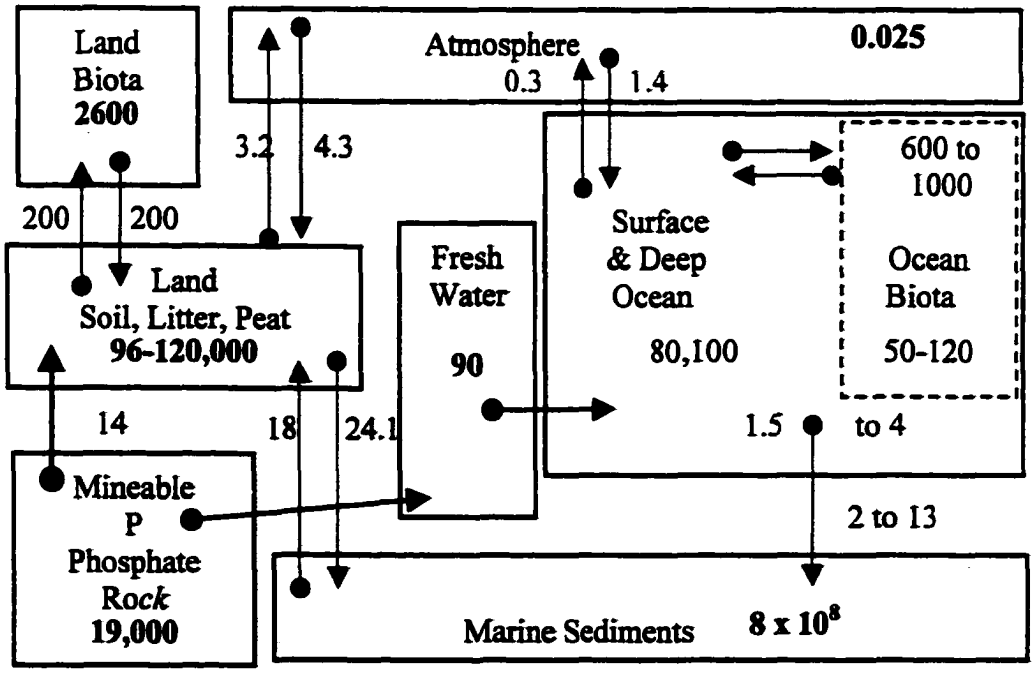

Figure 2.1 – The Global Phosphorus Cycle: Its Reservoirs and Pathways (From Bolin and Cook, 1983)

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A second cycle proposed by Lerman (1975) and Graham (1977) estimates most of the same reservoir sizes to be within a factor of two of Bolin and Cook, except for the accumulated marine sediment in their model, which are approximated at 40 X 10^8 MMT.

A reference to mineable P, shown in Figure 2.1, represents deposits of this phosphate rock that are preferential in the making of fertilizer because of the rich phosphorus content. Plant life is responsible for bringing the majority of phosphorus into biological cycles, taking its supply from the soil (Tiessen et. al., 1995). Animals consume the plants and pass on the phosphates up the food chain. Replenishment of phosphorus that is lost from the ground due to crop harvesting and rain runoff, is needed to maintain agricultural production, and phosphate rock is the source of that replenishment. Fertilizers made from bovine or other manure, and rendering plants that process animal skeletons into bone meal, recycle the phosphorus back to plants and other animals, but do not return that which is lost to waterways and sediments.

Average P concentrations in phosphate rock vary from 125 mg/g (12.5%) in Oceania to 156 mg/g (15.6%) in the former Soviet Union. Rock types which are not considered to be phosphorus bearing, such as limestone, contain average P concentrations of 6 mg/g (0.6%). Basalt contains 3.5 mg/g (0.35%), calcareous siltstone 1-2 mg/g (0.1-0.2%), and Greywacke sandstone ~0.5 mg/g (0.05%). A small fraction of apatite, varying between 0.02% and 1.2%, has been found in igneous rocks (Tiessen et. al., 1995).

A major illusion created by numbers in the Global Phosphorus Cycle, is that the magnitude of phosphate reserves, estimated at 19 x 10^3 MMT, appear that they might

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last for over a thousand years when compared to the withdrawal (mining) rate of only 14 MMT/yr. To the contrary, a simple calculation indicates these reserves will be exhausted in just over 110 years from 1999, at a point when the Earth's population reaches approximately 120 billion people. This calculation can be performed by assuming that (a) the rate of mining increases identically to the present rate of increase in the population (i.e. 3.0%), (b) a 1999 population of 4.5 billion, and that (c) calculations begin in 1983, the year the model was published. This is a conservative calculation, since the mining rate of phosphate rock has increased an average of 10% per year since 1900 (Halling-Sorensen et. al., 1993).

2.1.4 Phosphorus in Cells

Though small in numbers as compared to the carbon, nitrogen and hydrogen molecules of Redfield's protoplasm (eq. 2.1), phosphorus is found in a wide variety of functions in life. Its functions include (a) being an irreplaceable link in maintaining heredity, (b) a major component of bones and teeth, (c) a facilitator of many metabolic pathways, (d) a participant in carbon fixation, creating carbohydrates, (e) a structural member of cell membranes and organelles, and (f) ATP, the energy carrier found in all life forms from microbes to mammals.

In heredity, the phosphate molecule connects the individual deoxy-ribose molecules that line the nucleic bases in both the DNA and the RNA family of molecules: messenger, transfer and ribosomal. Lim (1998) describes how the phosphate molecule makes up the hydrophilic (outer) side of the phospholipid molecule found in cell membranes. Alberts et. al., (1998) illustrates how the phosphate molecule participates in

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all steps of the anaerobic EMP, or glycolytic pathway, that oxidizes glucose into two molecules of pyruvate while generating ATP in the process. Phosphates are intrinsically involved with photosynthesis in cyanobacteria (once referred to as blue-green algae), algae and plants by way of the ATP and the NADPH molecule (from $NADP^+$) which provides reducing power needed for hydrogen ion transfer. ATP and NADPH are used within the choloroplast to drive the carbon fixation cycle to produce glucose from CO_2, H_2O and light. The phosphate molecule transfers chemical energy when it is removed from ATP (adenosine triphosphate) leaving ADP (adenosine diphosphate). Organic phosphates can be found in phospholipids and nucleotides. In hydroxylated aldehydes and ketones, they are referred to as sugar phosphates. Organic phosphates are essentially the orthophosphate form but are tied up in biochemical compounds.

Qasim (1999) reports that organic phosphorus is bound in amino acids and proteins. That is true in the sense that phosphates form weak relationships with amino acids in proteins, in contrast with the mandatory relationship to DNA. Harrington, (1998) describes weak relationship to mean that phosphorus can be associated with amino acids and proteins, but is not found as a required member of all.

Stryer (1995) identifies the fixed set of twenty amino acids that are used by living organisms. To make proteins, only acids from this group are used. They are chained together in a linear series by peptide bonds. A three nucleotide base called a codon in the DNA double helix molecule specifies the order in which they are chained. The codon sequence specifies the amino acids and their order in the protein, but not explicitly a metal or other compound. Proteins perform their function because of the three dimensional shape or conformation that results from the amino acid sequence. In

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some conformations, phosphate may be found associated with certain amino acids such as serine and threonine, the site of phosphate residues in proteins (Unz, 1999). Not only phosphorus but other trace elements and metals such as iron can be found in proteins. One such example of a protein with an iron molecule, described by Alberts et. al., (1998) is hemoglobin, found in blood. Phosphate however, is not part of the hemoglobin protein.

Just as it is distributed throughout living forms, so it is found in foods. Table 2.1, an abbreviated form from Petersen (1949), describes the amount of phosphorus (in percent) found in crops and food products. Dicalcium and monocalicum phosphates are placed in many livestock and poultry feeds.

Table 2.1 Phosphorus Content of Foods, Percent of Wet Mass

Crop	% P	Crop	% P	Crop	% P
Apples	0.011	Grapes	0.018	Potatoes	0.053
Beans	0.055	Rice, whole	0.31	Soybeans	0.633
Celery	0.101	Peanuts	0.394	Walnuts	0.309
Corn	0.11	Peas	0.124	Wheat	0.342
Product	% P	Product	% P	Product	% P
Beef	0.198	Eggs	0.111	Pork	0.262
Butter	0.004	Fish	0.221	Sardines	0.55
Cheese, hard	0.547	Flour, white	0.096	Veal	0.235
Chicken	0.218	Milk	0.088	Wheat bran	1.43

2.1.5 Phosphorus in Wastewater

Greater than 98% of the phosphorus taken in with nourishment is lost from the body in the form of perspiration or body wastes. This is where it enters the wastewater treatment cycle. Metcalf and Eddy (1991) state that phosphorus in wastewater occurs

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mainly in one of three forms: (1) orthophosphate, (2) polyphosphates and (3) organic phosphate. The ortho-P species is characterized by one phosphate (PO_4^{2-}) molecule. Polyphosphates have also been referred to as macromolecular colloidal phosphates, as well as meta-, and condensed-,. Representatives of these groups are pyrophosphate, tripolyphosphate, and trimetaphosphate.

Typical fractional concentrations of these three forms in U.S. sewage reported by Halling-Sorensen (1993) are ortho- 49%, poly- 38%, and organic 13%. This estimate, however, is an extremely variable estimate because wastewater composition depends upon the clientele, or industry generating the waste stream. Infrequent but large contributions might come from storm runoff in a residential area, carrying with it the fertilizer residuals from lawns.

Sedlak (1991) claims that contributions of phosphorus to wastewater made from domestic sanitary sewer systems originate from three main sources:

(1) human waste (including disposed food), 0.6 kg P/capita/yr.

(2) laundry detergents (without legal limitation), 0.3 kg P/capita/yr.

(3) other household detergents and cleaners, 0.1 kg P/capita/yr.

(4) Using 100 gal/capita/day as a representative volume for an individual's sewer discharge rate, the 0.6 kg P/capita/yr. value amounts to an average concentration of 4.3 mg-P/l. For Clark County in 1998, a figure of 0.736 kg TP(total phosphorus)/capita/yr. is calculated using the plant reported (average) influent TP concentration of the wastewater as 5.33 mg-TP/l, an average flow of 68.9 MGD and a typical personal discharge rate of 100 gal/capita/day.

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In a compendium of articles, Horan (1994) reported data on flows, concentrations and absolute weights of wastewater phosphorus at locations around the world. A sampling of that report is reproduced in Table 2.2. The average P concentration of total lbs/day influent (column four) is 7.7 mg/L.

Table 2.2 Phosphorus Concentrations in Wastewater, Global Sampling

Location	Flow in Reported Units	Flow MGD	Total-P mg/L	Total-P lbs/day
Richmond, VA	1.97 m3/s	45	3 - 5	1501
Seneca, MD	0.22 m3/s	5.0	5 - 7.2	254
Elkhart, IN	0.88 m3/s	20	4	667
Dale Mabry, FL	0.26 m3/s	5.9	6.5	320
Blue Plains, D.C.	16.2 m3/s	370	3.6-6.2	15120
Alexandria, VA	2.37 m3/s	54	4 - 7	2477
Korneuburg, Austria	1535 m3/hr	584	15.6	75981
Parkway WWTP, Chesapeake Bay	28,373 m3/d	7.5	6	375
Terneuzen WTP, Netherlands	1140 m3/h	7.2	7.2	432
Kelwona, British Columbia	22.5 ML/day	5.9	6.5	320
Waiblingen WTP, Germany	8280 m3/d	0.5	8.3	35
St. Jean d'Illac, France	2100 m3/d	2.2	18	330

All of these concentrations were taken at least two years after the U.S. ban of phosphates in detergents from 1988. The drop in influent P concentration resulting from the ban, is seen in many of the charts to range between a factor of 1.5 and 3.

The phosphorus in detergents came from pentasodium triphosphate ($Na_5P_3O_{10}$), also known as sodium tripolyphosphate (STP). STP used as a detergent builder, one of the two main components of modern detergents. The second component is the active ingredient, surfactant, or syndet, which can be manufactured with anionic, cationic, nonionic or amphoteric ion adsorption properties. A popular surfactant is linear

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alkylbenzene sulfonate, or LAS (Wang, 1992). Alkyl sulfates as a chemical group, are readily biodegradable, but may be substituted with other sulfonic or carboxylic acid groups. The environmental effects, focusing on the biodegradability of modern surfactants, are still under intense scrutiny, but at this point.

STP was first introduced immediately after WWII (McGucken, 1991). These builders sequester calcium and magnesium ions in hard water and allow the syndets and bleaches to better perform their functions. With increased production, the eutrophication and saprobion problems in open waterways advanced quickly. Beginning around the mid 1980's, many countries have legislated a reduction or elimination of STP from detergents.

Kiessling, (1997), defines a optimum detergent builder as one exhibiting the properties of (a) sequestering of the magnesium and calcium ions, (b) dispersion of sparingly soluble precipitates, (c) support of the active detergent surfactants in soil removal, (d) stabilization of the colloidally distributed soil in the washing liquor, (e) sufficient buffering effect (keeping the pH value constant), and (f) ensuring good powder structure.

STP was able to meet the large number of requirements for a builder by itself. On the other hand, finding a single substitute that exhibited all these properties has not been possible, so combinations of non-phosphate substitutes are used. Sitting (1979), identifies some of these substitutes as derivatives of oxalic, malonic, succinic, citric, and glucaric acids. Additional inorganic compounds used as builders have been aluminate salts, sodium silicate, sodium tetraborate (Borax), and zeolites. Zeolites are not water

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soluble and act primarily as an ion exchangers, taking up calcium ions and releasing sodium ions in exchange (Kiessling, 1997).

Dudzinska and Montusiewicz (1996) discuss the use in Poland of chelating ligands like ethylenediaminetetraacetic acid (EDTA) and nitrylotriamineacetic acid (NTA) as builder substitutes. These were selected because they also have many uses in commercial processes such as plating, metal complexation, metal separation, and stabilization of herbicides, cosmetics and carbonated beverages. EDTA however, is not biodegradable in activated sludge. NTA appears to be biodegradable but its complexation compounds may not. It should be noted that Polish law defines Phosphate-Free as lacking polyphosphates only.

Introduced in the early 1980s and more widely accepted as of recent, have been poly(acrylic acid) and co-poly(acrylic-maleic acid)s. These two compounds are used in combination with zeolites and come from the larger group of compounds known as polymeric carboxylic acids (PCAs). The optimum molar mass for these compounds ranges between 40,000 and 70,000 Da, and have very good dispersive effects that prevent graying of textiles and scaling on washing machine parts. The negative features of PCAs are poor biodegradability in the aqueous environment, resulting in an increasing accumulation of these acids in the environment (Paik, Simon, Swift, 1996). The challenge now is to increase desirability by discovering a formulation that will be highly biodegradable.

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2.2 Background on Specific Topics Related to EBPR

2.2.1 Stoichiometric Models and Metabolic Pathways for EBPR Systems

Mino et. al. (1994) proposed three different metabolic models for PAOs during anaerobiosis. These models describe the anaerobic uptake of acetate and propionate and subsequent conversion to polyhydroxyalkanoates (PHAs) by utilizing the reducing power of NADH, the reduced form of NAD^+, or nicotinamide adenine dinucleotide (Stryer, 1995). NADH is supplied via the Embden–Meyerhof-Parnas (EMP) pathway when producing pyruvate from glucose. The EMP is also called the fermentative pathway because it occurs only under anaerobic conditions. Use of the EMP can cause a drop in pH (Koneman, 1997). Two other pathways used by bacteria, that hydrolyse glucose into pyruvate are the Entner-Douderoff (ED) and the Warburg-Dickins or Hexose MonoPhosphate (HMP) pathways. The ED pathway is also called the aerobic pathway because of the strict requirement for the presence of oxygen for the metabolism to occur. The HMP is sometimes called the pentose cycle because it also provides a means of metabolizing pentose sugars and glucose by a number of bacterial species which are facultatively anaerobic (Koneman, 1997). The HMP can be thought of as a hybrid of the EMD and ED pathways, because it begins similar to the ED and ends more similar to the EMP pathway.

The ability to oxidize substrates under anaerobic conditions, in particular VFAs is essential for PAOs to gain a competitive advantage over other bacteria in the activated sludge process. Mino et. al. (1994) also describes a probable metabolism of the G Bacterium, a competitor to Acinetobacteria. The G bacterium, first described by

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Cech et. al. (1990), also accumulates phosphates but does not sequence through the release and uptake cycles of phosphate removing PAOs. Glucose can stimulate the G bacterium to multiply to the extent of degrading a normally functioning EBPR.

Other researchers have attempted to evaluate microbial processes of EBPR both stoichiometrically and kinetically without the presence of a pure culture. Using the work of Harder (1977), Shapiro (1984, 1991), and Noack (1986), van Loosdrecht (1997) noted that only ten generations from isolated (pure) cell line can change the characteristics of the future generations to such an extent that they no longer represent the characteristics of the original cells. Therefore, to study one variety of PAO .and attempt to predict a dependable outcome in an activated sludge process is extremely unproductive. Bacteria have such a large range of responses for surviving in a dynamically changing environment that predicting a specific outcome requires a multivariate measurement matrix of the entire wastewater chemistry.

Many substantial and intricate biochemical models describing the metabolic pathways of EBPR and *Acinetobacter* spp. have also been developed by authors such as M.C. Wentzel, L.H. Lötter, T. Mino (1994), T. Matsuo (1994), K.J. Hall (1995), T. Fukase (1984), M.C.M Loosdrecht (1997), Nicholls, H.A. (1986), Osborn, D.W. (1986), and M. Shibata (1984). The results of these authors is a study in itself, but a concise summary of these models is presented in two papers by Wentzel et. al. (1986 and 1990). The summary clearly organizes the research findings of his own and other scientists, some of which are mentioned above.

In his 1990 paper, Wentzel states that there are two main models. These are termed the Comeau/Wentzel model (Comeau, Hall, Hancock and Oldham, 1995;

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Wentzel, Lototter, Loewenthal and Marais, 1986), and the Mino model (Mino, Arun, Tsuzuki and Matsuo, 1987.)

A schematic of the Mino model under anaerobic conditions is first shown in Figure 2.2. It describes acetate being brought through the cell wall, where the energy to process it first to acetyl co-enzyme A (acetylCoA) and then to PHB, is supplied by ATP. PolyP stored inside the cell provides one source of energy to drive ADP to ATP, and then the ortho-P molecule is released from the cell. The second source of energy for the oxidation of carbohydrates to pyruvate employs the EMP pathway that also provides protons to reduce NAD^+ to the $NADH_2$ required for reduction of acetylCoA to intracellular PHB.

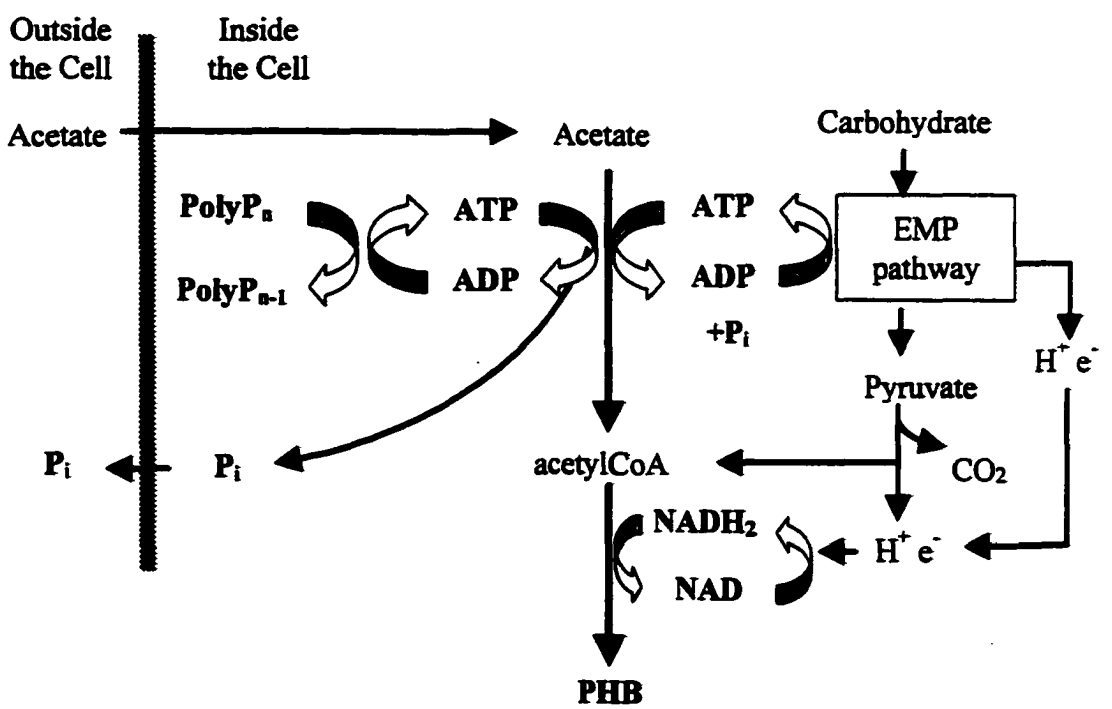

Figure 2.2 The Mino Model Under Anaerobic Conditions

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The anaerobic Comeau/Wentzel model and its contrast with the Mino model are presented in Figure 2.3. Acetate is taken in through the cell wall as before, but a fraction of the acetylCoA is instead, brought into the TCA (tricarboxylic acid, citric acid or Krebs) cycle which then supplies the proton to needed by NAD to build the remaining acetylCoA into PHB. Comeau/Wentzel model inserts a path for cations (M^+) exiting and protons (H^+) entering the cell. Stored polyP alone supplies the energy needed by ADP/ATP for the entire process. Phosphate leaves the cell in the form of phosphoric acid (Figure 2.3) while bringing in a hydroxyl ion in to balance the pH. Supported by each of the models, is the uptake of VFAs and release of phosphate during the anaerobic phase.

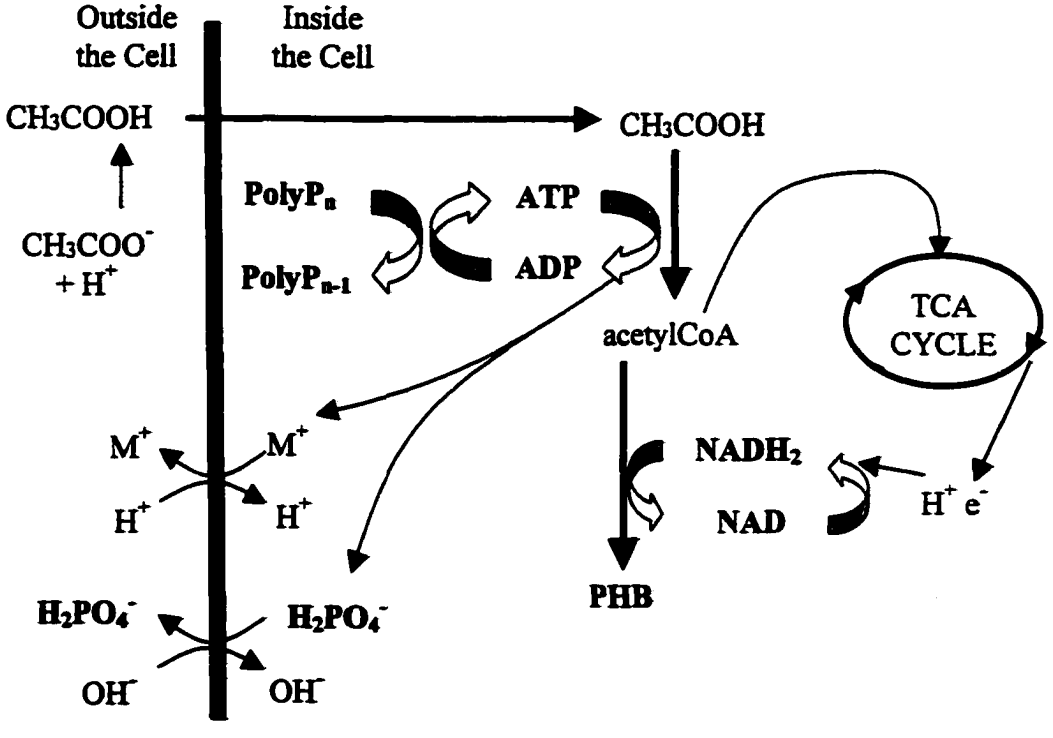

Figure 2.3 The Comeau/Wentzel Model Under Anaerobic Conditions

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The aerobic phase of the Mino and Comeau/Wentzel models are shown in Figures 2.4 and 2.5, respectively. Uptake and external phosphate and storage as intracellular polyP is accomplished with energy from the ATP molecule. The ADP transforms to ATP using a proton from $NADH_2$. PHB stored during the anaerobic phase, is now degraded to acetylCoA and carbohydrates. Part of the reducing power to generate $NADH_2$ comes from this breakdown, and part comes from the TCA and glycolytic cycles used in the electron transport which creates water as an end product.

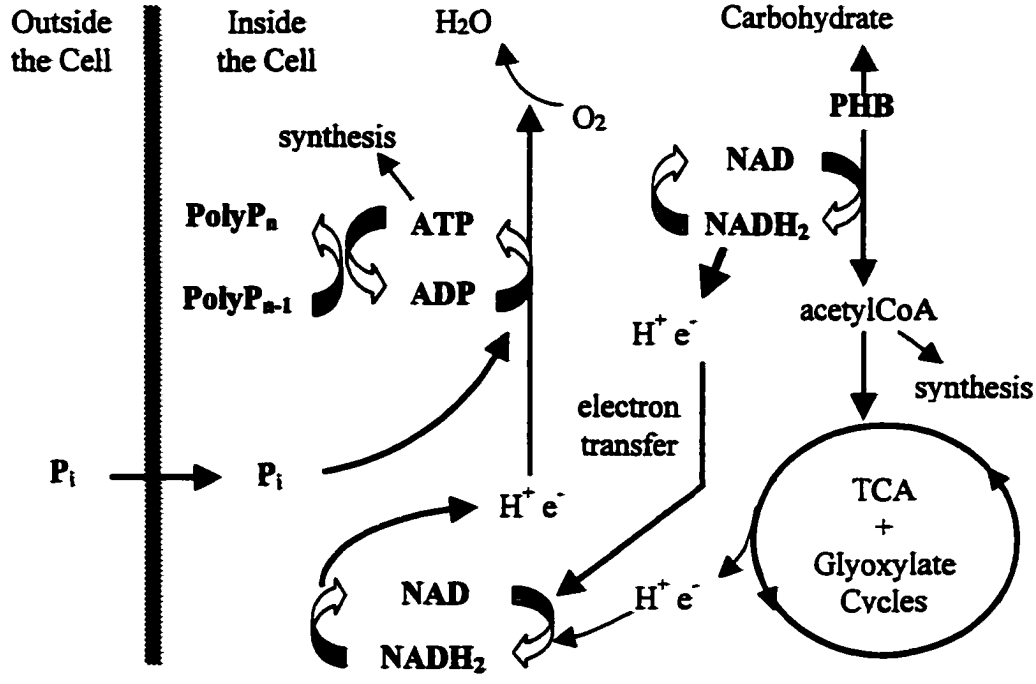

Figure 2.4 The Mino Model Under Aerobic Conditions

The major difference between the Mino and the Comeau/Wentzel aerobic models, is that PHB is not used to generate carbohydrates, but transforms to acetylCoA only. The paths of cations and phosphoric acid through the cell wall are now just reversed.

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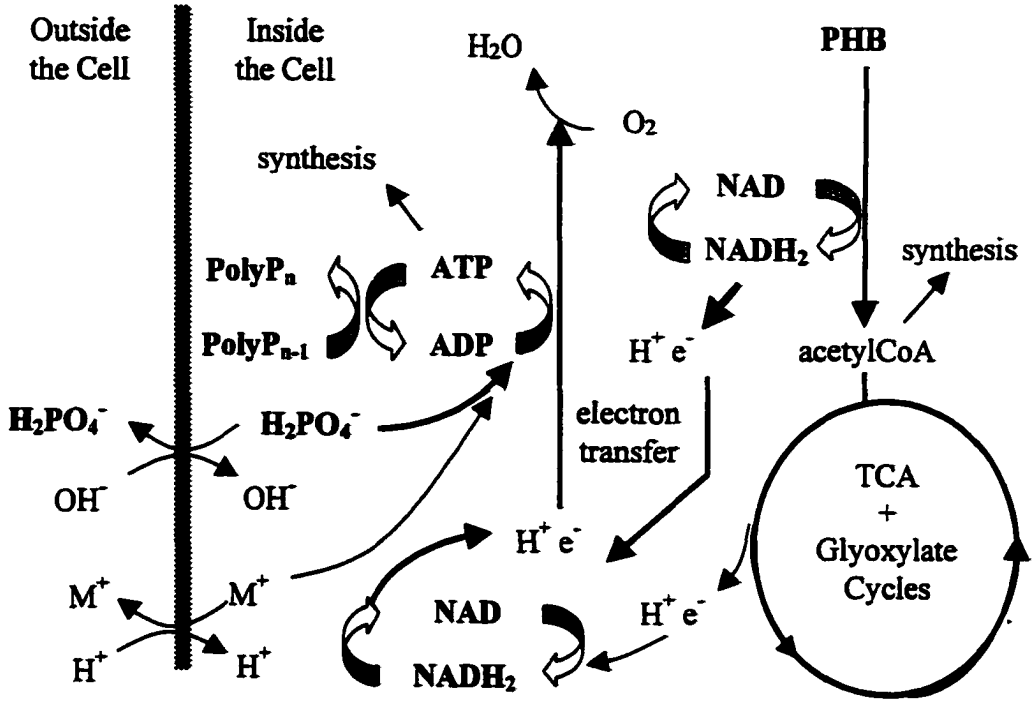

Figure 2.5 The Comeau/Wentzel Model Under Aerobic Conditions

Wentzel et. al. (1986) concluded that the main regulation for accumulation and degradation of PHB and polyP are the ratios ATP/ADP and NADH/NAD. These ratios are in turn controlled by substrate concentration, internal PHB, extracellular acetate, and the degree to which electron acceptors are present.

2.2.2 Solids and Hydraulic Retention Times (SRTs and HRTs)

The solids retention time (SRT), often called the mean cell residence time (MCRT), is most often calculated as the ratio of the mass of microbes (MLVSS) in the active sludge basin divided by the steady state rate at which the microbes are wasted, or wasted activated sludge (WAS). While compact as a definition, researchers have used varied approaches to redefine the SRT and then evaluate its effects on biological P (and

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N) removal. They have also tailored the definition to reflect the differences between batch, continuous, laboratory, and full scale facilities. Each of these approaches lead to unique adjustments that could be considered system specific in the factors influencing P and N removal.

During the investigation of anaerobic SRTs, Gerber and Winter (1984) determined that phosphate removal capacity per unit MLSS increased with increasing anaerobic retention time. Four parallel batch (Phoredox) systems were operated simultaneously, each with constant flow, COD, P (@20 mg/L) and separate total treatment volumes and anaerobic fractions. Anaerobic retention times were set at 6, 12, 18 and 24 hours. Anaerobic SRTs of 6 hours were found to remove phosphates between 9 and 10 mg/L, while 12 hour periods removed up to 15 mg/L. The longer anaerobic SRTs were also more reliable in P removal. The COD, TSS, nitrification and sludge separation characteristics were unaffected after long periods of anaerobiosis. Nitrates ranged from 1.7 to 18 mg NO_3-N/(g-MLSS-hr).

Matsuo et. al., (1994) independently made similar observations to Gerber and Winter (1984) in evaluating three mainstream, laboratory scale systems. They found that short anaerobic SRTs failed to stabilize P removal performances. This was due in part, to a culture of microbes that were able to take up dissolved carbon in the anaerobic zone without releasing phosphates. Long anaerobic SRT seems to aid polyP accumulators competing with other heterotrophs, but is not always a requisite. The amount of dissolved organic carbon (DOC) absorbed in the anaerobic zones, did not vary with PO_4-P (amount of phosphorus released in the anaerobic zones), but a Px (phosphorus content in the sludge) varied directly with PO_4-P. This was highly

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noticeable when the anaerobic SRT was dropped from 6.4 to 0.9 hr, the maximum range. Oxic SRTs varied from 3.8 to 5.9 hours.

Fukase et. al. (1984) discovered that creating an anaerobic zone ahead of an aerated zone did not necessarily cause excess removal of phosphorus. BOD could be absorbed under anaerobic conditions without storing or releasing polyphosphates, or storing PHB within the cell in anaerobic conditions. Detention times were controlled by flow changes, and SRTs began at 14.2 days, but were then changed to 54.0 and 27.9 days in the last two phases. This lead to microbes other than polyP that dominated the non-aerated zone, and P removal failed and yields dropped from about 0.55 to 0.20. .

An experiment by Janssen et. al. (1987) showed that anaerobic HRT that were greater than the aerobic HRTs were a benefit to P removal. This work involved two similar, full scale continuous feed systems, each with two activated basins and a forward contacting (non-aerated) tank where recycled sludge was mixed with the influent. This work determined that longer, non-aerated periods prior to the aerated (mostly) tank provided a higher P removal efficiency when the influent contained higher N and carbon substrate loading. The unaerated periods in the first tank lasted up to 83% of the day, while the second tank was aerated 75% of the day.

2.2.3 Organic Carbon Substrates

The concentration of influent carbonaceous biological oxygen demand (CBOD) has an unmistakable correlation between BOD_5 and total phosphorus removed. Qasim et. al. (1996) used the results from a ten year period of research, performed at the University of Texas, Arlington. Bench scale and pilot plant operations contributed data

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used to develop two mathematical functions, each expressing the same, closely correlated relationship between phosphorus removed and BOD:

(1) P removed% $= 98.6*(1-\exp(-.0200* S_0))$, $R = 0.95$ eq. 2.8

(2) P removed% $= -10.9+2.36* S_0 + 0.0215* S_0^2+9.03E-5*S_0^3 - 1.40E-7* S_0^4$ eq. 2.9

where: $S_0 < 200$ mg/L; R=0.98.

P removed% represents the % average phosphorus removed, and S_0 the average concentration of BOD_5 (w/S_0 > 25 mg/L). Plotting these functions reveals that an S_0 = 200 mg/L will remove at least 97% of influent P, regardless of the influent P concentration. This curve fit appears to reflect only the COD/P requirements for a mainstream system. Phosphorus removal in a (sidestream) stripper has been measured at 2 mg-COD/mg-P, as compared with a mainstream process that is closer to 20mg-COD/mg-P. The sidestream requirements for COD/P are ten times lower polyP biomass concentration than the mainstream process (Smolders et. al., 1996).

Table 2.3 describes a compilation of research from Liu et. al. (1997). The Table describes a strong relationship between P content of the influent (% TSS) and other parameters associated with increased P removal capabilities.

Liu et. al. (1997) found that the P/C feeding ratio (wt/wt) was a key factor in determining the competitive outcome between the polyphosphate-accumulating bacteria (PAB) or glycogen-accumulating bacteria (GAB). Measurements found that when the P/C ratio was 0.20 or greater, the PAB could consistently out-compete the GAB species in faster uptake of acetate and higher P accumulation. Reduction of the P/C ratio below

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0.02 favored growth and majority speciation by the GAB. Phosphorus and PHA accumulations within the bacteria cell also increased with increasing P/C ratio and reached steady state (maximum) values of Px = 8% (Pi = polyP weight fraction).

Table 2.3 Max Amount and Rate of Anaerobic Pi Release and Acetate Uptake

Reference	Date	P Fraction (% TSS)	Max P Released (mgP/gVSS)	Max acetate Taken up (mg C/g VSS)	P Release Rate (mgP/gVSS-hr)	Acetate Uptake Rate (mgC/gVSS-hr)
Fukase	1984	2	5.9	108.6	3	60
Mino	1987	3	14	40.4	14	42
Mino	1987	6.1	63.7	63.6	52	71
Smolders	1994	7.0-7.5	ND	ND	42-130	41
Fukase	1984	9.6-10.0	125.2	133	100-110	105-139
Wentzel	1988	14.6-15.4	196.6	245.8	114-155	48-112

From Liu et. al., 1997

Kuba et. al. (1996) was able to use a two sludge system with sequencing batch reactors (SBRs) to achieve P removal by sludge uptake in the anoxic zone. This process reduces aeration requirements (30% to 50%) and COD demands (up to 50%) less than for conventional aerobic P and N removal systems. The SBRs consumed only 3.8 g COD/g-N, allowing the removal of 15 mg/L P and 105 mg/L N using only 400 mg COD/L Hac (acetic acid). Optimum P and N removal were obtained near an influent N/P ratio of 7/1 and approximately 3.4 g COD/g-N. Above the 3.4 ratio, P removal efficiency dropped precipitously. The process depends on (1) culturing a species of denitrifying phosphate removing bacteria (DPB) which absorb P beyond normal biological requirements and (2) using a two sludge system with the aerobic zone ahead of the anoxic reactor, and the influent flow being sent to the anaerobic reactor.

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Glycogen (starch), a branched chain of glucose molecules joined by hydrolysis, has been individually investigated to determine its role in polyhydroxyalkanoate (PHA) synthesis. The results of anaerobic inhibition studies supported the assumption that glycogen degradation through glycolysis supplies the required ATP and reducing power for PHA synthesis from acetate and consumed glycogen. Under aerobic conditions to follow, the accumulated PHAs were depleted and the consumed glycogen recovered to the same level as that at the start of the anaerobic phase (Liu et. al., 1994). The study suggested that external glycogen could be used as an energy source for PHA synthesis rather than intracellular polyphosphates while in the anaerobic phase.

Continued investigations by Liu et. al. (1997) reinforced earlier findings that separate species of glucose metabolizing bacteria were able to absorb short chain acids, thereby accumulating deposits of PHA granules with the potential to dominate the water culture.

Earlier, Satoh et. al. (1992) demonstrated that glycolysis of intracellular carbohydrates provided the energy for formation of PHAs from acetate and/or propionate, rather than by polyphosphate hydrolysis. At the same time, glycogen can regulate the redox balance within the cell. Thus, bacteria exhibiting glycogen storage might provide competition for the polyP bacteria under certain conditions, affecting the P removal efficiencies. The influent water contained a low P/C ratio for inhibition of polyP accumulating bacteria.

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2.2.4 Volatile Fatty Acids and Fermentation

The carboxylic acid sequence, limited to four or five carbons including the branched isomeric constructions, have been referred to as VFAs, SCFAs or lower fatty acids (LFAs). These are considered to play an important role as the preferred substrate for the polyP bacteria in the A^2 (anaerobic/anoxic) zones. Addition (or sufficient presence) of these products of fermentation has increased the strength of P release under anaerobic conditions which is intrinsically connected to the P uptake in the aerobic zones. Hang-Bae et. al., (1997) evaluated five kinds of these short chain (carbon) substrates in three different laboratory sequencing batch reactors. The acids were acetic, propionic, butyric, and valeric (caprionic) varieties. P release was greatest during the anoxic period when using acetate alone, while a 50% combination of glucose and acids had about half the effectiveness. Acetate alone produced a sludge with poor settling characteristics. Findings also indicated that TOC above 200 mg/L could inhibit P release.

2.2.5 Oxidation Reduction Potential (ORP) and Anaerobiosis

The oxidation-reduction potential (ORP) is an electromotive potential that has been attributed by de la Menardiere et. al. (1991) as being a descriptor of anaerobiosis. In wastewater, anaerobiosis is the biochemical state of oxygen starved water which is concurrently occupied by living organisms and nutrients. Under non-oxygenated conditions, the ORP becomes increasingly more negative with time. In the presence of aeration, the decrease in the ORP value may be gradual, remain constant or increase

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with time, depending upon the influx of oxygen and the immediate biological, chemical and nutritional state of the water.

ORP has been investigated for use as a indication parameter in optimizing the biological nutrient removal of P and N, together and separately. The overwhelming majority of investigations found that ORP did not exhibit a relationship with P removal processes, but was a very effective predictor of N removal.

Wareham et. al. (1995) found that the presence of nitrates slowed the rate of drop in the ORP, but once the nitrates were exhausted, the drop in ORP accelerated. This salient knee in time sequenced data could be relied upon to indicate exactly when complete denitrification had occurred. Also investigated was whether strong P release, which is required for a strong uptake, could be promoted by adding VFAs at the moment of nitrate exhaustion, thereby give polyP bacteria an advantage in substrate uptake over other denitrifiers present. This behavior, however, was never seen.

In a municipal treatment plant in France, de la Menardiere et. al. (1991) found successfully located constant values for the ORP which maximized nitrogen removal by optimizing the aerated and non-aerated periods.

Schon et. al. (1993) suggested that ORP could be used to optimize the aeration rate for N removal, and simultaneously produce compact sludge flocs with a low sludge volume index (SVI) rather than small, dispersed flocs grown with non-optimized aeration and non-aeration periods. They also concluded that dissolved oxygen (DO) concentration controlled the polyP bacteria release/uptake cycles while the value of the ORP had little predictable effect.

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Lo et. al. (1994) investigated ORP as a retrofit process control on existing Extended Aeration Treatment System (EATS) batch reactors around Hong Kong. They were able to empirically determine fixed ORP limits, which consistently aided the reduction of effluent NO_3 and boosted P removal efficiencies in random cases. It was clearly noted that the ORP value was a function of zone location or position along the tank, and did not represent a fixed value that could guarantee similar efficiencies in another geometry.

Using sequencing batch reactors (SBRs), Randall et. al. (1994) determined that EBPR was dependent on acidogenesis creating fermentation products ahead of. the anaerobic zones. Responsibility for improvement of P removal resulted from the presence of C_1-C_5 carboxylic acids, with the exception of formate. Branched isomers showed improved response to the linear molecular form of the acid. The presence of alcohols C_1-C_3 did no aid or disrupt the P removal process. Substrates with detrimental effects included glucose and amino-rich substrates. Although a numerical value was not specifically called out in the paper, this comment indicates that a high TKN/COD ratio would also have detrimental results on an anaerobic/aerated P removal process.

Gerber et. al. (1986) supported these conclusions by stating that anaerobiosis provides the environment in which compounds are converted to (acidogenic) products that trigger phosphorus release. Therefore, EBPR is primarily dependent on the nature of the substrate interacting with the bacterial mass, and not an anaerobic state. The proper substrate and its concentration (i.e. COD) initiates a strong P release, which in turn stimulates a strong P uptake.

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Skalsky and Daigger (1995) investigated on-site fermentation of volatile acids (VA) at the Orange County Water and Sewer Authority (OWASA) in California, using two full scale designs for the purpose of EBPR performance. The thickened WAS is then mixed with the sludge from the primary clarifiers before entering the holding tank. The VA yield averaged 0.05 mg/mg volatile solids (VS) from the primary sludge that were sent to the holding tank. The average VA composition of the first fermented product stream consisted of 41% acetic, 44% propionic, 9% butyric and 5% valeric acid(s) (Skalsky, 1995). The product concentrations in the stream of the second fermented product were within 20% of the first. The only drawback to the process might have been found in phosphorus recycle. Approximately 25-40% of total-P was released in the first four hours after mixing the WAS with the sludge. This recycle might increase P concentrations at the influent 20 to 30%. This is not a problem where the influent P is not high enough to support a strong EBPR process, as the recycled P might help to strengthen it.

2.2.6 Effects of Nitrogen: Nitrates, Ammonia, and Total Kjeldahl Nitrogen

The biological removal of phosphorus is an integral part of the overall task of biological nutrient removal (BNR) from wastewater. BNR includes the removal of the nitrogen compounds, principally NH_3–N and NO_3–N, which are the only forms of nitrogen useable to plants (Griffith et. al., 1973). The oxidation/reduction steps mainly identified with removing NH_3–N and NO_3–N, respectively, are nitrification and denitrification.

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Nitrification is the oxidation of ammonia NH_3 –N to nitrate NO_3^--N. The first oxidation step is carried out by Nitrosomonas, creating the species NO_2^-. The approximate anabolic oxidation equation for the Nitrosomonas bacteria is:

$$55NH_4^+ + 76O_2 + 109HCO_3 \longrightarrow C_5H_7O_2N + 54NO_2^- + 57H_2O + 104H_2CO_3 \quad \text{eq. 2.10}$$

The second step creating NO_3^- is carried out by Nitrobacter. The approximate equation for Nitrobacter oxidation is:

$$400NO_2^- + NH_4^+ + 4H_2CO_3 + HCO_3^- + 195O_2 \longrightarrow C_5H_7O_2N + 3H_2O + 400NO_3^- \quad \text{eq. 2.11}$$

Stoichiometry for the combined two nitrification steps requires 11.1 mg of O_2 and 8.6 mg HCO_3^- for each mg of NH_4^+-N consumed (Qasim, 1999).

The oxygen requirement in nitrification is referred to as the NBOD or nitrogenous oxygen demand. Using an immature microbial broth, Nitrosomonas can take up to 8 days for incubation, and over 28 days for the NBOD to be completely exerted. When added to the BOD over this longer period, the UBOD or ultimate biological oxygen demand of the water is determined.

Qasim (1999) has also found that nitrifying bacteria are sensitive organisms and extremely susceptible to a wide variety of inhibitors. A narrow pH range between 7.5 to 8.6 allows for best nitrification, but acclimated systems have successfully nitrified at lower pH. Dissolved oxygen concentrations above 1 mg/L are essential for nitrification to occur.

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Metcalf & Eddy (1991) identify two general denitrifying pathways that use NO_3^--N as an electron acceptor, thereby convert NO_3^- to reduced nitrogen forms such as NH_4^+ and N_2 gas. One of the two paths is termed assimilatory, converting NO_3^--N to NH_3-N for use by cells in biosynthesis. NO_3^- reduction occurs when it is the only existing form of nitrogen. The other is called the dissimulatory path, this reducing NO_3^--N to N_2 gas, which escapes the water. The second path is more commonly known in wastewater treatment as the denitrification process and occurs only under anoxic conditions (Metcalf & Eddy, 1991).

Once nitrates have been reduced to NH_3, specialized microorganisms are able to utilize NH_4^+ and HCO_3^- (inorganic carbon) in biomass synthesis. Examples of these organisms, are cyanobacteria, phytoplankton and algae, all of which contain chlorophyll.

From Qasim (1999), the biomass synthesis from ammonia and bicarbonate can be written as:

$$NH_4^+ + HCO_3^- + 4CO_2 + H_2O \longrightarrow C_5H_7O_2N + 5O_2 \qquad \text{eq. 2.12}$$

The stoichiometry in the equation above requires 4.4 mg HCO_3^- and 12.5 mg CO_2 consumed for each mg of NH_4^+-N oxidized.

The biosynthesis reaction using oxygen, bicarbonate and ammonia can be written:

$$NH_4^+ + 1.83O_2 + 1.98HCO_3^- \longrightarrow 0.021C_5H_7O_2N + 0.98NO_3 + 1.041H_2O + 1.88H_2CO_3 \qquad \text{eq. 2.13}$$

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Stoichiometry in the equation above requires 4.3 mg O_2 and 8.64 mg HCO_3^- consumed for each mg of NH_4^+-N oxidized (Qasim, 1999).

Denitrifiers are classified as heterotrophic microorganisms because they need a source of organic carbon for biosynthesis. The empirical equation (eq. 2.14) from Metcalf and Eddy (1991) was developed on the basis of laboratory studies. It provides a Stoichiometric relationship for the nitrate-removal reaction for bacteria when nitrate was the only source of nitrogen, and methanol the source of carbon:

$$NO_3^- + 1.08CH_3OH + H^+ \rightarrow 0.065C_5H_7O_2N + 0.47N_2 + 0.76CO_2 + 2.44H_2O \quad \text{eq. 2.14}$$

This relationship states that 2.6 mg methanol are consumed for each 1.0 mg NO_3^- -N. Normally, when nitrites and dissolved oxygen are present in the wastewater, the expression for the concentration of methanol required (C_{meth}) needed for denitrification was found closer to:

$$C_{meth} = 2.47\ NO_3^- + 1.53\ NO_2^- + 0.87\ DO \quad \text{eq. 2.15}$$

U_{dn}, the specific denitrification rate [lb. NO_3]/[lb. MLVSS-day], is controlled by temperature and DO in the following equation:

$$U_{dn} = U_{dn} * [\ 1.09^{(T-20)}\ ] * [1\ mg/L - DO] \quad \text{eq. 2.16}$$

where T is °C and DO is dissolved oxygen. Typical U_{dn} values are found to range from 0.12 to 0.20 [lb. NO_3]/[lb. MLVSS-day] at 20 °C using methanol, and from 0.03 to 0.11 [lb. NO_3]/[lb. MLVSS-day] when wastewater temperatures are between 15 and 27 °C.

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It is widely accepted that the presence of nitrate and subsequent denitrification to the anaerobic zone competes with the phosphorus (P) release process. A number of BEPR (biological excess phosphorus removal) systems have been designed to prevent the presence of nitrate in the anaerobic zones (Barker et. al., 1996). One of the interpretations for this competition is being that (non-polyP) denitrifying bacteria out-compete the polyP bacteria for the available VFA substrate. Support for this conclusion came from Kuba et. al. (1994) by observing that the presence of denitrifying phosphorus removing bacteria (DPB) utilize acetic acid (HAc) for denitrification and not phosphorus release. Similar in behavior to the polyP bacteria, PHB was always stored during the anaerobic phase and phosphorus was released by DPB microorganisms when nitrate and HAc were simultaneously present.

Opposition to that view is written in a paper by Barker et. al. (1996). The collective data from this paper find that a significant fraction of polyP bacteria are able use nitrate as an electron acceptor in the absence of oxygen for oxidation of the stored PHB, with simultaneous uptake of phosphorus (Barker et. al. 1996). Thus, some polyP bacteria which participate in denitrification within the anaerobic zone, can create a simultaneous and opposing metabolic reaction of normal polyP organisms, which release P to obtain the energy for uptake of acetate and other VFAs to be stored as PHB.

A unique opportunity to study BNR efficiencies related to influent concentrations of P and N came at two wastewater treatment plants in the Netherlands. These plants had very similar physical and process designs but were experiencing contrasting P removal efficiencies. The plant with the high P removal received effluent from a lemonade factory, while the second accepted influent with a high nitrogen

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concentration from the fishing industry. It was concluded that the wastewater with the high percentage of easily biodegradable compounds and the low N-content of the Bunnik (Netherlands) wastewater have a positive influence on the excess P-removal. The high percentage of Nitrogen in the wastewater of Bunschoten and Bennekom causes less P-removal (Janssen et. al., 1987). This again supports the theory that a high TKN/COD ratio is detrimental to the P removal process.

2.2.7 Important Cations (Metals) in the P Removal Process

Microorganisms require various nutrients in the form of cations. Cations as potassium, magnesium, calcium and iron, must be present above critical concentrations in culture media (Drdjaovic et. al., 1996). Lim (1998) states that magnesium affects the stability of the ribosomes, membranes, and nucleic acids. It is also a component of chlorophyll and a cofactor for enzymes. Calcium is also a cofactor for some enzymes and provides endospores with heat resistance. Iron is a constituent of cytochromes, a cofactor for some enzymes and is associated with nitrogen fixation. Potassium is one of the principal inorganic cations, a cofactor for some enzymes and constitutes nearly 1% of the dry weight of the microbial cell.

It was shown by Drdjanovic (1996), that when a severe shortage of potassium persisted over several days, that polyphosphate concentration decreased exponentially and phosphorus removal ceased. The potassium concentration in domestic sewage can be based on human production of the potassium excreted with feces and urine, and in the potassium content of the tap water. Since the normal K/P ratio in excreted faces and

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urine of humans is 0.8 and 1.9 mg K/mg P respectively, a severe shortage of K is unlikely in domestic sewage.

Fukase (1984) found a strong relationship between P uptake and Mg^+ and K^+ uptake was measured in the sludge content, the molar ratios for Mg/P and K/P being 0.335 and 0.29 respectively. In sludges having low P uptake, little Mg^+ or K^+ was found in the sludge.

2.2.8 Wastewater Designs for EBPR

The biological removal of phosphorus is accomplished using two general processes: (1) mainstream and (2) sidestream. Both rely on subjecting systems having acclimatized and specialized polyP microbes to alternating non-oxygenated (anaerobic/anoxic) and oxygenated (aerobic) zones. Anaerobiosis produces a strong release of phosphates into the water, while the subsequent aeration produces a luxury uptake in which the polyP bacteria store phosphates in concentrations up to eight times greater than required for normal cell functioning.

The sidestream process diverts part of the settled sludge from the clarifier into an anaerobic zone or stripper tank where the polyP microbes release their stored phosphates. The P-rich supernatant from the stripper is sent to a chemical precipitation tank where a compound such as CaO (lime) or $FeCl_3$ (ferric chloride) is often used as the precipitating agent. The P stripped sludge and supernatant from the stripper tank is then sent back to the aeration basins. The major functional groups in a sidetream removal method known as the (patented) PhoStrip process is shown (next) in Figure 2.6.

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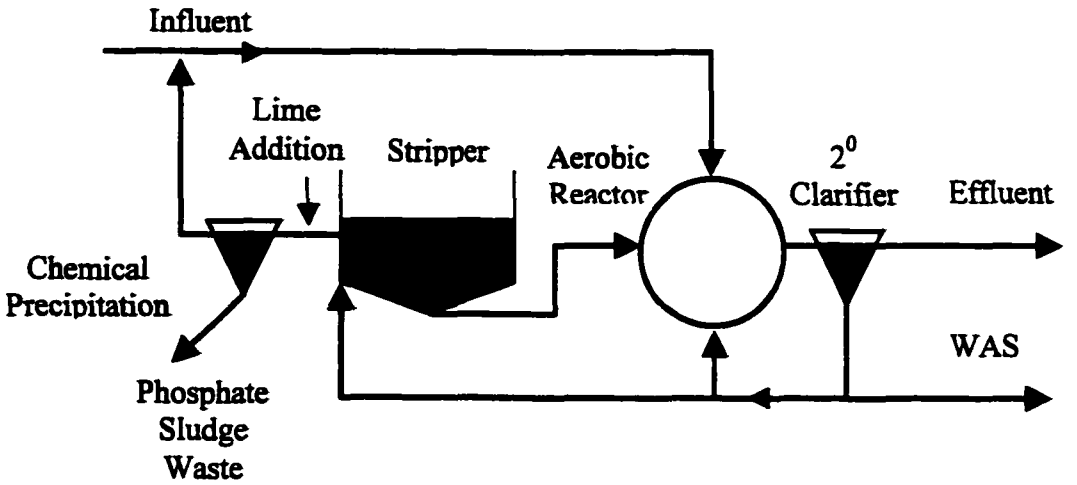

Figure 2.6 The Patented Phostrip Process

One issue in performance with the PhoStrip process is that the carbon substrate in the stripper zone is not high enough to permit denitrification, although complete nitrogen removal is not required in some operations.

In contrast, the mainstream approach removes phosphorus by wasting a portion of the flocculated, settled, polyP microbes from the 2^0 clarifier after luxury uptake in the aeration basin has occurred. The majority of the P-enriched sludge is returned to the anoxic or anaerobic zones where P release into the water begins again. The functional groups of a mainstream process are shown (next) in Figure 2.7.

Desirability of the mainstream systems permit design configurations which are capable of concurrent nitrification and denitrification, i.e. the removal of nitrogen. In comparison, the mainstream is a completely biological process where sidestream is actually a bio-chemical process.

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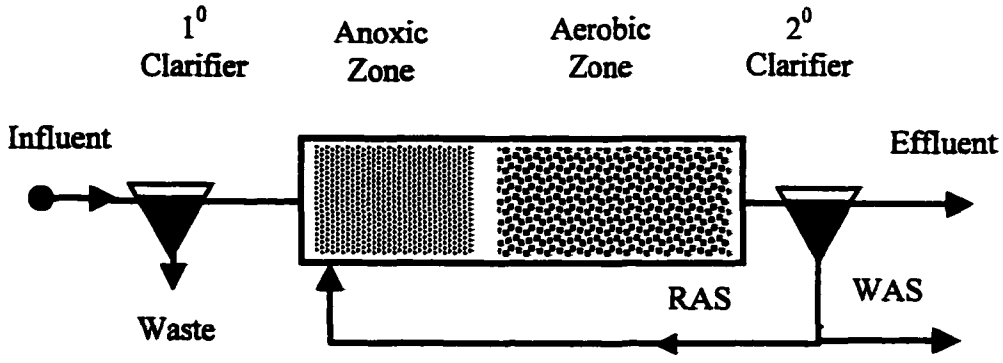

Figure 2.7 The Mainstream Process

Three variants most often used in the mainstream removal designs are: (1) the Bardenpho (five stage), originally proposed by Barnard (1973) as a four stage process, (2) the UCT (University of Capetown, S.A.) and the A^2/O (Anoxic/Anaerobic/Oxic) processes.

The five stage Bardenpho process, shown in Figure 2.8, is capable of removing phosphorus, nitrogen and carbon.

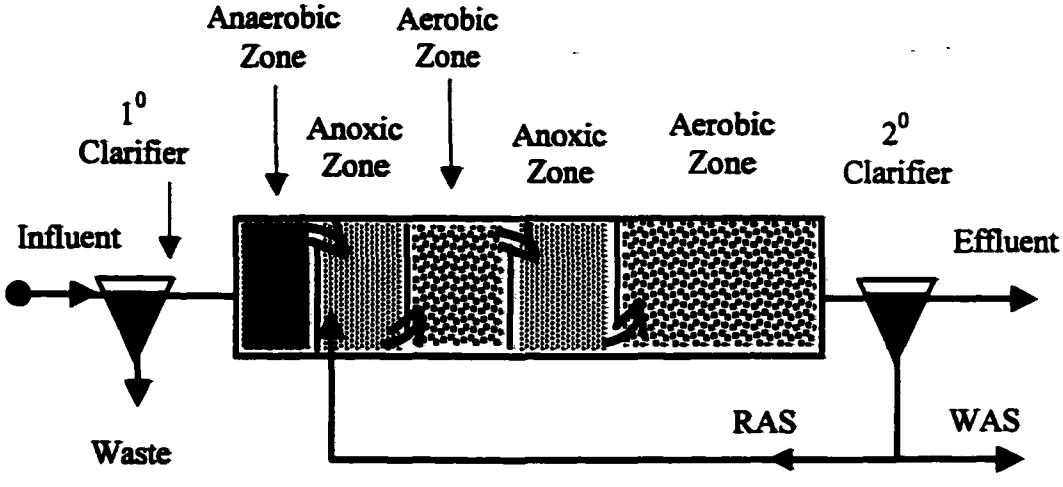

Figure 2.8 The Modified Five Stage Bardenpho Process

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It uses recycled sludge from the 2^0 clarifier mixed with the influent, combined with intermediate recycle of sludge for the purpose of denitrifying. Phosphorus is removed in the fifth stage through luxury uptake and wasted as sludge, settled from the clarifier. N_2 gas is also stripped from the water during fifth stage aeration.

The UCT approach, shown in Figure 2.9, incorporates two intermediate sludge recycle lines with return settled sludge brought back to the anoxic zone instead of the influent. The objective of returning nitrified sludge from the aeration to the anoxic zone leaves an anaerobic zone to combine with the influent, thereby promoting fermentation and short chain fatty acid production to promote stronger release of P in the anoxic zone.

The original version of the A^2/O process, shown in Figure 2.10, returns the sludge with nitrates to the first zone downstream of the anaerobic influent. CCSD uses this hydraulic configuration in basin #1 only. For the remaining seven basins, CCSD uses the modified A^2/O process shown in Figure 2.11.

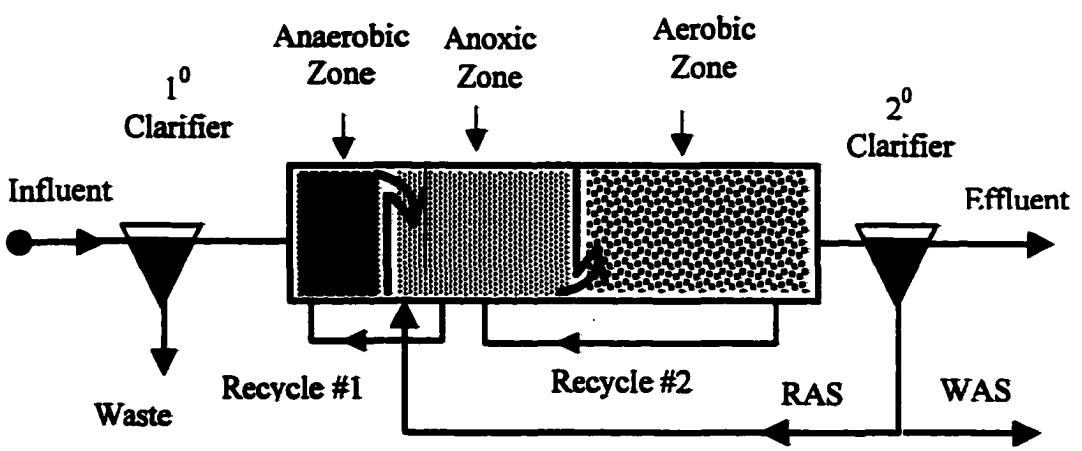

Figure 2.9 The University of Cape Town (UCT) Process

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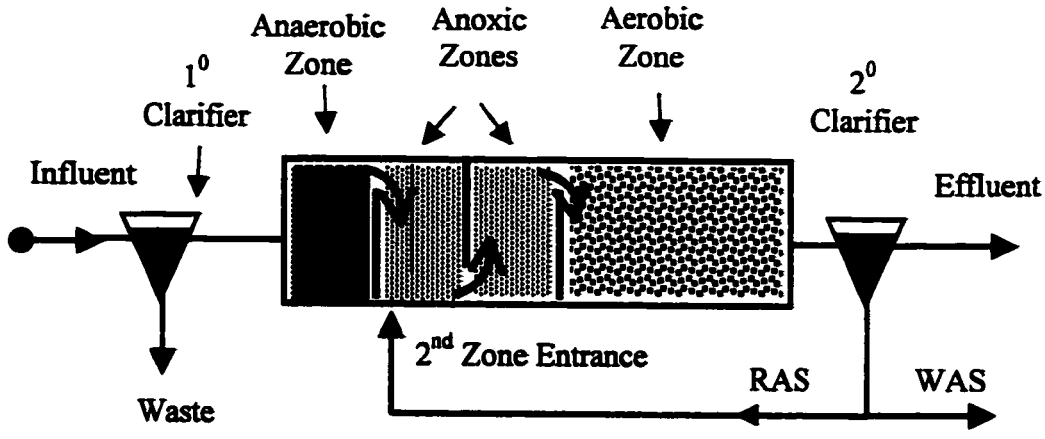

Figure 2.10 The Original A^2/O Process

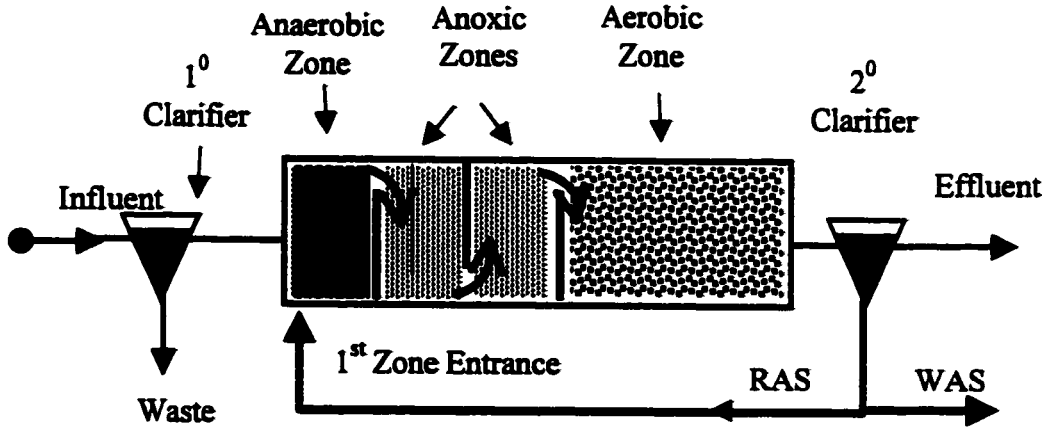

Figure 2.11 The Modified A^2/O Process

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CHAPTER 3

METHODS AND MATERIALS

3.1 The Selected Research Site

The investigation took place at the Clark County Sanitation District (CCSD) wastewater treatment plant. The plant is located at the eastern end of Flamingo Road and situated near the Las Vegas Wash, into which the plant effluent is discharged. Located upstream is the sewage treatment plant from the City of Las Vegas, while downstream is the City of Henderson's treatment plant, both of which discharge effluent into the Wash (Figure 3.1).

The plant is comprised of eight individual treatment units, an activated sludge basin and dedicated secondary clarifier, grouped into two groups of four units, the eastern and western cluster. These units remove carbonaceous BOD, nitrogeneous BOD and phosphorus. A block diagram describing the plant's treatment train and water sampling points is shown in Figure 3.2.

This research, with the agreement of the CCSD personnel, chose Basin #4 and its respective clarifier as the site for the experiment. It is positioned at the SE corner of the plant's western cluster and also identified in Figure 3.2. Isolation of unit #4 from the other seven was possible because of the unique physical design of the basins, which

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hydraulically couple each of the activated sludge basins to a single clarifier. Thus, each basin and clarifier is an independent system.

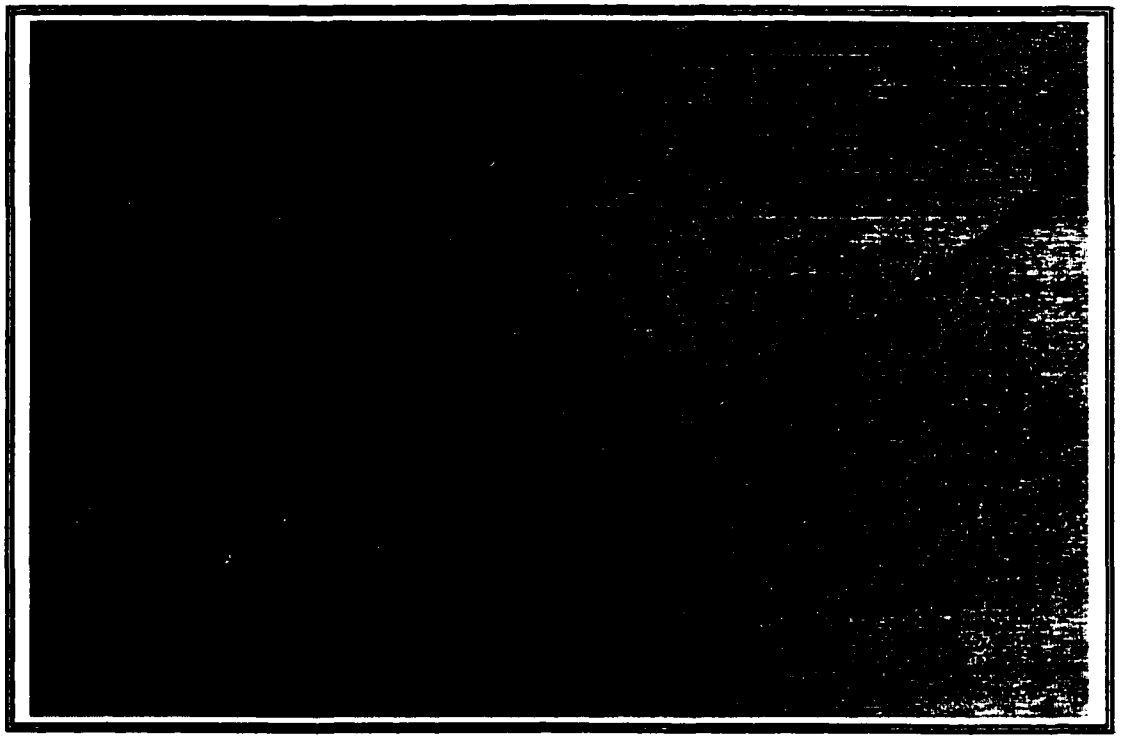

Figure 3.1 Location of the Clark County, Las Vegas and Henderson Treatment Plants

The flow in Figure 3.2 begins at the plant influent (PI), where the wastewater enters the plant and splits into the eastern (square) and western (round) primary clarifiers, passing through the two points central plant west influent (CPWI) and central plant east influent (CPEI). Settled sludge from both primaries is sent to the gravity thickener overflows (GTOs), and the thickened GTO sludge is sent to a mixing tank next to the dissolved air flotation thickener (DAFT).

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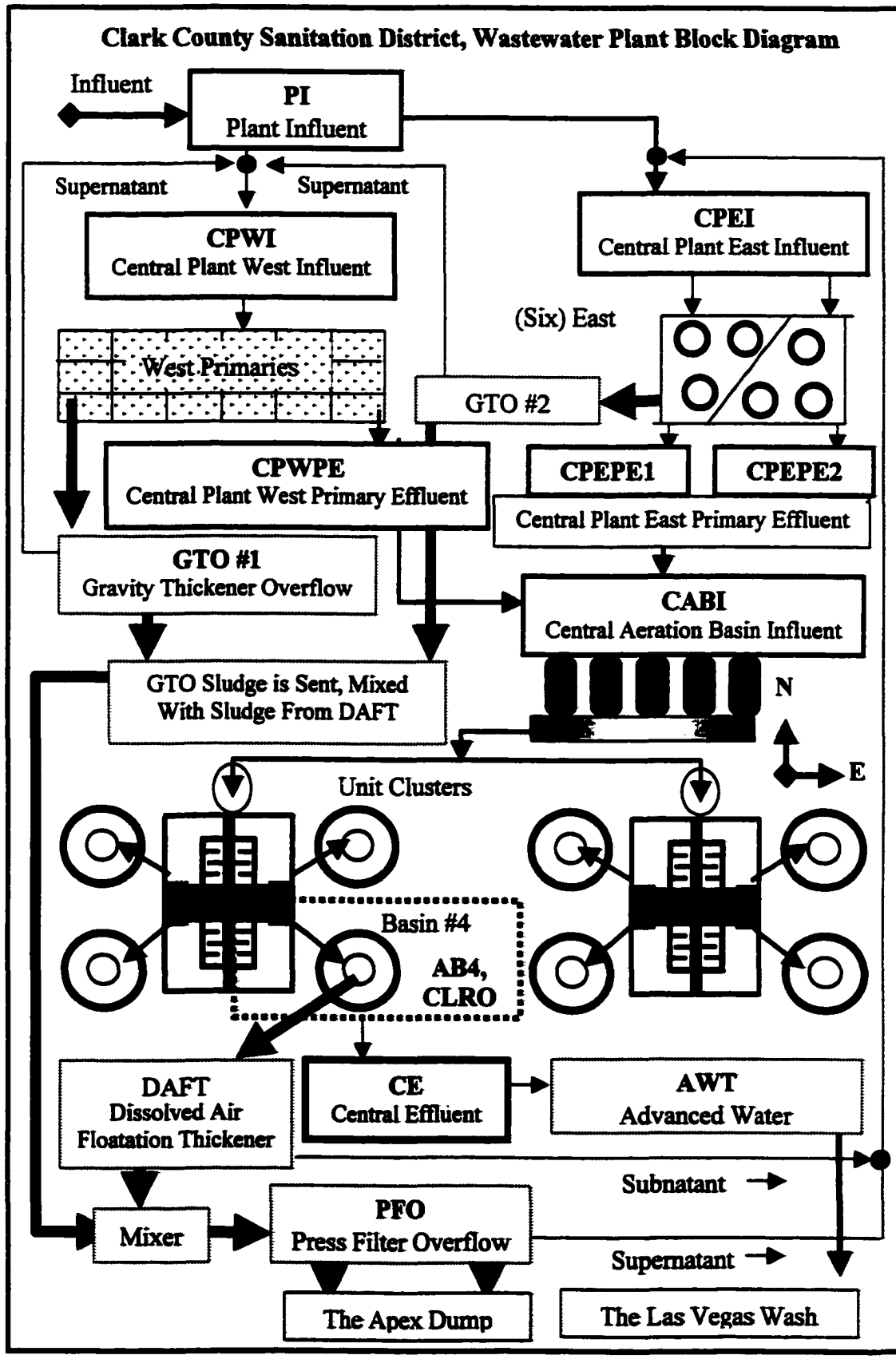

Figure 3.2 CCSD Plant Flow and Recycle Flow Block Diagram

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Overflow from the western primaries passes through central plant west primary effluent (CPWPI) and from the eastern primaries, through the two points central plant east primary effluent #1 and #2 (CPEPE1 and CPEPE2). Both primary overflows collect at the central aeration basin influent (CABI), the cylindrical objects in Figure 3.2. This point is visually referenced on the plant by the Archimedes lift pumps (see Figure 3.3).

Settled wastewater is then distributed to the eight treatment units. Waste activated sludge (WAS) from the secondary clarifiers is pumped to the DAFT, where the supernatant (microbes) are mixed with the GTO sludge and then sent to the press filter overflow (PFO). Dewatering and processing of the combined sludge is performed at PFO, and the solids loaded onto a truck and sent to the APEX dump.

Overflow from the secondaries collects at the central effluent (CE) location, and is then sent to the advanced water treatment (AWT) plant for filtration and disinfection. A UV lamp array has now replaced the chlorinator for the disinfection step. The chlorination equipment, however, has been retained as a back-up and remains functional in the event of unforeseen necessities.

While individual treatment units are isolated from each other hydraulically, the small volume return flows, shown in Figure 3.2, still couple all the basins together microbiologically. These are the supernatant from the GTOs, returning just above CPWI, the subnatant from the DAFT and that from dewatering at PFO, both returning just above CPEI. The strongest coupling, i.e. mixing of microbes from all eight basins and subsequent redistribution through the treatment train results from the DAFT subnatant. A small percentage of the microbes left in the clarified subnatant are

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ultimately dispersed between all six eastern primaries from CPEI. This distribution permits a single basin, perhaps having a growth of detrimental microorganisms, to spread its imbalances over all eight basins within a period of time.

3.2 Sampling Locations

3.2.1 Sampling Locations Within the Plant

Water samples for the research were collected within the plant at the normal monitoring locations, and within basin and clarifier #4. Table 3.1 provides the designated names of the sampling locations, the specific water quality tests and the frequency at which they were performed. In the Table, the first eight sample points with their names and labels are shown as placed in a top-down, flow sequenced order as they would occur within the plant. These plant locations can also be located on Figure 3.2. The last three points, beginning with the designation AWT, are found at the advanced water treatment facility, located on the eastern (opposite) side of the Las Vegas from the Central Plant. They were not used for sampling.

The data produced from analytical measurements at the locations listed in Table 3.1 are given as part of the CCSD, AWT Laboratory's daily reporting log.

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Table 3.1 CCSD Plant Sampling Points, Measurements, and Periods								
Measurements Taken Daily							Taken Weekly	
1. PI: Plant Influent							VFA	
BOD_I	BOD_U	TSS	NH4	OP	TP		NO3	NO2	TKN
							TDS	ALK	Cl
2. CPWI: Central Plant West Influent								
BOD_I	BOD_U	TSS	NH4	OP	TP		TKN	VFA
3. CPEI: Central Plant East Influent								
BOD_I	BOD_U	TSS	NH4	TP	OP		TKN	VFA
4. CPWPE: Central Plant West Primary Effluent								
BOD_I	BOD_U	TSS	BOD_IS	TP	OP		TKN	VFA
NH4								
5. CPEPE1: Central Plant East, Primary Effluent Source #1								
BOD_I	BOD_U	BOD_IS	TSS	OP	TP		TKN	VFA
NH4								
6. CPEPE2: Central Plant East, Primary Effluent Source #2								
BOD_I	BOD_U	TSS	BOD_IS	OP	TP		TKN	VFA
NH4								
7. CABI: Central Aeration Basin Influent (plant average)								
BOD_I	BOD_U	BOD_IS	TSS	OP	TP		TKN	VFA
TEMP	ALK	COD_T	COD_S	NH4	NO3			
8. CE: Central (Plant) Effluent (plant average)								
BOD_I	BOD_U	COD_T	COD_S	TP	NH4		TKN	
NH4	NO3	NO2	ALK					
Plant monitoring points below are not used for in Bio-P project								
9. AWT H: Advanced Water Treatment, Headworks								
TSS	TP	OP	NH4	NO3			NO2	
10. AWT P: Advanced Water Treatment, Primary								
Cl2	pH	Temp						
11. AWT EFF: Advanced Water Treatment Effluent								
BOD_I	BOD_U	TSS	TP	OP	Cl2		TKN	ALK
NH4	NO3	NO2	pH	Temp			TDS	Cl

A view of CABI is shown in Figure 3.3 on the next page. This is where the effluent from the primary clarifiers is combined. Water samples are taken by the automated compositor which is seen on the walkway, below the cylinder that is second from left.

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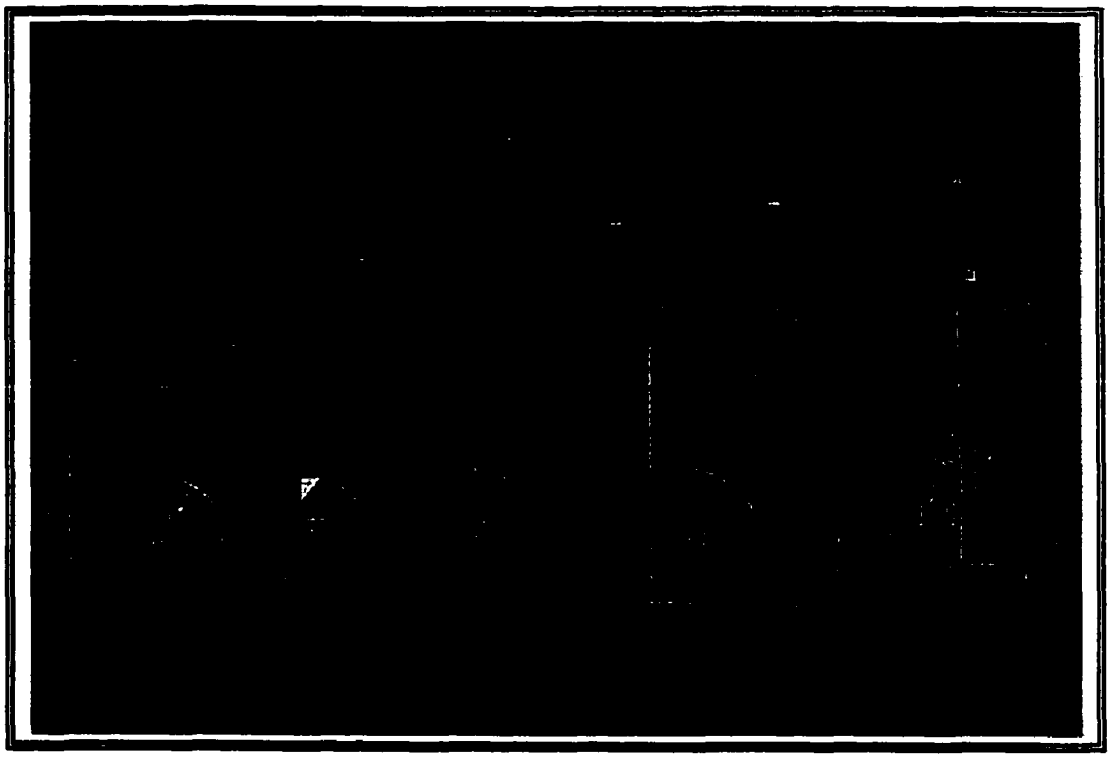

Figure 3.3 The Archimedes Lift Pumps at CABI – Central Aeration Basin Influent

3.2.2 Sampling Locations Within Basin and Clarifier #4

The Activated Sludge basin #4 consists of four anaerobic cells that are connected in series to form a quasi-plug flow channel with the aerobic zone following. This is the fundamental A^2/O configuration. The anaerobic zones and the relationship of the secondary clarifier to the basin are drawn in Figure 3.4.

Grab samples within the basin and clarifier were taken three times a week from nine, individual locations, identified in Figure 3.4 as small, shaded circles with their respective labels immediately adjacent. Sampling at locations internal to the basin and clarifier was a unique activity since these locations are not normally monitored. A

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further description of those nine points, and the volumetric and hydraulic characteristics of zones within the basin are given in Table 3.2.

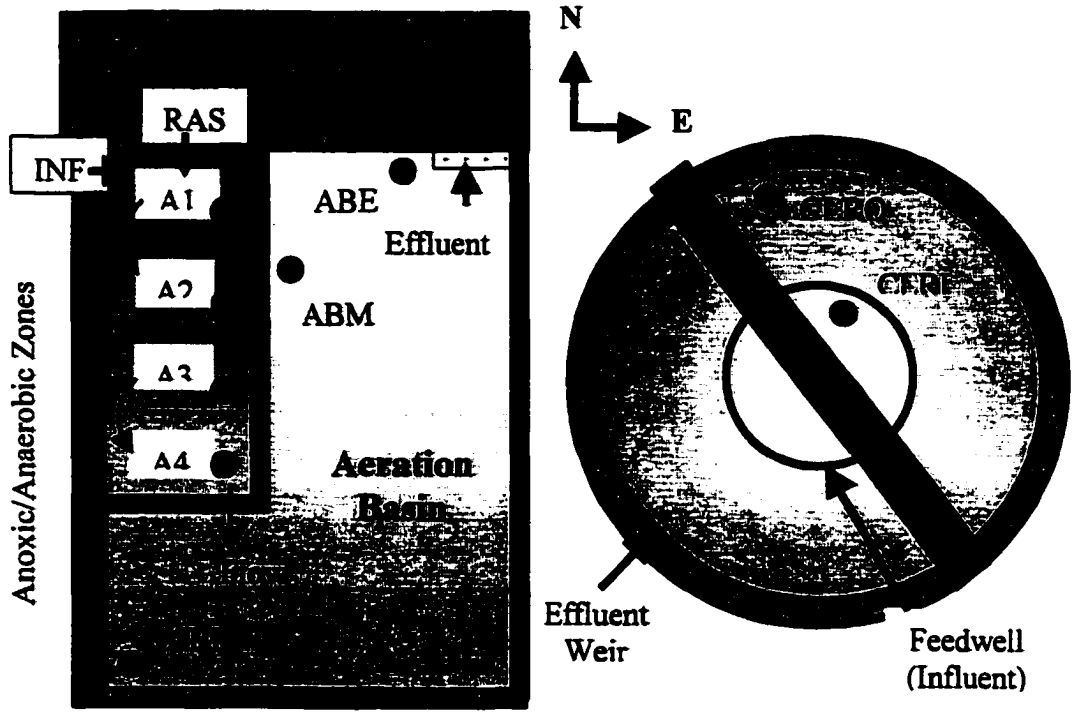

Figure 3.4 Treatment Unit #4 and Associated Sampling Points

The flow of 10.94 MGD in the third column of Table 3.2 represents the maximum average when all eight treatment basins are in service and the plant is operating at the maximum average designed flow of 88.0 MGD. Typical diurnal flows measured by the plant's supervisory control and data acquisition (SCADA) system can vary from a high of 14 MGD around 11:30 am to 7 MGD around 3:00 am.

Chemical analysis of the grab samples were performed by the CCSD Advanced Water Treatment Lab (AWT Lab), and water parameter readings measurements were taken by UNLV. The Plant process lab made measurements of Total- and Ortho-P

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from a 24-hour compositor located by clarifier #4. A description of the measurement responsibilities by AWT Labs, plant process labs and UNLV are provided in Table 3.3.

Table 3.2 Location and Description of Sampling Points, Basin Dimensions			
Sampling Point ID	*Description of ID and Water Content*	HRT, Hours @10.94 MGD	Vol., MG (Net)
A1	Anaerobic Zone 1 (RAS+ Influent)	0.27	0.12
A2	Anaerobic Zone 2 (RAS+ Influent)	0.27	0.12
A3	Anaerobic Zone 3 (RAS+Influent)	0.27	0.12
A4	Anaerobic Zone 4 (RAS+Influent)	0.27	0.12
A1-A4	Total, Zones 1 - 4	1.06	0.49
ABI	Aeration Basin, Initial Point; Sludge	4.20	1.91
ABM	Aeration Basin, Mid Point; Sludge		
ABE	Aeration Basin, Effluent Point; Sludge		
CLRO	Clarifier, Outer (Near Weir); Effluent	3.54	1.61
CLRI	Clarifier, Inner (Inside Feedwell); Sludge		

Table 3.3 Basin #4 Water Chemistry Measurements	
Measured by UNLV	
DO – Dissolved Oxygen	ORP – Oxidation Reduction Potential
Temp – Water Temperature	Cond - Conductivity
pH – The 'pH' of the water	COD – Chemical Oxygen Demand
TSS – Total Suspended Solids	VSS – Volatile Suspended Solids
TDS – Total Dissolved Solids	VFA – Volatile Fatty Acids
Measured by AWT Laboratory	
T-PO_4 (TP) - Total Phosphorus	O-PO_4 / OP - Ortho Phosphorus
NH_3 – Ammonia	TKN – Total Kjedahl Nitrogen
ALK - Alkalinity	NO_3NO_2 –Nitrate and Nitrite, Combined
Measured by Plant Process Labs	
T-PO_4 (TP) - Total Phosphorus @ AB4	O-PO_4 / OP - Ortho Phosphorus @ AB4

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A view of the anoxic zones as they would appear, standing by location A4, is given in Figure 3.5. The photograph is taken on the walkway between A4 and ABI.

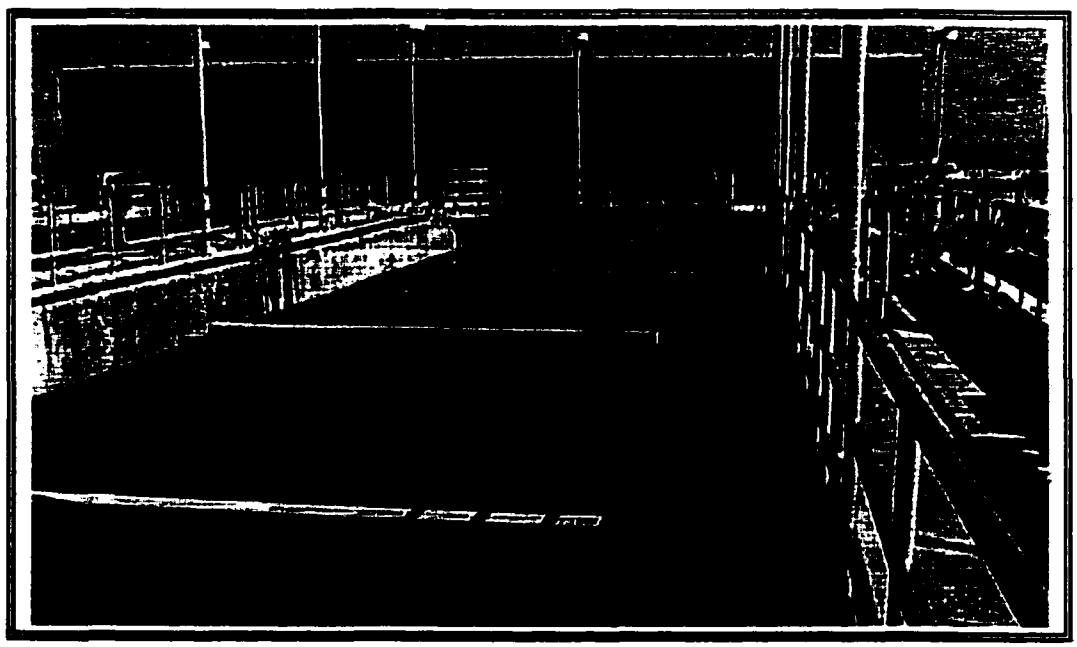

Figure 3.5 The Anaerobic Cells of Basin #4, Clark County Sanitation District

Figure 3.6 shows a view from ABI with Sunrise Mountain is in the background.

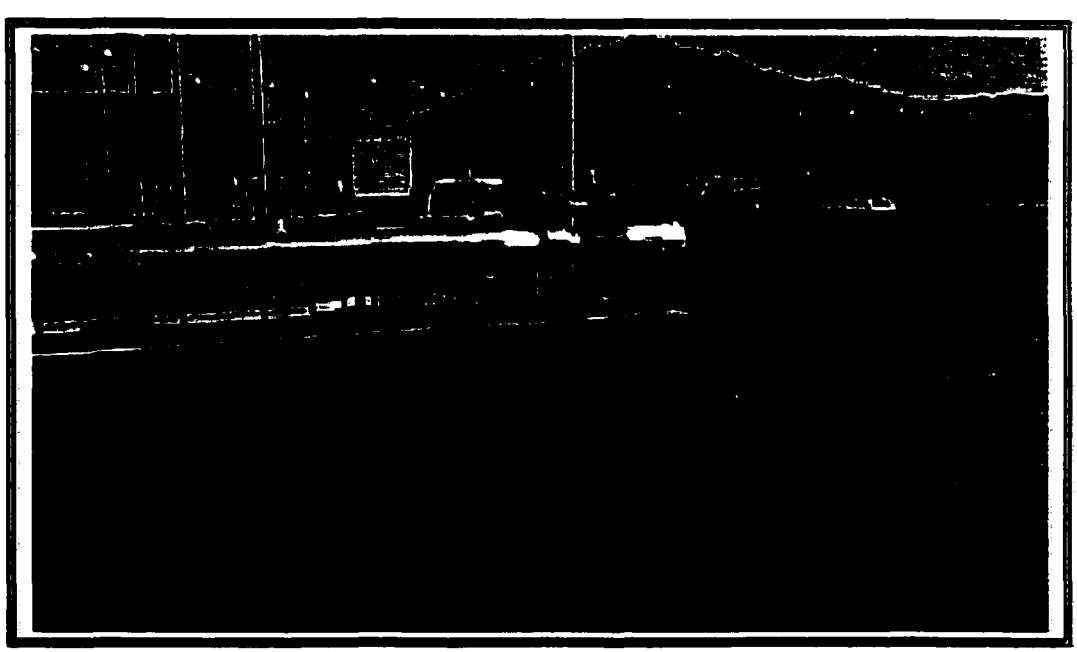

Figure 3.6 The Aeration Basin from ABI

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The clarifier sampling locations CLRI and CLRO are visible in Figure 3.7.

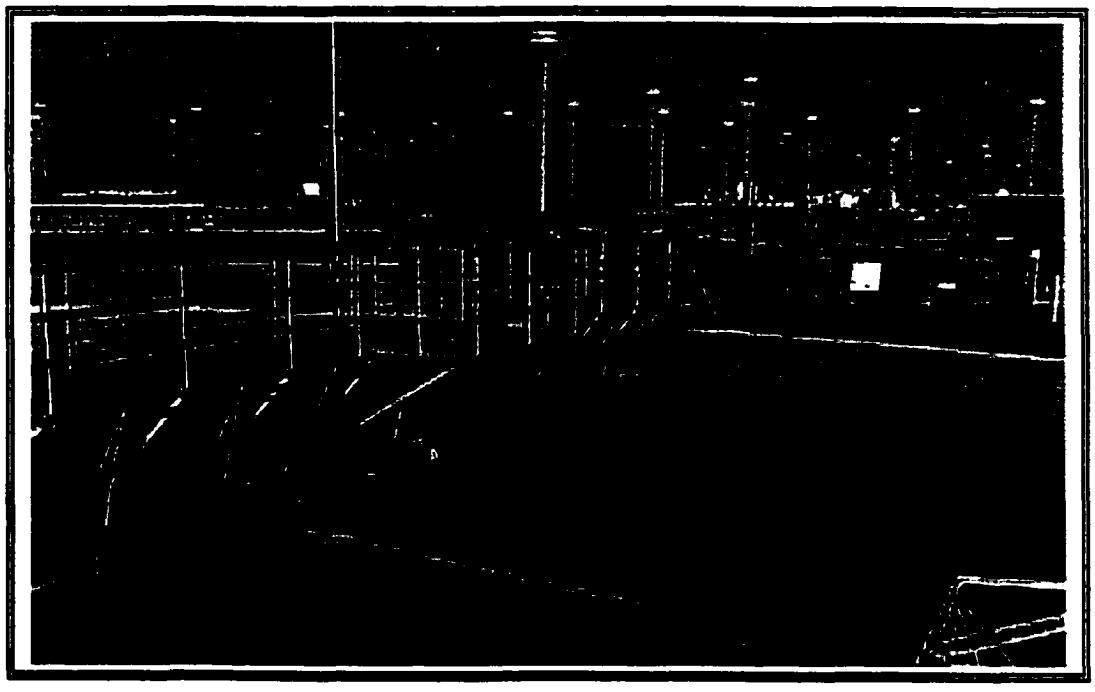

Figure 3.7 The Clarifier Sampling Points

The location CLRI is just inside the feedwell (inner ring), and CLRO is near the weirs (outer cement retainer). In the background is the brick control house, seen at the top of the aeration basins in Figures 3.4 and 3.5.

3.3. Important Operating Parameters

Two major parameters which characterize and guide the operation of the CCSD plant are solids retention time (SRT) and Food to Microbes Ratio (F/M). Numerical descriptions, plots and tables of the SRT and F/M ratio during the experimental period are given in section 4.4.

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3.3.1 Solids Retention Time

The mathematical definition of SRT, used by the SCADA system software, is given as:

$$SRT = \frac{\text{Microbe Mass in Treatment Basin}}{\text{Microbe Mass Wasted/Day}} = \frac{\text{(MLSS conc)} * \text{BasinVolume}}{\text{(WAS conc)} * \text{QWAS}} \qquad \text{Eq. 3.1}$$

Where: Conc = concentration, mg/L

WAS = waste activated sludge

QWAS = WAS flow (as taken from the 2^0 clarifier), Volume/Day

A mass to conversion ratio, lbs./gal or kg/m^3, appears in the numerator and denominator of the second term, forcing mutual cancellation.

The SCADA system uses only the WAS concentration and WAS flow to calculate the mass of sludge wasted per day. In truth, there are two other factors that can potentially alter the mass wasted. These are (1) the MLSS that flows in the secondary clarifier effluent, and (2) the microbe fraction in the return flows from the DAFT (see Figure 3.2 and section 3.1 for returned flows).

The two factors modifying the denominator in eq. 3.1 are shown in eq. 3.2.

$$SRT_{TRUE} = \frac{\text{(MLSS conc)} * \text{BasinVolume}}{[\text{(WAS conc)} * \text{QWAS} * \text{(DAFT efficiency)}] + (2^0\ \text{Eff conc}) * \text{QAB4}}$$

Eq. 3.2

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where: DAFT efficiency $\geq$ 99% (estimated)

2^0 Eff Conc = MLSS concentration in the secondary effluent

QAB4 = Flow through basin #4

The SCADA system is not equipped to measure these two parameters, but an estimate by CCSD operating personnel reduces the target SRT by approximately 10%. CCSD plant data shows the average total suspended solids (TSS) at CE averages 8.0 mg/L between April 1 and August 31, 1999. However, none of the factors in equation 3.2 were taken into account.

3.3.2 The Food to Microbes Ratio

Another important parameter in the operation of an activated sludge basin is the F/M, or Food to Microorganisms ratio.

Qasim et. al., (1996), defines this parameter as:

$$F/M = \frac{\text{Food Mass [BOD}_5\text{ as lbs./day]}}{\text{Microbe Mass in Basin}} = \frac{(\text{BOD}_5\text{_U}) * \text{Qbasin \{Inf\}}}{(\text{MLVSS conc}) * \text{Basin_Vol.}}$$

Eq. 3.3

Where: MLVSS ~ MLSS concentration, mg/L (fr/ SCADA)

BOD_5_U = BOD_5 N_2-Uninhib. @CABI (fr/AWT Labs)

Qbasin = Basin influent flow, MG (fr/ SCADA)

Basin_Vol. = 2.3 MG (fr/ design specifications)

Widely published in design literature is that low F/M ratio often leads to formation of bulking sludge and scum on the basin surface. *Nocardia* spp. was

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observed to form during the higher SRT period (see Figure 3.6). Magnified photographs of *Nocardia* spp. and *Acinetobater* spp., the most populous PAOs from basin #4, are shown in section 4.1.7.

3.4 Analytical Methods

The data set from the measurements taken from water samples of basin #4 are given in Appendix A, AWT Laboratory Data, Phase I, BIO-P Removal Study. The data set from in-situ measurements of basin #4 water, taken by UNLV using the HydroLab probe, are given in Appendix B, HydroLab Data, Phase I, BIO-P Removal Study.

3.4.1 Sample Collection and Preservation

Water samples from the eight plant locations described in Table 3.1, result from automated hardware installed at each sample location, that periodically withdraws a small volume of wastewater from the underlying flow. These small volumes are then deposited into a refrigerated, two-gallon container that forms a 24 hour composite which is collected each day at midnight and placed into refrigerators at the AWT Lab. Processing of those samples by lab personnel begins at 6:00 am each morning.

The water sample used to measure iron levels in the water was collected from these containers in 250-mL bottles and taken back to UNLV in a cooler for atomic absorption analysis. The same eight plant locations, plus GTO #1 and PFO are used to collect samples for VFA analysis. One of the CCSD electric carts is used to transport UNLV personnel to each location, where a small sample of wastewater is extracted from the flows using the manual options of the automated hardware and used to fill a

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small glass jar. From the jar, a syringe is filled and emptied twice with the water, the third volume being passed through a 0.45 micron filter to fill a 2.0 ml vial completely. Using a hand operated crimper, an aluminum cap was molded around the vial opening to seal it completely from the atmosphere. The sealed vial and capped jar were then placed into a cooler for transport to UNLV.

Figure 3.9 shows the wastewater compositor jugs used by the compositors to hold samples, as they appeared in the lab in the morning. Grab sample collection from the nine basin locations was accomplished using a two liter, polyethylene bottle connected to the end of a twelve foot pole. This allowed water collection down to a depth of approximately two feet. The continuous mixing of all basin zones however, prevents any measurable stratification from occurring. The bottle is submerged and emptied at least once at each new location, and the funnel is rinsed once with that wastewater.

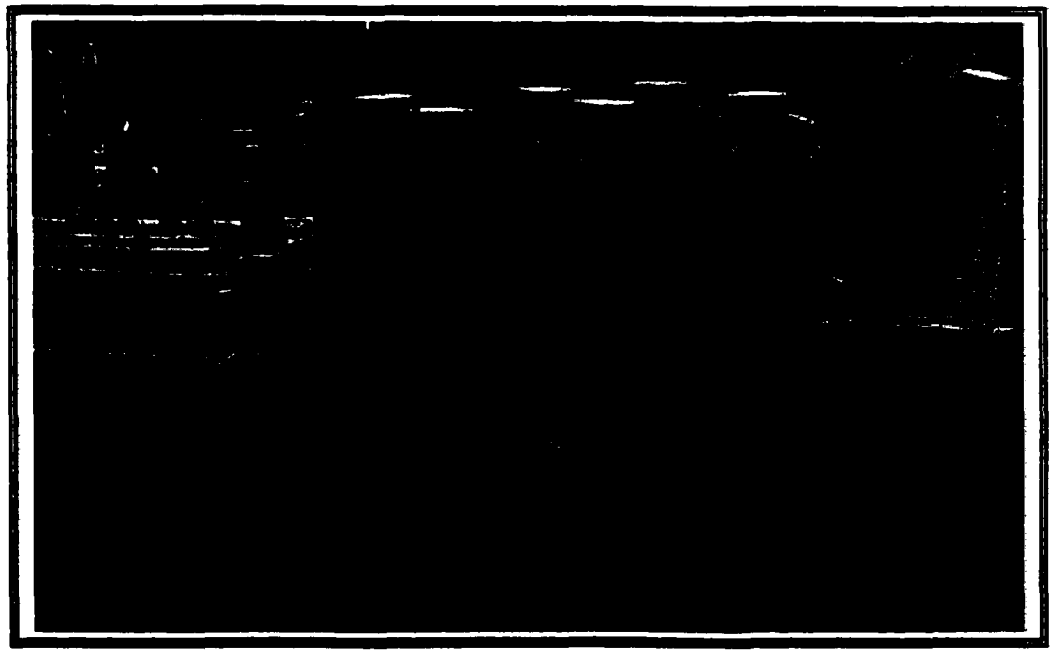

Figure 3.9 CCSD Plant's 24 hour Composite Sample Bottles

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AWT Lab analysis requires two, one-quart polyethylene aliquots to be filled at each basin location with the unfiltered water. One aliquot is preserved with 1 ml of concentrated H_2SO_4, and immediately thereafter placed into a cooler of ice. Attached to the aliquots are printed labels prepared by CCSD, that have the sampling point ID (from Table 3.3) and bar coded information necessary for them to be entered into the Lab's chain of custody and processing management system.

In addition, one 250 ml bottle is also filled with unfiltered, non-preserved wastewater from a grab sample for UNLV analysis and placed in another ice cooler. The 250 ml bottles are labeled with their respective location using a marking pen,. are taken back for COD, TDS and TSS measurements.

3.4.2 The HydroLab Probe

A HydroLab H2O probe was used to make each of the water parameter readings simultaneously available on a LCD screen, and measurements were confined to readings in the basin. This instrument is a hand held device in the shape of a cylinder approximately five feet long with six individual sensing capabilities, grouped together at one end to form a sensor complex, seen in Figure 3.10.

When placed into service, the sensor complex is surrounded with a protective cover made of heavy plastic that is perforated to allow the free passage of the water around the sensor to circulate through the complex. The HydroLab is connected to a portable processor designated the Scout II via a 50 foot cable. The length of the cable had no impact on the calibration of the sensor.

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In order to take the readings in the treatment basin, the HydroLab was taped to one end of a twelve foot long, collapsible steel pole. The submergence depth into the water averaged about 3 feet. A twenty foot pole was used in the beginning, increasing the submergence depth on the Scout II to approximately eleven feet. This extra depth however, did not produce any distinct differences in the readings, primarily because each of the anaerobic zones was well mixed through the use of submerged propellers. The mixing process in the aerobic zones was also quite complete, facilitated by the upwelling of the diffused air which is fed into the basin at rates varying between 3500 and 5500 SCFM. The air flow to the basins utilizes energy at a rate of approximately 35,000 kilowatt hours/day.

Figure 3.10 The HydroLab Sensor Complex

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3.4.2.1 HydroLab Calibration

Calibration was carried out according to the manufacturer instructions, the exact details of which are duplicated in Appendix AA. Temperature measurements were the only readout not requiring calibration other than at the factory. Comparative measurements in water using a VWR Scientific #61016-046 mercury thermometer demonstrated identical readings to an absolute ½ degree, the limit of the thermometer.

Conductivity was calibrated according to the type of water and band of conductance expected, in this case freshwater ranging from 1.5 to 10 milliSeimens/cm (mS/cm). This range was found to be suitable as the conductance excursions encountered within treatment unit #4 ranged from 1700 μS/cm to 2100 μS/cm. Calibration was achieved by using the best fit molar concentration of KCl, that of 0.292M, with a conductance of 2.0 mS/cm as called out in the HydroLab manufacturer's calibration manual (p. 37).

pH was calibrated similar to other pH probes by using two buffer solutions of known pH, in this case 7.0 and 10.0. The 7.0 solution located the readouts absolute sense, while the 10.0 solution provided the 'end point' with which to set the slope on points in between.

The method for calibrating dissolved oxygen from the manual required only the current barometric pressure reading to be input to the Scout II. The temperature readings necessary for the internal atmospheric density calculations by the Scout II were taken from the HydroLab itself. The pressure reading came from a mercury column barometer located in the UNLV Ventilation and Acoustic Systems Laboratory (VAST). This instrument, model 453, serial #W13406, was manufactured by Princo,

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Inc., of Southhampton, PA 18966. The barometer offered a vernier scale with an accuracy of +/- 0.1 mm Hg. A common pressure in Las Vegas is approximately 715 mm Hg. Air temperature measurements immediately next to the barometer were available from a Hg thermometer, a VWR Scientific #61099-035, ASTM 63C, 2V9837.

3.4.3 HydroLab Measurements of DO, ORP, Conductivity, pH and Temp

The HydroLab simultaneously measures (1) dissolved oxygen or DO, (2) oxidation-reduction potential or ORP, (3) conductivity, (4) pH, (5) temperature and (6) depth. These values are presented on the LCD screen of the Scout II and recorded manually on a small card. The reason for the card is that the basin surface at times, would be completely covered with several inches of scum. While being taken out of the water after a measurement, the HydroLab and pole would be covered with a thick scum that also coated the gloves. The pen and paper would often become stained with this scum, particularly when the wind blew. Therefore, a temporary recording medium, one that could be discarded was required.

3.4.4 Measurements of TSS, TDS, VSS, and COD

The measurement of total suspended solids (TSS), total dissolved solids (TDS) and volatile suspended solids (VSS) are interdependent. TSS in units of mg/L, began by placing a 0.45 micron glass filter in a small, aluminum sample dish and placing them inside a dessicator for twenty four hours. The filter and dish were weighed on a Sargent-Welch gram scale with four decimal sensitivity. The calibration by Precise Weighing Systems is guaranteed accurate through March, 2000.

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A thoroughly shaken, 50 ml sample of wastewater was then passed through this filter. The filter and dish were placed in an oven for one hour at 105 ^{o}C, then put into a dessicator for fifteen minutes to reach room temperature, and afterward weighed. The difference in weight over the initial 50 mg water sample constitutes the TSS measurement.

VSS in units of mg/L, begin next by placing the same filter and dish in a furnace at 550 ^{o}C for ½ hour, then back into a dessicator for fifteen minutes to reach room temperature. The dish is weighed again, and the difference over that from the initial 50 mg water sample constitutes the VSS measurement.

TDS measurements in units of mg/L, start with 20 ml of the filtrate generated from the TSS procedure which is placed into a previously weighed, aluminum that has just been in a dessicator for twenty four hours. The filtrate is completely evaporated in the dish above a steam evaporator, placed in an oven at 105 ^{o}C for 24 hours, and then through a dessicator for fifteen minutes and finally weighed. The extra mass over that of the empty dish constitutes the TDS measurement.

Water for the COD, also with units of mg/L, was placed in a blender until homogenized. Five hundred (500) μL was then put into Hach Hi-range COD vials, 1.5 ml of DI water added, the cap was closed and the vial then shaken until well mixed. This solution was then incubated for two hrs and allowed to cool before being placed into a Hach Spectronic 20 spectrophotometer. The transmission reading is translated directly into a COD level using a look-up table printed by Hach. A blank vial with two ml of DI water was used to calibrate the spectrophotometer each day it was used.

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Soluble COD measurements were performed in the same manner, except that the samples were filtered through a one micron glass fiber filter, prior to sample digestion in the COD reactor.

3.4.5 Measurements of NH_4, NO_2, NO_3, and TKN

Approved procedures for measuring ammonia are described in STDM_18 by 4500-NH_3 H, EPA 350.1 and lab SOP 41. NH_4^+ is measured in mg-N/L with an automated phenate, colorimetric method and the preserved water samples. NH_4^+ as well as NO_2 and NO_3/NO_2 are taken with the BRAN LUBBE/Technicon TRAACS 800 continuous flow analyzer, though not simultaneously.

Approved procedures for measuring nitrite are described in STDM_18 by 4500-NO_2 H, EPA 353.1 and lab SOP 88. NO_2, is labeled NO_2_HYZ in the lab data base and measured in mg-N/L with an automated, colorimetric method without hydrazine reduction on the non-preserved samples.

Approved procedures for measuring nitrate are described in STDM_18 by 4500-NO_3 H, EPA 353.1 and lab SOP 45. (NO_3NO_2 and NO_2 have the same EPA procedure number.) NO_3NO_2, is labeled NO_3NO_2_HYZ in the lab data base is measured in mg N/L with an automated, colorimetric method with hydrazine reduction on the preserved water samples. NO_3 can be known by subtracting the NO_3NO_2 from theNO_2.

Approved procedures for measuring TKN are described in EPA 351.3 and lab SOP 135. TKN is measured using a steam distillation, titrimetric method. This particular procedure is labeled TKN_DIST in the data. After distillation, a Buchi 339

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distillation unit takes the measurements and prints them out on a paper strip. The numbers are then manually input to the AWT Lab database.

3.4.6 Measurements of BOD_5-I, BOD_5-U, and BOD_5-IS

All BOD test procedures are EPA approved with procedures described in STDM_18 by method 5210B (Standard Methods, Vol. 18, procedure 5210B) and EPA 405.1. AWT Lab SOP references are 9 for BOD_5-I, 10 for BOD_5-IS, and 11 for BOD_5-U. The parameters BOD_5-I, BOD_5-U and BOD_5-IS are all five day biochemical oxygen demand, carbonaceous (BOD_5) tests, measured in units of mg DO/L. BOD_5-I is nitrification inhibited, BOD_5-U is nitrogen uninhibited, and BOD_5-IS is soluble BOD. The soluble sample is filtered through a 0.45 micron filter which removes (most wastewater) bacteria, and must therefore be seeded to produce the demand measurement. The seed used is called Polyseed® from InterBio, Inc., a dehydrated, non-refrigerated inocuium stored inside a capsule of precisely known volume, that is prepared each day before the BOD_5-IS tests. The automated measurements are taken with a YSI model 59 DO meter and a YSI 5905 BOD probe. Readings are taken after a thirty second period where jitter is less than +/- 0.03 mg/L, then transferred via an RS232 cable and input to the data base program BOD Magic, authored by Labtronics, Inc. BOD Magic further qualifies the readings for validity using several, pre-established criteria.

3.4.7 Measurements of Alkalinity and Temperature

The approved procedures for measuring alkalinity (ALK) are described in

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STDM_18 by method 2320B, EPA 310.2, and lab SOP 3. ALK is measured as $mgCaCO_3/L$ using an automated, titrimetric method with an end point at pH 4.5. Automated measurements are taken on a Mettler DL21 titrator connected via an RS232 cable to a dbase program, which stores the numbers on the hard drive.

3.4.8 Measurements of Ortho and Total Phosphorus

Ortho phosphorus, at times called 'reactive phosphorus', is labeled PO_FIA in the lab data base, and measured in mg P/L using a colorimetric, ascorbic acid method on the non-preserved, not filtered and not digested sample. Approved procedures for measurement are described in STDM_18 by 4500-P F, EPA 365.1 and lab SOP 150. Ortho- and total phosphorus are both measured on an automated process using the ALPKEM FS3000 flow injection analyzer. The data is transferred via an RS232 cable to proprietary software written by ALPKEM and stored on the hard drive.

A second ortho phosphorus measurement (AB4) is performed by the plant process laboratories using Hach chemistry and designated the "PhosVer 3 Method, Test'N Tube Procedure". The procedure is described in Hach Method 8048. It is a USEPA accepted method for reporting wastewater analysis. It is a colorimetric technique that measures transmission at 890 nm. Hach chemical reagents and proprietary laboratory equipment are required to recreate this measurement.

Approved procedures for measuring Total phosphorus are described in STDM_18 by 4500-PB 5F, EPA 365.1 and lab SOP 152. (Total and ortho phosphorus have the same EPA procedure number.) Total phosphorus, labeled PT_FIA in the lab

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data base and TP in this report, is measured in mg-P/L using the colorimetric, ascorbic acid method on the non-preserved, not filtered, the sample being digested with H_2SO_4.

A second total phosphorus measurement (AB4) is performed by the plant process laboratories using Hach chemistry and designated the "PhosVer 3 Method with Acid Persulfate Digestion; Test'N Tube Procedure". The procedure is described in Hach Method 8190. It is a USEPA accepted method for reporting wastewater analysis. It is an acid digestion, colorimetric technique that measures transmission at a wavelength of 890 nm. Hach reagents and proprietary laboratory equipment are also required to recreate this measurement.

3.4.9 Measurements of Free (Dissolved) Iron

One hundred (100) ml, unfiltered samples of wastewater from each plant location in Table 3.1 except AWT-P were taken at the Labs three times a week, placed in a cooler and brought to UNLV. A disposable, plastic syringe was used to extract three volumes, the last volume only being passed through a 0.45 micron filter until approximately 5 ml was collected in a small vial. This sample was then analyzed for free iron concentration using a Perkin Elmer AAnalyst 100, atomic absorption spectrometer with an absolute sensitivity of 0.1 mg/L. The critical flame parameters used a monitoring wavelength of 248.3 nm and a linear calibration profile with an endpoint at 5 mg/L. At that wavelength, changes in iron concentrations alter the optical path absorption linearly, up to 6 mg/L.

The entire data set from the free iron (ion) measurements is given in Appendix E, Iron Measurements.

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3.4.10 Measurements of VFA Concentrations

Vials collected from the ten collection points described in section 3.3.1 were used to extract a liquid sample to be analyzed by a Hewlett Packard 5890A Gas Chromatograph. The column used was a Nukol, Fused Silica capillary column, 30mx0.25mmx0.25μm (film thickness).

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CHAPTER 4

RESULTS AND ANALYSIS

4.1 Solids Residence Time (SRT), F/M Ratio and Related Parameters

SRT is one of the dynamic parameters used by the SCADA system at CCSD to operate and control each individual basin on a real time basis, and was selected as the operating parameter to be increased during the second part of the experimental period. The value of the SRT was changed from the normal value of 4.85 days for this time of the year, to 6.0 days. Throughout the remainder of this Thesis, the word "before" (the change) refers to the SRT of 4.85 days, and "after" (the change) refers to the longer SRT value of 6.0 days.

The mathematical definition of the target SRT is given in section 3.3.1 by eq. 3.1. All basins normally use the same target value for operation, and this value varies as a function of temperature over the year. Figure 4.1 describes the profile of the target SRT and the approximate times of the year when they change radically. As can be seen in the Figure, the desired SRT is above seven days from the first week in November, and through the winter until the middle of April, at which time the water temperature rises above 23 ^{0}C. The target SRT then drops rapidly to a value of five days by the end of May, when the water temperature rises to 25 ^{0}C.

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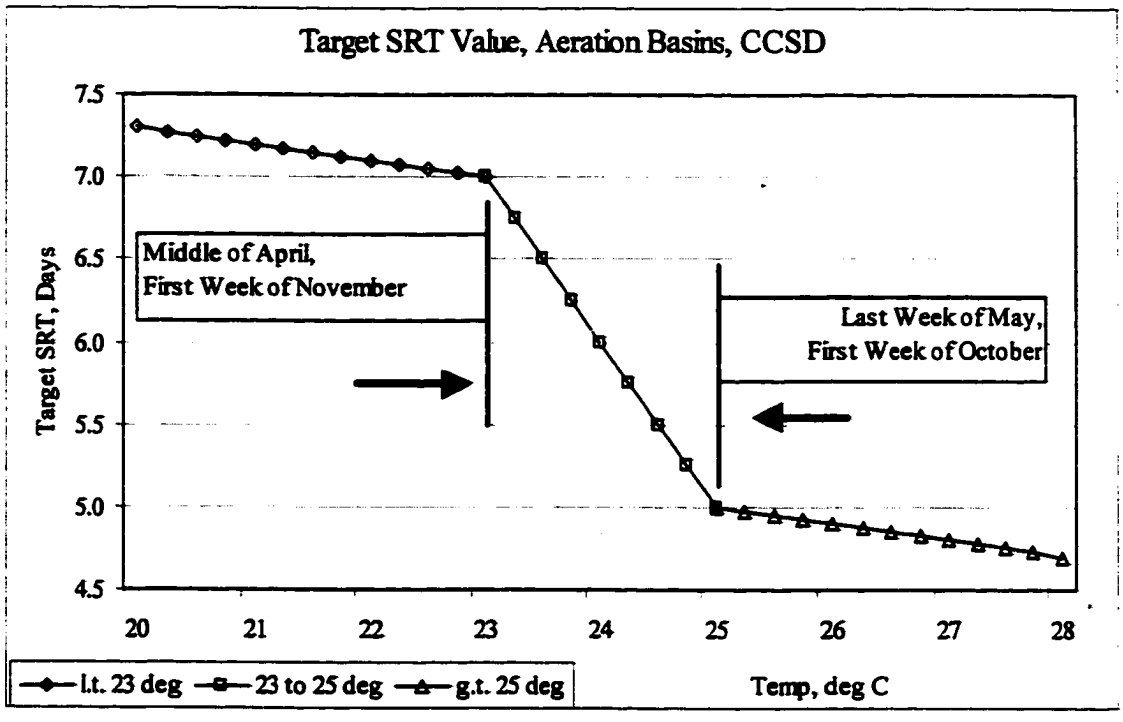

Figure 4.1 Target SRT Values for the Aeration Basins at CCSD

After the first week of October, the SRT begins to climb rapidly to a value of seven days which is reached in the first week of November.

The three functions describing the SRT target profiles are given in Table 4.1.

Table 4.1 The Controlling SRT Functions

Temperature Range	Function	Ramp Type
Less than 23 ^{0}C	$=[9.3-0.1*^0C]$	Shallow
23 to 25 ^{0}C:	$=[30.0-1.0*^0C]$	Steep
25 ^{0}C and greater	$=[7.5-0.1*^0C]$	Shallow

Figure 4.2 shows the daily water temperature for the plant, the target and actual values of the SRT experienced from June 1 to August 13, 1999, the experimental period.

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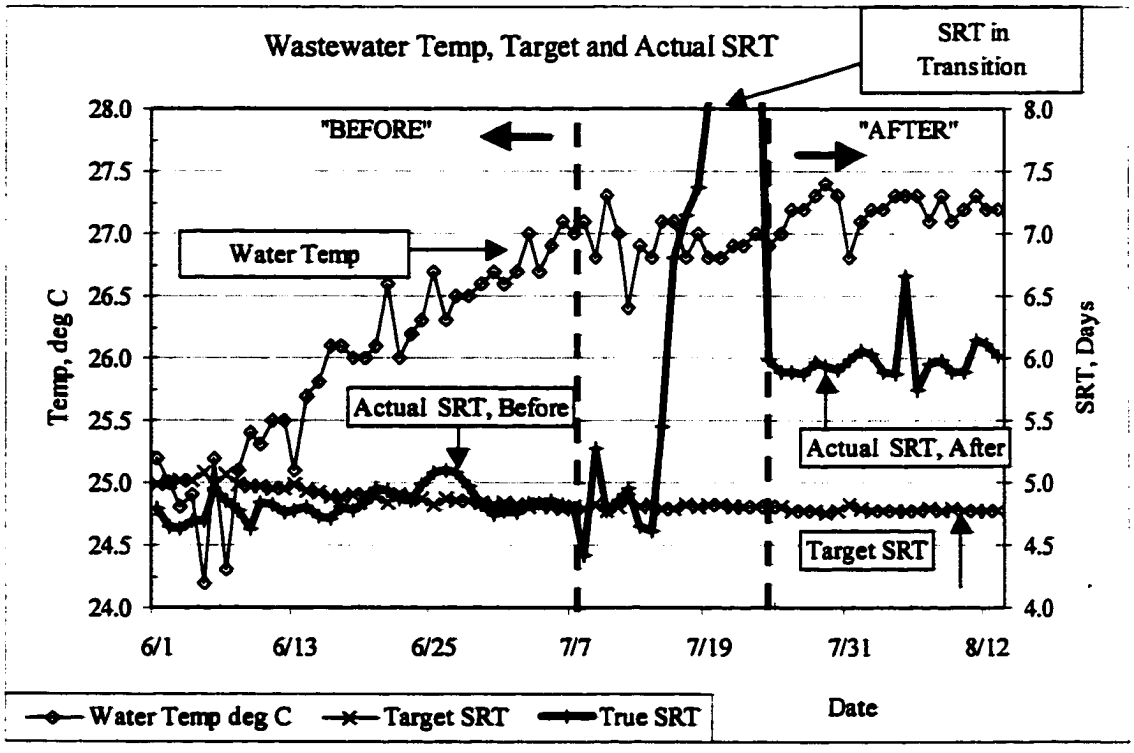

Figure 4.2 Wastewater Temperature, Target and Actual SRT Values

It shows that by June 1, the measured daily water temperature had reached 25 ^{0}C. The target SRT was now found on the slowly changing, (stable) shallow ramp, shown in Figure 4.1. Therefore, June 1 was the day selected as the beginning of the "before" period because the profile had reached 5.0 days along the slowly changing profile.

The end of the "before" period is July 7, the beginning of the transition period, as indicated by the left-most dashed line. During this period, the true value of the the SRT became artificially high because the basin wasting rate was severely reduced, and these artificially high SRT values were not plotted nor their effects analyzed.

The right most dashed line indicates that the SRT value of 6.0 days was reached on July 24, the beginning of the "after" period, and continued until August 13, the end of

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the "after" period. The 6.0 day SRT period was not varied with temperature during the "after" period. Figure 4.2 continues to show that the actual SRT values remained very close to the downward ramp of the target SRT during the "before" period, and very close to the 6.0 day value during the "after" period. The target SRT, shown during the "after" period, was the guide for the remainder of the seven basins

Figure 4.3 shows the three related parameters of MLSS and WAS concentrations, along with the pounds of WAS wasted each day. It can be seen that none of these parameters remained constant on a daily basis during the experimental period. In contrast, the SRT was held very close to it's desired value (Figure 4.2).

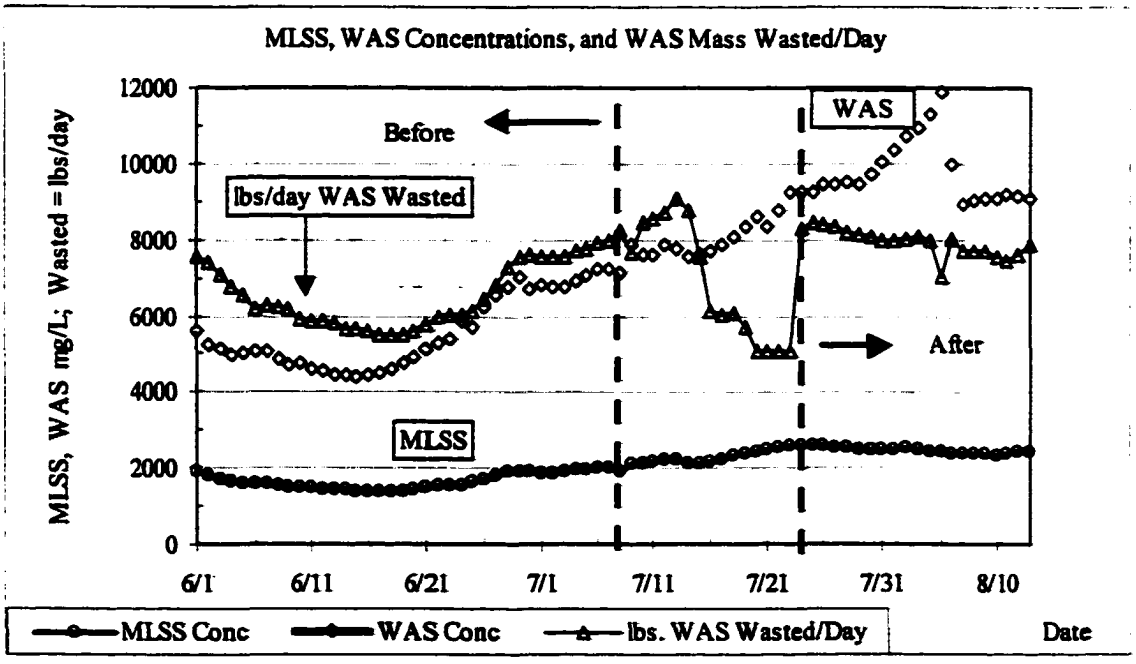

Figure 4.3 MLSS, WAS Concentrations and WAS Mass Wasted/Day

Figure 4.3 and Table 4.2 show that the MLSS increased from a minimum of about 1640 mg/L during the "before" period, to 2470 mg/L during the "after" period,

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and increase of about 50%. The wasted WAS dropped sharply during the transition period, and then returned to a high value of approximately 8200 lbs./day, from which it is seen to gradually decrease during the "after" period.

Table 4.2 SRT Related Parameters During the Experiment

	MLSS #4	WAS #4	QWAS #4	WAS Wasting Rate	Wt. of MLSS in Basin #4	SRT
Before 6/1 - 7/7	*mg/L*	*mg/L*	*gpm*	*lbs./day*	*lbs.*	*days*
Average	1641	5,559	99.2	6,554	31,623	4.83
Stdev	210	975	8.9	844	4046	0.116
After 7/24 - 8/13	*mg/L*	*mg/L*	*gpm*	*lbs./day*	*lbs.*	*days*
Average	2,471	9,757	68.2	7,936	47,447	5.98
Stdev	78	835	6.3	345	1466	0.18
After/Before			*(the change)*			
Average	50.5%	75.5%	-31.2%	21.1%	50.0%	24.0%
Entire Period	*mg/L*	*mg/L*	*gpm*	*lbs./day*	*lbs.*	*days*
Average	2,007	7,281	84.8	7,034	38,672	5.55
Stdev	414	2,025	18.6	1,114	7983	1.21

Table 4.2 shows the average values of parameters that are associated with, and determining the length of the SRT. The average increase of 50.5% in the MLSS is more than the approximate 24% increase that steady state kinetic theory would require, using equation 3.1. The table also shows that the WAS mass wasting rate increased 21% during the higher SRT period, when steady state kinetic theory would have required it to be negative with a constant influent BOD. Reference to Table 4.16 shows that the influent BOD to basin #4 dropped and average 13.7% during the "after" period, furthering the requirement that the SRT should go negative.

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The increase in WAS mass wasted/day, however, is an artifact of the SRT being adjusted in the plant by the SCADA system. In actuality, excess sludge had accumulated in the basin during the transition period, was being withdrawn from tank at a slow rate. A regression analysis of the slopping WAS wasting data in Figure 4.3 indicates a change in the rate of change of –42.4 lbs./day^2. At some future point, the rate of change for the wasting rate would have dropped to zero when the SCADA system found steady state conditions.

Table 4.3 shows the SRT related parameters of F/M ratios, the BOD and the SVI for the entire experimental period.

Table 4.3 F/M Ratio and Associated Values

	SRT	F/M	F/M	BODI	BODU	SVI
	Days	N_2-Inhib.	N_2-	lbs./day	lbs./day	
Before 6/1 - 7/7						
Average	4.83	0.074	0.087	2,302	2,722	185
Stdev	0.12	0.018	0.026	503	846	31
After 7/24 - 8/13						
Average	5.98	0.045	0.051	2,126	2,429	104
Stdev	0.18	0.005	0.006	255	299	8
After/Before - 1			*(the change)*			
Average	24%	-40%	-41%	-8%	-11%	-44%
Entire Period 6/1 – 8/13						
Average	5.55	0.060	0.073	2,193	2,709	149
Stdev	1.21	0.020	0.025	424	721	43

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The change in F/M ratio at –41%, followed the change in SVI more closely than the theoretical change of –23%, dictated by the relationship to SRT:

$F/M \sim 1/SRT + b_0$.

where b_0.is the slope intercept of the F/M ratio.

4.2 Intra-Basin Measurement

4.2.1 ORP (Oxidation Reduction Potential)

ORP was monitored during the experimentation process (using a HydroLab H20G probe), and it's relationship to phosphorus removal examined. Figures 4.4 and 4.5 show the ORP profile as it was measured in basin #4 during the periods "before" and "after" the SRT change, respectively. ORP values are plotted in the order of hydraulic flow (flow sequenced) that is experienced in the basin. The plots describe the typical behavior of the ORP that was found in each of the two periods.

The abscissa in all ORP plots reference the hydrogen (H_2) equivalent probe. This readings are always 200 mV below those of the AgCl probe used by the HydroLab for ORP measurements. (Researchers must identify the specific type of ORP probe used.)

Both Figures show that the ORP continues to drop as it passes from the first anaerobic cell A1, to the last cell A4. The longer the anaerobic period, the more the potential drops. Once into the aeration zone near ABI, the potential rises sharply as the water passes through the remainder of the basin and clarifier.

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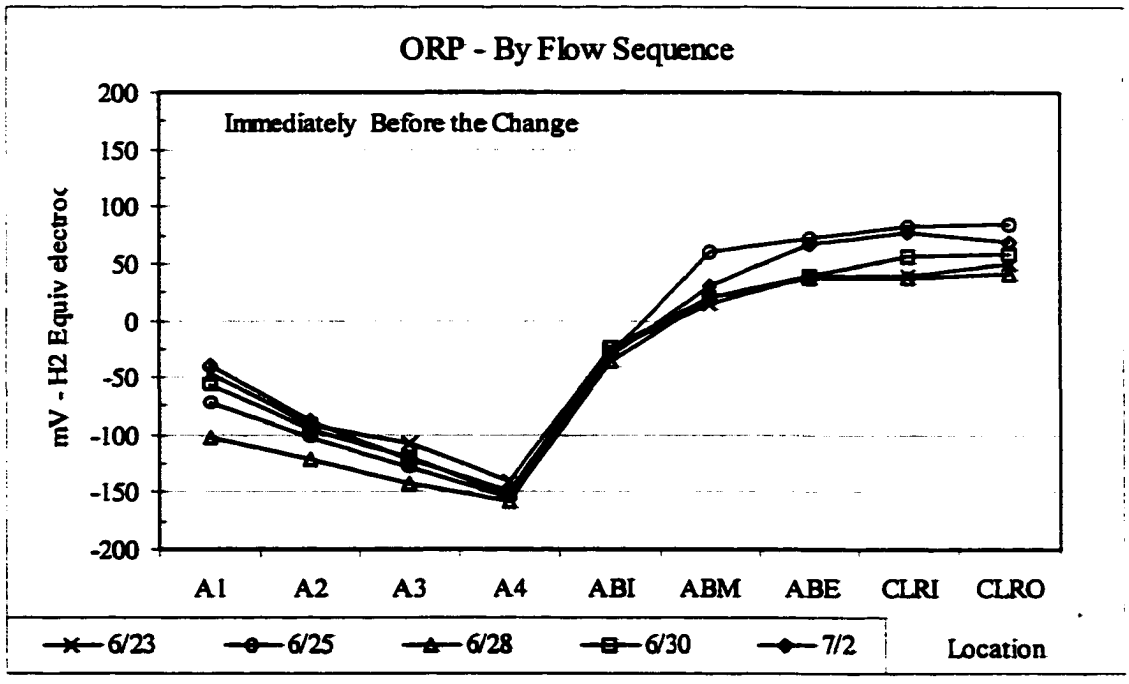

Figure 4.4 ORP Before the Change, by Flow Sequenced

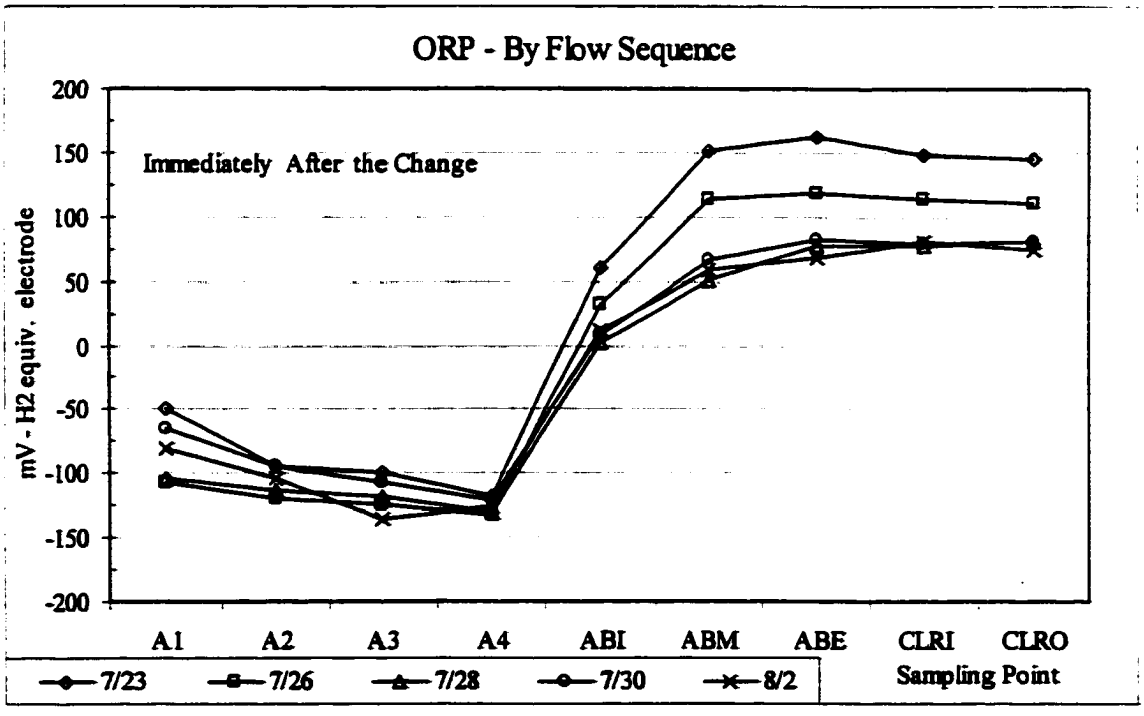

Figure 4.5 ORP After the Change, by Flow Sequence

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Notice that in the anaerobic zones, the ORP value did not level off. In the aerobic zones however, it quickly reached a maximum value around 75 mV and leveled off as it passed through the clarifier. Lack of aeration in the clarifiers, where the DO levels reach anaerobic values (Figure 4.12), does not lower the ORP back to the anaerobic cell values. It can then be concluded that ORP values and DO levels are not directly correlated.

Figures 4.6, 4.7, and 4.8 and Table 4.4 display the same ORP data as a function of time for the anaerobic, aerobic and clarifier zones respectively.

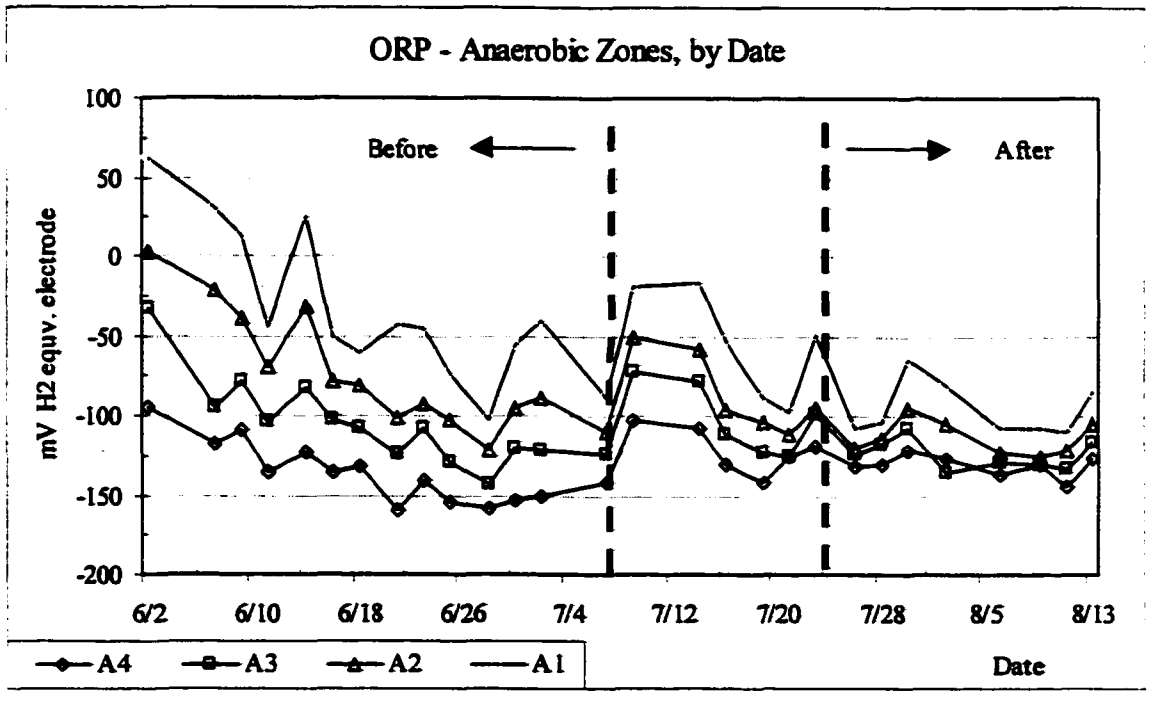

Figure 4.6 ORP – The Anaerobic Zones

The ORP values of the anaerobic zones (Figure 4.6) experience the largest changes between the two SRT periods. However, the ORP continued to decrease during

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the "before" period, to a value close to that of the "after" period. The only water parameter to change measurably during the "before" period was the temperature, increasing from ~25.0 ^{0}C on 6/1 to ~26.8 ^{0}C on 7/6. Increased temperature would increase microbial activity, and might result in the lower the ORP value as shown (Figure 4.6).

Interesting to note in Figures 4.7 and 4.8 is the abrupt, shock like behavior in the ORP at the beginning of the "after" period that was measured in the aerobic and clarifier zones, respectively. This point in time corresponds only to the sludge wasting valve being reopened. No other significant changes were introduced into the operation of the aeration basin. This suggests that the microbial activity in the entire basin is somehow affected by the sludge wasting function. No other explanation is known at this time.

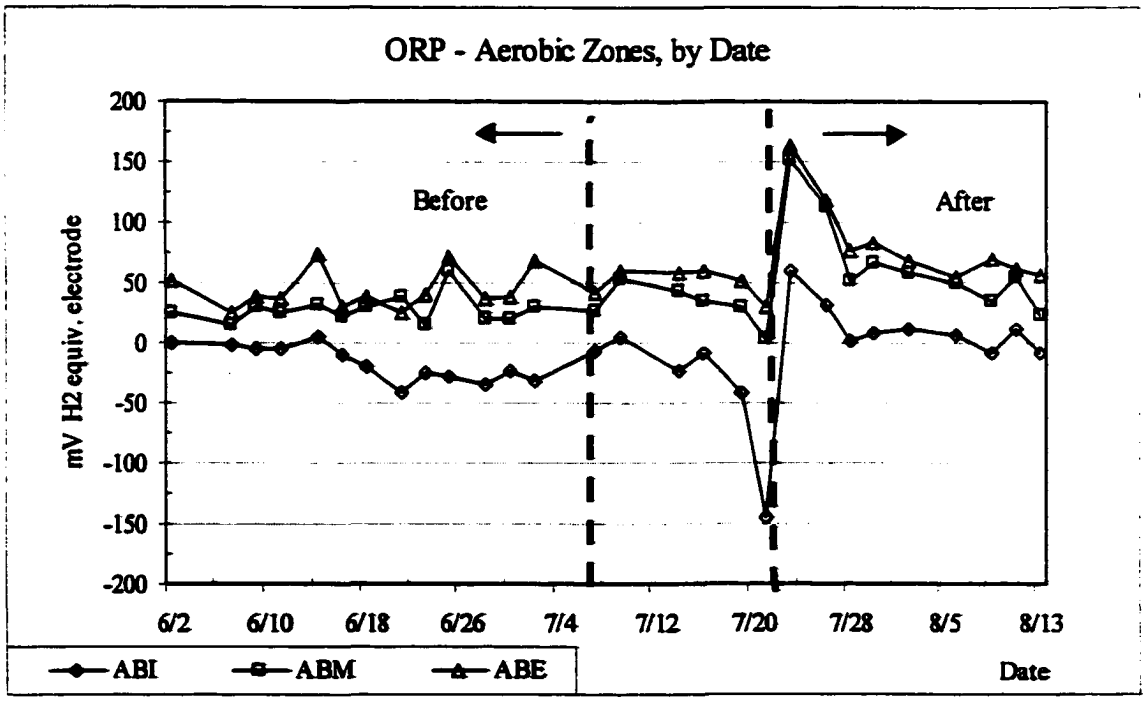

Figure 4.7 ORP – The Aerobic Zones

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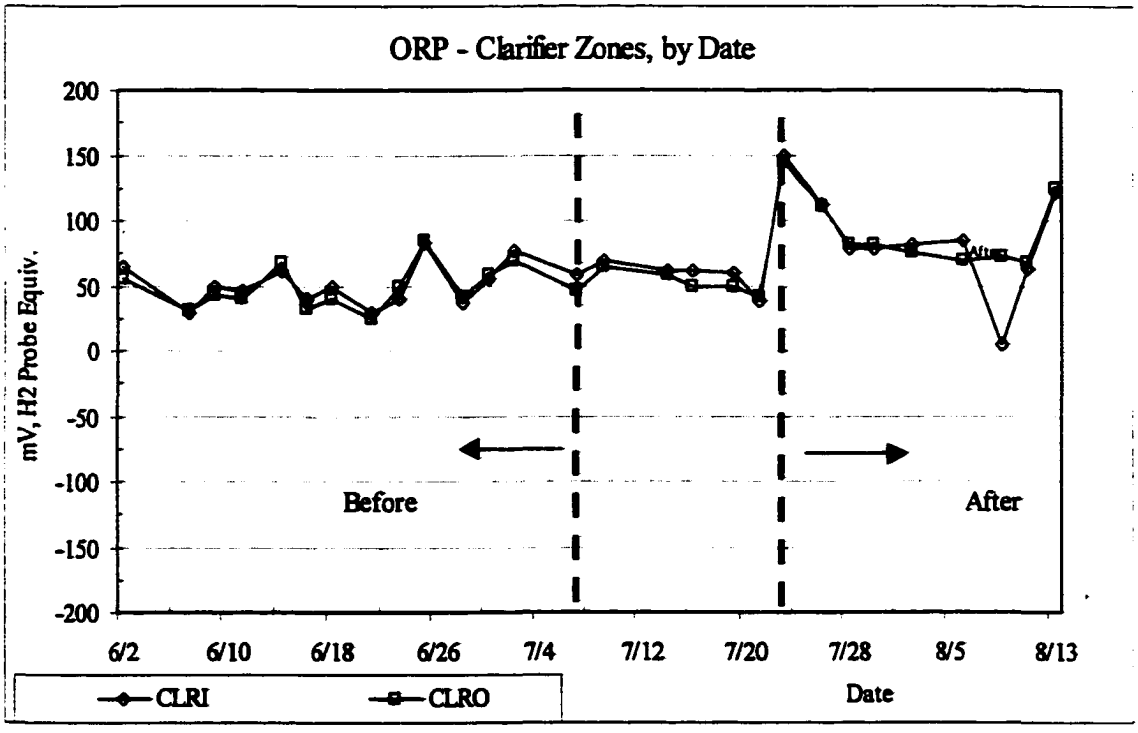

Figure 4.8 ORP – The Clarifier Zones

Table 4.4 ORP Readings									
	A1	A2	A3	A4	ABI	ABM	ABE	CLRI	CLRO
Before				*mV (H2 probe equivalent reading)*					
Average	-29.7	-70.8	-103.7	-135.5	-17.0	27.8	44.1	51.1	48.9
Stdev	47.2	36.8	28.0	20.0	15.0	11.9	16.9	16.9	17.1
After				*mV (H2 probe equivalent reading)*					
Average	-90.9	-111.6	-121.4	-129.8	12.8	67.3	83.7	85.9	91.9
Stdev	22.3	11.9	12.1	7.7	21.6	40.3	35.5	40.8	28.1
After/Before-1 Note: (-) or (+) = the percentage by which ORP became more negative or positive, respectively									
Average	(-)206%	(-)58%	(-)17%	(+)4%	(+)175%	(+)142%	(+)90%	(+)68%	(+)88%
Entire Period				*mV (H2 probe equivalent reading)*					
Average	-56.0	-87.6	-109.8	-131.4	-11.7	41.4	58.1	63.8	63.4
Stdev	46.2	33.3	23.8	16.3	34.1	30.5	29.2	29.8	27.9

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4.2.2 DO (Dissolved Oxygen)

Figures 4.9 shows the DO concentrations in basin #4 in flow sequence. The behavior is typical of that found on most other days that the data were collected, before and after the change.

Notice in Figure 4.9, that the DO concentrations in the anaerobic zones gradually decrease from 0.38 to 0.25 mg/L, while in the aerobic zone, DO concentrations increase from about 1 mg/L at ABI to 3 mg/L at ABE. Once the water has left the aeration basin, the drop in DO concentration is abrupt. DO levels in the clarifier (~0.4 mg/L), measured at the surface, are nearly the same as those in the anaerobic zones (~0.3 mg/L).

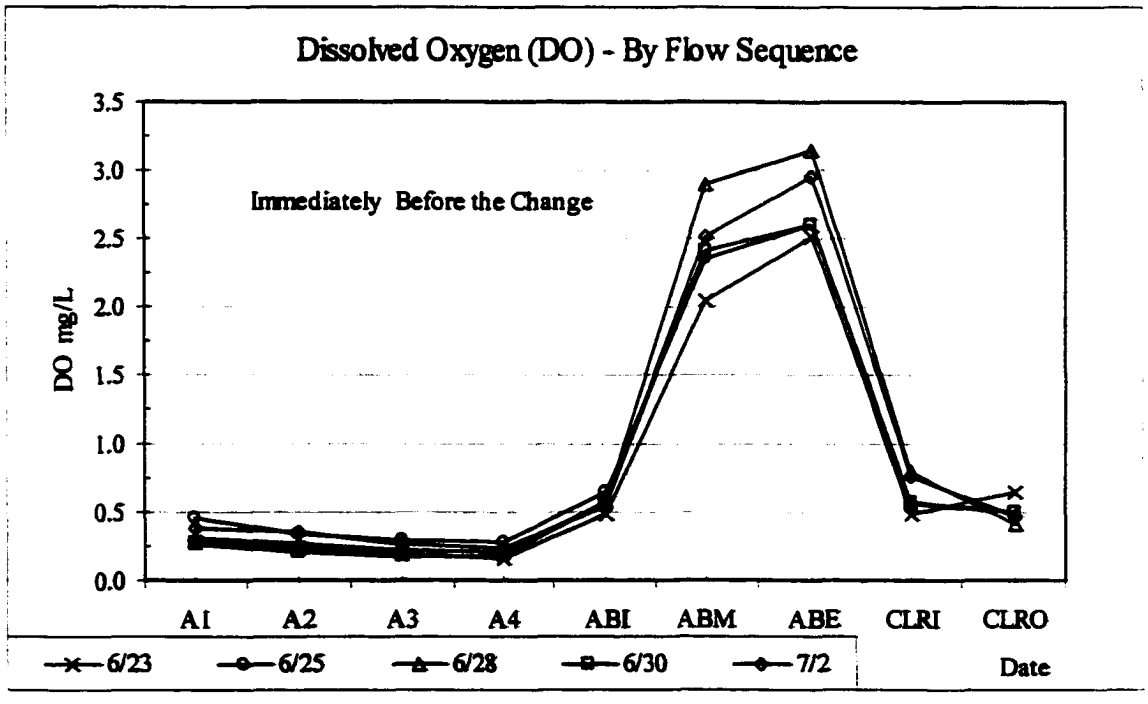

Figure 4.9 DO by Flow Sequence

Figures 4.10, 4.11, 4.12, and Table 4.5 describe the DO concentrations as a function of time for the anaerobic, aerobic and clarifier zones, respectively. Figures 4.10

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and 4.11 show that the DO concentration changed little in the anaerobic or aerobic zones during the two SRT periods. Such levels of DO in the anaerobic zone are conducive to phosphorus release if sufficient levels of VFAs were present, for once the settled microbes (RAS) are returned to anaerobic zone A1, the breakdown of intracellular polyphosphates into dissolved, ortho-phosphates begins immediately.

Figure 4.12 shows that the clarifier zones did experience a large drop in DO concentration during the higher SRT period, but the DO appear to be dropping throughout the entire experimental period, and not just the transition between the "before" and "after" periods.

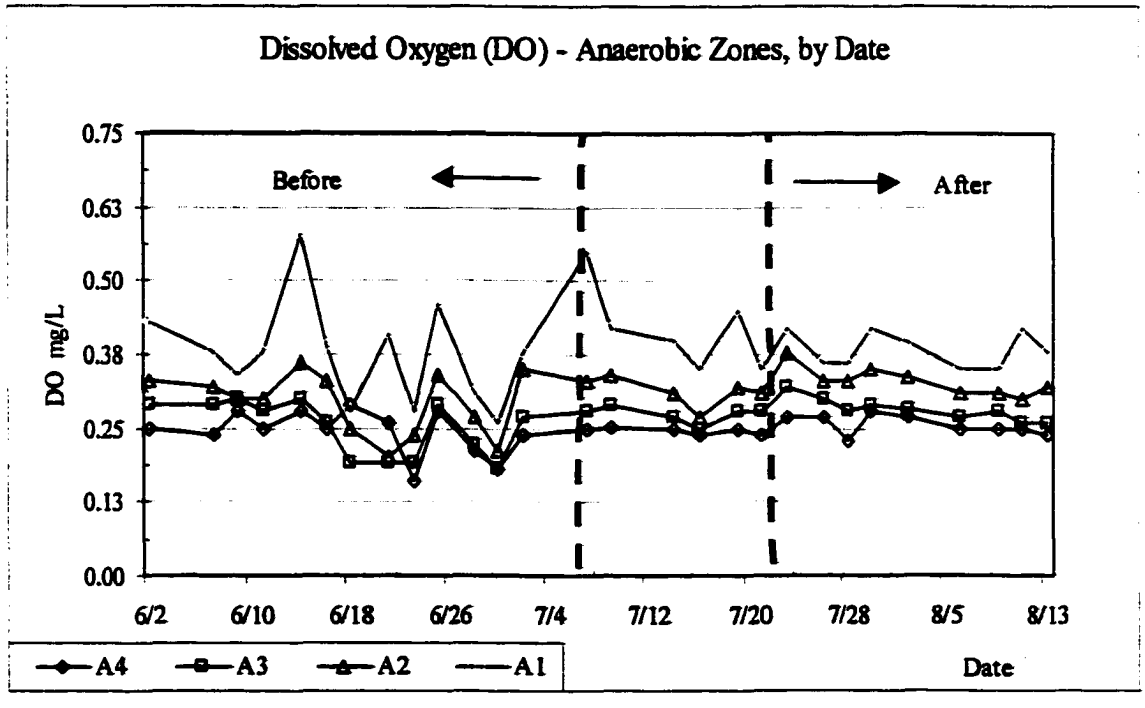

Figure 4.10 DO in the Anaerobic Zones, a Function of Time

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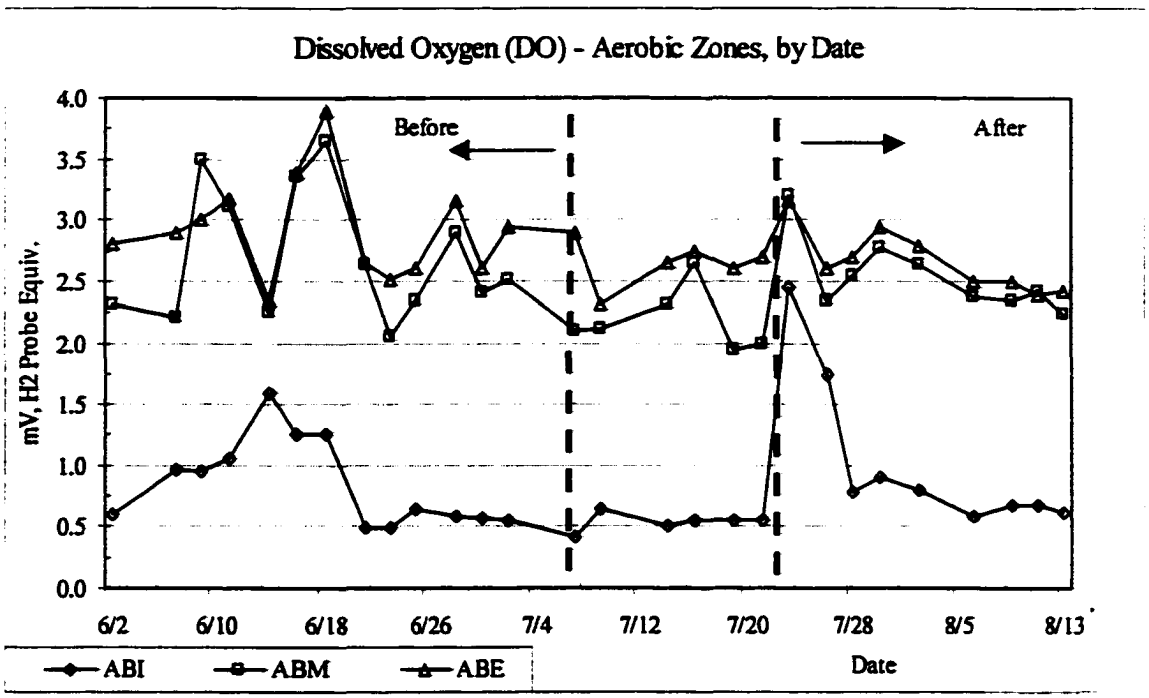

Figure 4.11 DO in the Aerobic Zones, a Function of Time

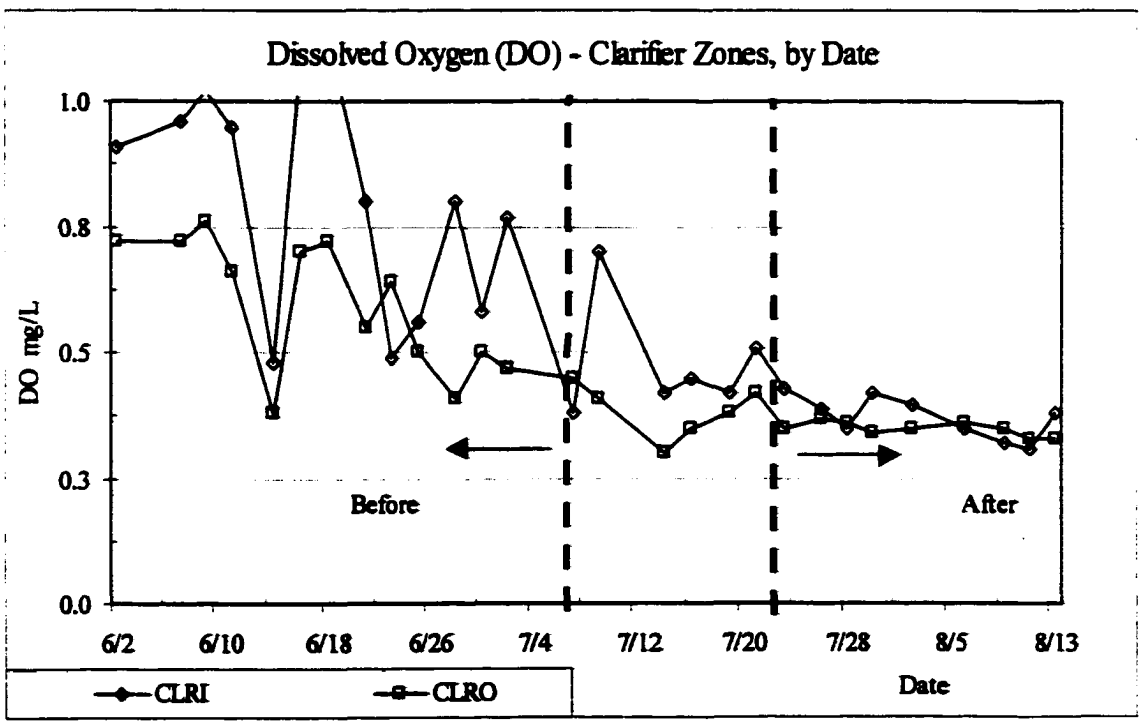

Figure 4.12 DO in the Clarifier Zones, a Function of Time

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Table 4.5 Dissolved Oxygen Readings									
	DO	DO	DO	DO	DO	DO	DO	DO	DO
	A1	A2	A3	A4	ABI	ABM	ABE	CLRI	CLRO
Before					*mg/L*				
Average	0.38	0.29	0.25	0.24	0.85	2.71	2.92	0.59	0.59
Stdev	0.09	0.05	0.05	0.04	0.36	0.54	0.42	0.13	0.13
After					*mg/L*				
Average	0.38	0.33	0.28	0.26	1.03	2.54	2.67	0.35	0.35
Stdev	0.03	0.02	0.02	0.02	0.64	0.30	0.26	0.01	0.01
After/Before-1									
Average	2%	13%	13%	5%	21%	-6%	-9%	-41%	-41%
Entire Period					*mg/L*				
Average	0.39	0.31	0.27	0.25	0.84	2.54	2.78	0.47	0.47
Stdev	0.07	0.04	0.04	0.03	0.46	0.46	0.35	0.15	0.15

Table 4.6 displays the averaged, total airflow fed to each basin as recorded by SCADA. The conclusion from this data, as it relates to the aerobic zones, is that the increased MLSS that occurred after the SRT change (+50% change, Figure 4.3), did not require a noticeable increase of air flow when compared to the other seven basins.

Table 4.6 Air Flows to Aeration Basins								
	AB1	AB2	AB3	AB4	AB5	AB6	AB7	AB8
Before				*SCFM*				
Average	1571	3972	1607	3690	5005	4652	6412	2092
Stdev	304	828	373	423	742	565	807	287
After				*SCFM*				
Average	2030	5006	1791	4074	4358	4038	3944	1892
Stdev	108	262	140	237	715	386	1818	208
After/Before-1								
Average	29.2%	26.0%	11.4%	10.4%	-12.9%	-13.2%	-38.5%	-9.6%
Entire Period				*SCFM*				
Average	1,803	4,513	1,741	3,870	4,509	4,193	5,334	1,908
Stdev	300	751	301	369	824	634	1,676	309

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4.2.3 DO vs. ORP

ORP has been investigated by researchers such as de la Menardiere et. al. (1991), Schon et. al. (1993), Lo et. al. (1994), and found to be a reliable indicator for use in optimization of nitrification. Those and other researchers have also looked to ORP as a process control indicator for phosphorus removal. For this reason, ORP was monitored during the experimentation process, and it's functional relationship to phosphorus removal examined.

The functional relationship is defined as the linear form:

$$DO = m*ORP + b_0 \qquad \text{eq. 4.1}$$

Where: DO = dissolved oxygen concentration

ORP = oxidation reduction potential

m = the slope of the line relationship

b_0 = the line intercept

The relationship between ORP and DO that was measured is shown in Figures 4.13, 4.14 and 4.15, representing the anaerobic, aerobic and clarifier zones respectively. The data points in the Figures represent the combined values of DO and ORP on separate days, and grouped by sampling point (A1, A2, ABM, etc.) using a common marker label that is identified in the legend.

The Figures all show that there appears to be a grouping that forms a centroid of unique coordinates, based upon the sampling point chosen. It is the regression analysis of each data set taken at one sampling point, however, that defines the existence of the

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functional relationship. Therefore, a regression analysis was run for 15 data points taken from each of the four anaerobic cells, during the "before" period.

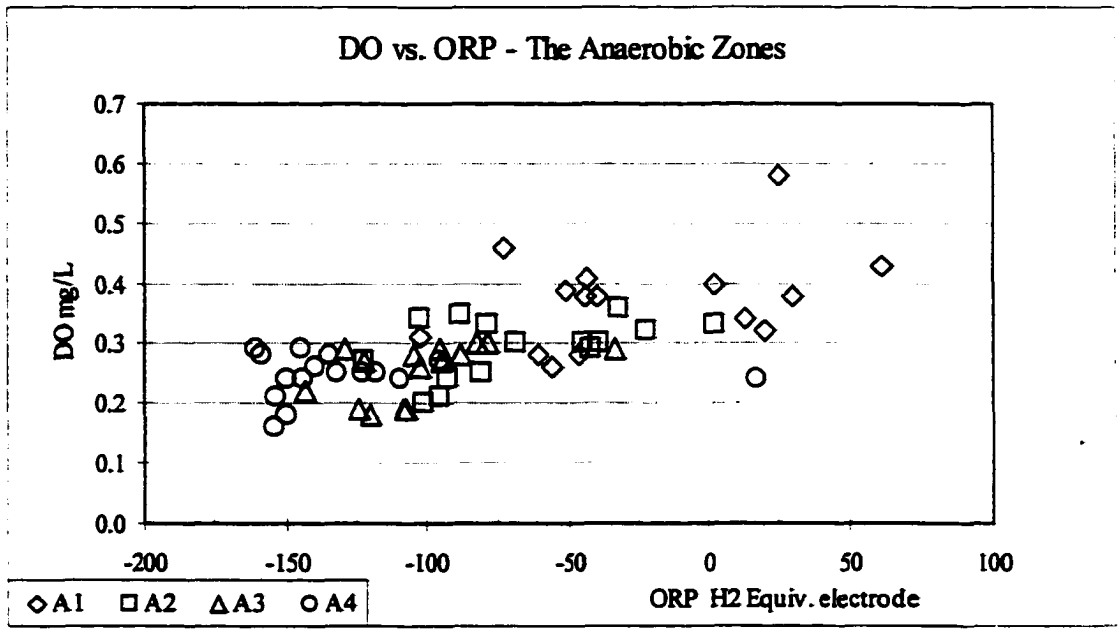

Figure 4.13 DO vs. ORP in the Anaerobic Zones

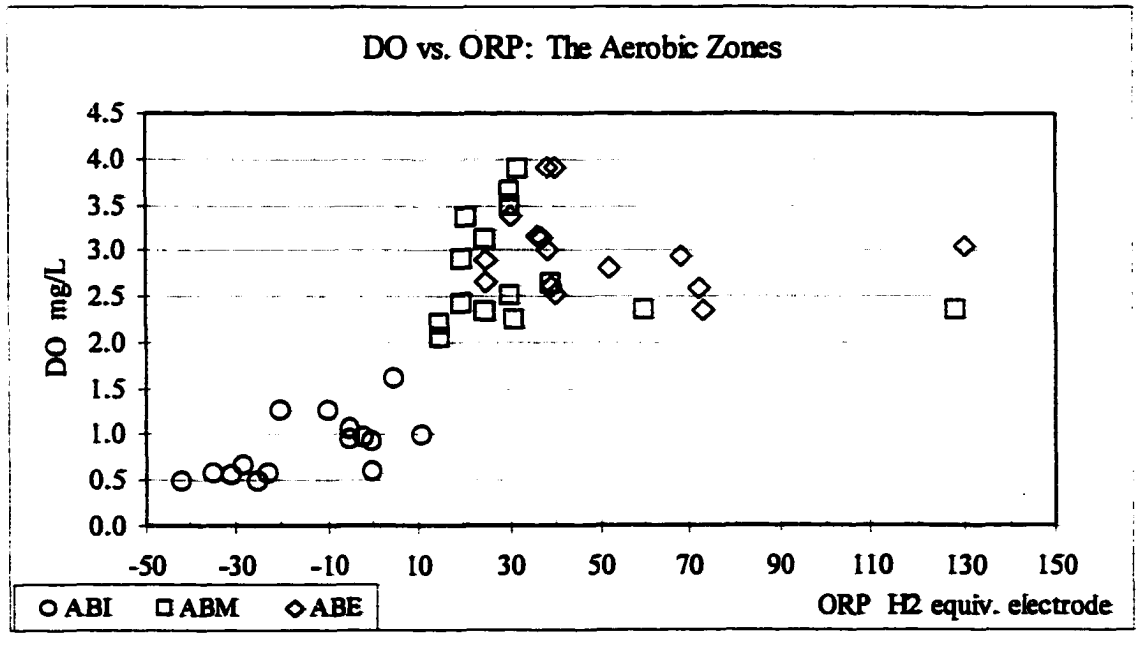

Figure 4.14 DO vs. ORP in the Aerobic Zones

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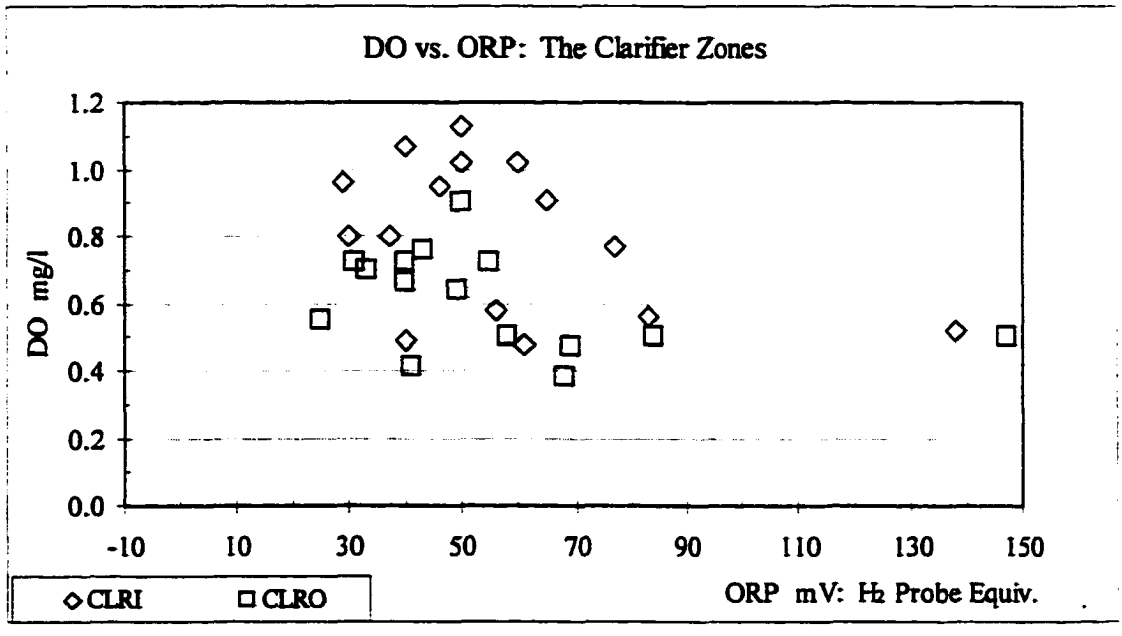

Figure 4.15 DO vs. ORP in the Clarifier Zones

Table 4.7 gives the results of that analysis. It is clear from the values of the slope given in the Table, that a linear functional relationship does not exist between DO and ORP. Similar conclusions were made for the aerobic and clarifier zones.

Table 4.7 Regression Results on DO vs. ORP

Variable	A1	A2	A3	A4
Slope, m (DO, mg/L)/(ORP, mV)	0.00085	0.00072	0.00087	0.00063
Intercept, b_0 (DO, mg/L)	0.401	0.343	0.340	0.329
R Square	0.213	0.245	0.253	0.101
"t" Statistic on Slope	1.725	1.888	1.929	1.109
P-value (in favor of relationship)	0.112	0.086	0.080	0.291

A description of the method used to compute the "t" Statistic and P-value given in Table 4.7 are described in Appendix C, Statistical Methods, Phase I, BIO-P Removal Study.

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4.2.4 Nitrogen: Ammonia and Nitrates

The ammonia concentrations by flow sequence before and after the change are shown in Figures 4.16 and 4.17, respectively . The influent ammonia concentration in the anaerobic zones remains basically the same from cell A1 through A4.

This behavior is expected, since the oxygen levels in these regions are not conducive to nitrification. Immediately after entering the aerobic zone at ABI, most of the ammonia is nitrified in the first, small portion of the aerobic zone. It drops from approximately 16 mg/L to 5 mg/L, in about 0.44 hours, a rate of 25.0 mg-NH_3/l-hr. This rate of decrease is based upon a volume of 0.20 MG for the ABI zone (Figure 3.4), and a basin flow of 11 MGD. This small zone has the dimensions of approximately 43.5'L x 35'W x 18'D.

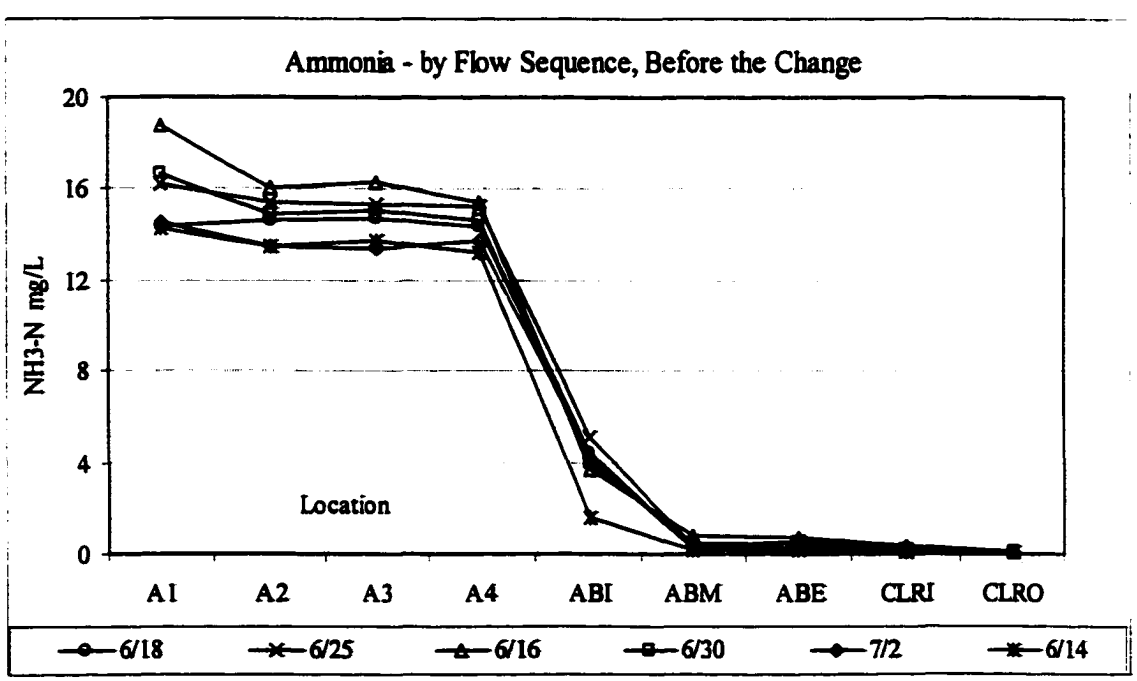

Figure 4.16 Ammonia by Flow Sequence, Before the Change

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After ABI, the ammonia concentrations throughout the tank dropped nearly to zero. A similar behavior for ammonia was observed after the change. As expected, the change in SRT did not affect ammonia.

Figures 4.18 and 4.19 show the nitrates in basin #4 by flow sequence, before and after the SRT was increased. No change in the pattern of nitrate levels was observed as a result of the SRT change.

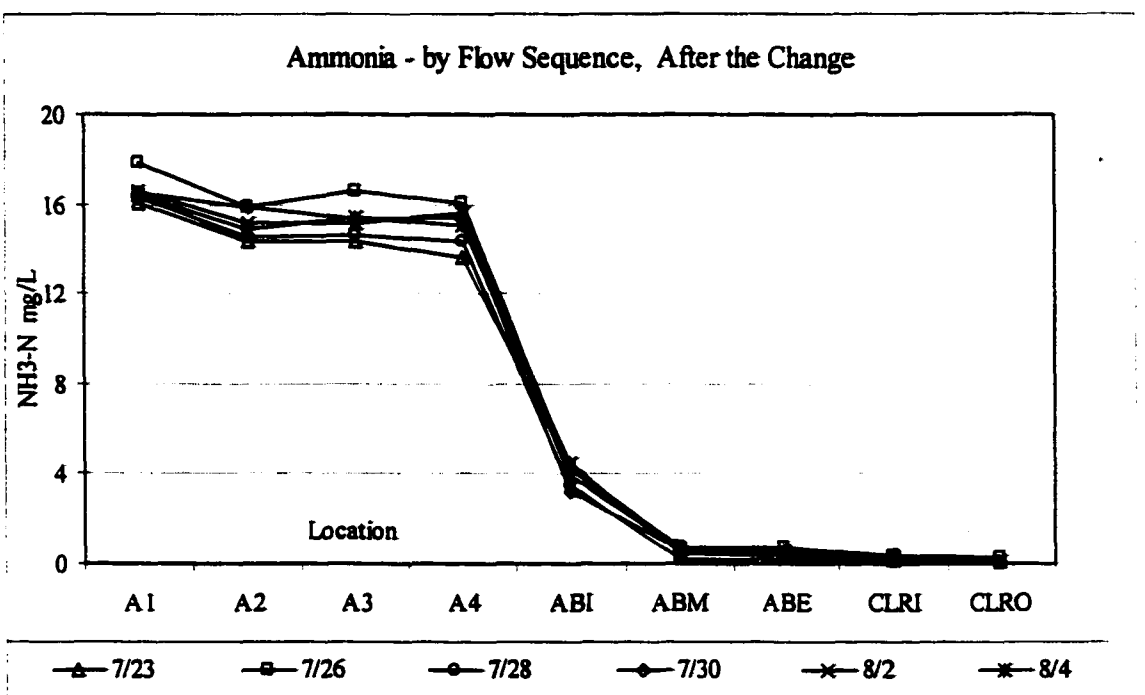

Figure 4.17 Ammonia by Flow Sequence, After the Change

The two Figures indicate that there is no measurable concentration of nitrates in the anaerobic zones. The nitrate level increases sharply by the time the flow has reached ABI, and levels off to a value of about 12 mg/L in the aeration zones and effluent of the clarifier (CLRO). The SRT change did not appear to affect the nitrification process.

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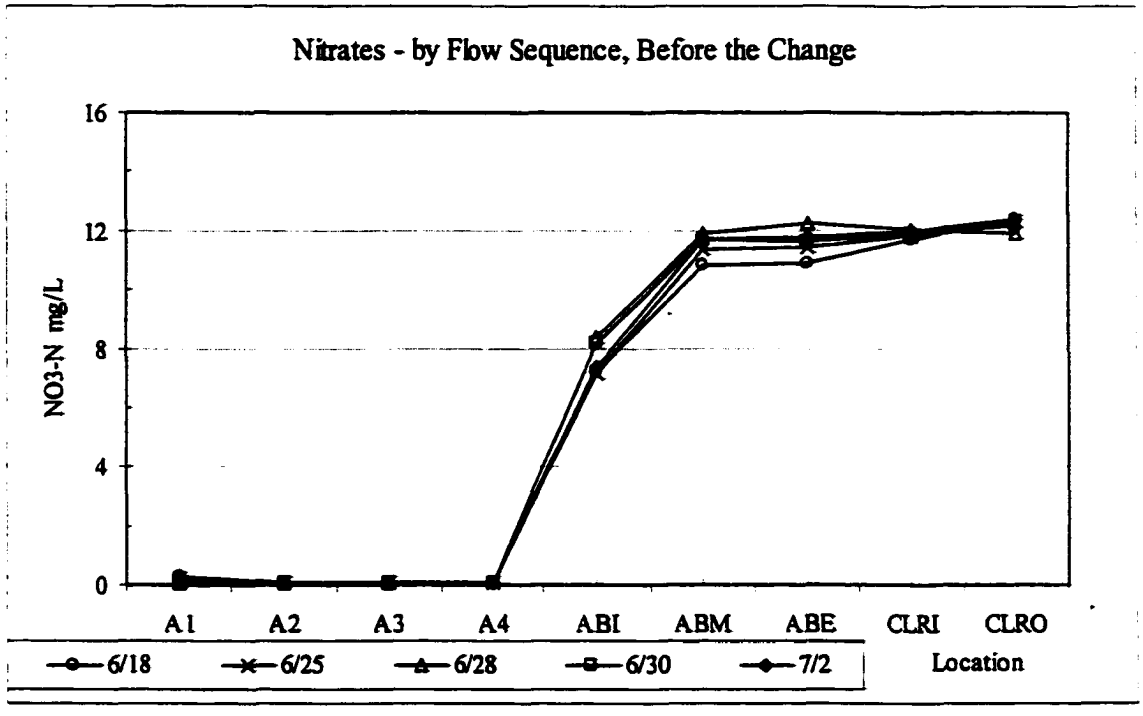

Figure 4.18 Nitrates by Flow Sequence, Before the Change

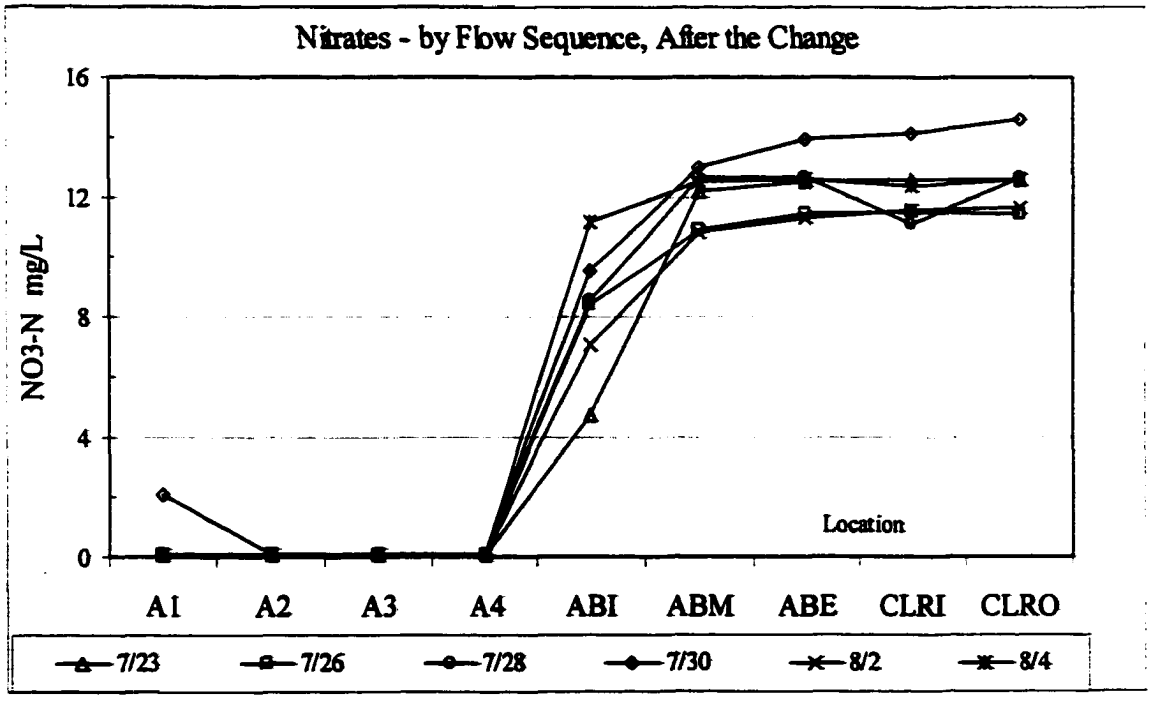

Figure 4.19 Nitrates by Flow Sequence, After the Change

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Because the clarifier effluent has been found to contain nitrate (Figures 4.18 and 4.19), it would be expected that the return activated sludge which is pumped from the sludge blanket at the bottom of the clarifier, would contain the same concentration of nitrate. Interesting to note, however, is that nitrate is not detected in zone A1, even though this is the location where RAS is returned to the basin from the clarifier. One explanation for this is that the RAS itself has lowered levels of nitrate which can drop to zero by the time they reach the anaerobic cell A1.

Figure 4.20 shows the nitrate concentration in the RAS of basin #4 that was measured during the second phase BioP program (beginning in Sept 1999). The Figure shows that nitrate concentrations are consistently around 7.5 mg/L, lower than the 12 mg/L found in the clarifier effluent. This indicates that denitrification is taking place the sludge blanket and/or RAS.

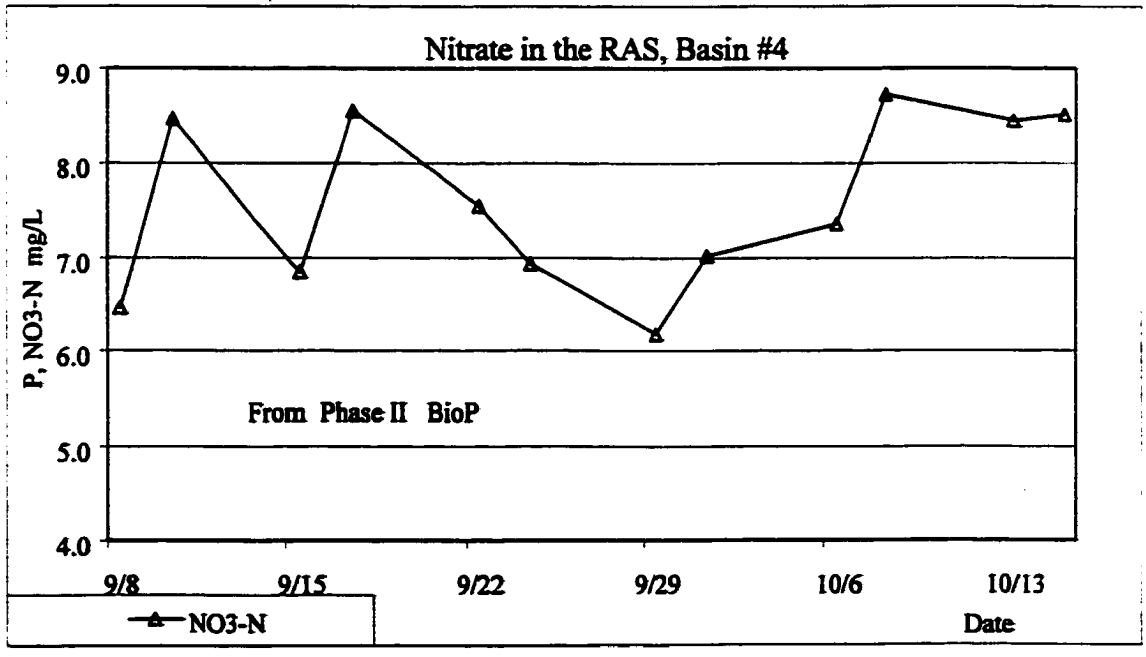

Figure 4.20 RAS Nitrate Concentrations, Basins #4, Phase II Bio P

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Nitrate concentrations in the RAS, measured by the plant process labs, are plotted in Figure 4.21 for the western four-basin cluster (basins #1-#4) during April through August, 1999. The thicker line in Figure 4.21 corresponds to the concentrations found in basin #4.

As can be seen, nitrate concentrations in the RAS vary from near zero to 12 mg/L, the maximum concentration found in the secondary clarifier effluent. The nitrate concentrations can vary somewhat independently from one another, indicating that each basin and clarifier combination operates as individual units.

Figure 4.22 shows the RAS nitrate levels for the eastern four-basin cluster (basins 5-#8) during the entire experimental period. Observe that the nitrate levels are still somewhat independent, but much lower than those in the western cluster.

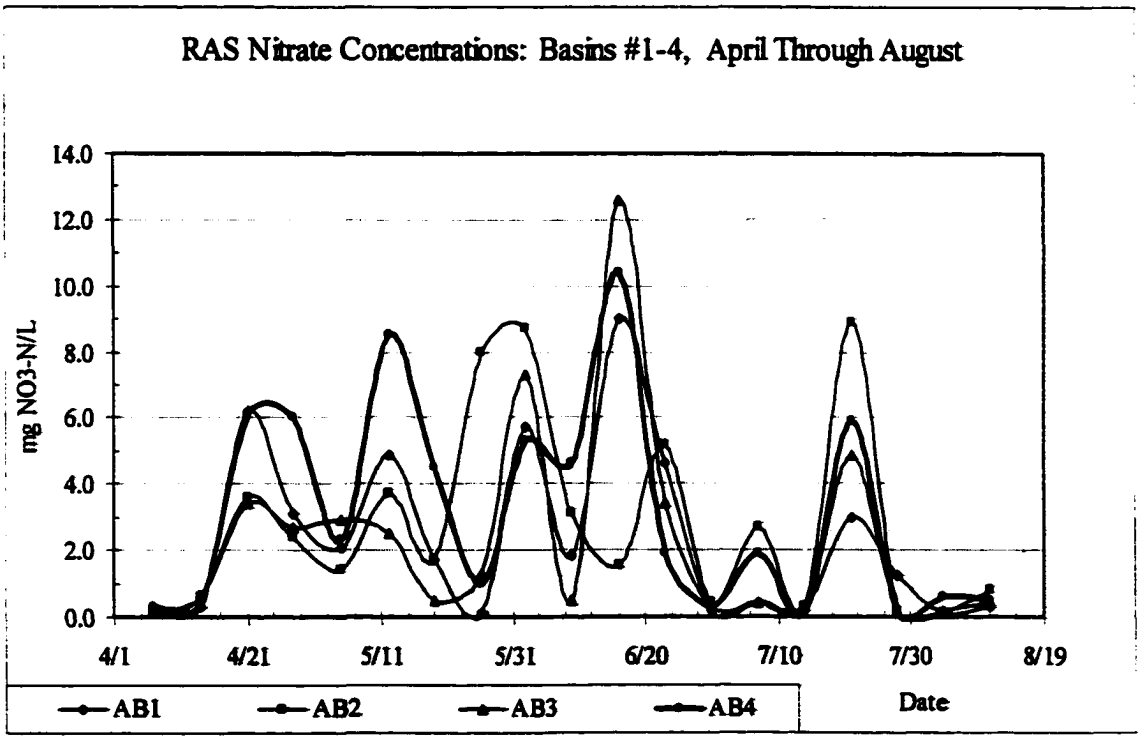

Figure 4.21 RAS Nitrate Concentrations, Basins #1-#4, April Through August

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For reasons not yet discovered, the fluctuation periods of the nitrate levels in both basin clusters appear to be approximately twenty days. Also not identified is the reason why denitrification in the RAS of the eastern cluster is much stronger, even though both clusters are given the same influent from CABI and are physical copies of one another. One contribution to the non-similar denitrification is that the mixing of the effluents from the east and west groups of primary clarifiers is not complete. The effect of this would have the western cluster of basins receiving more influent from the western primary clarifiers, and the eastern cluster receiving more influent from the eastern primaries. Another contribution might be due to differences in the average sludge blanket thickness between the two clusters.

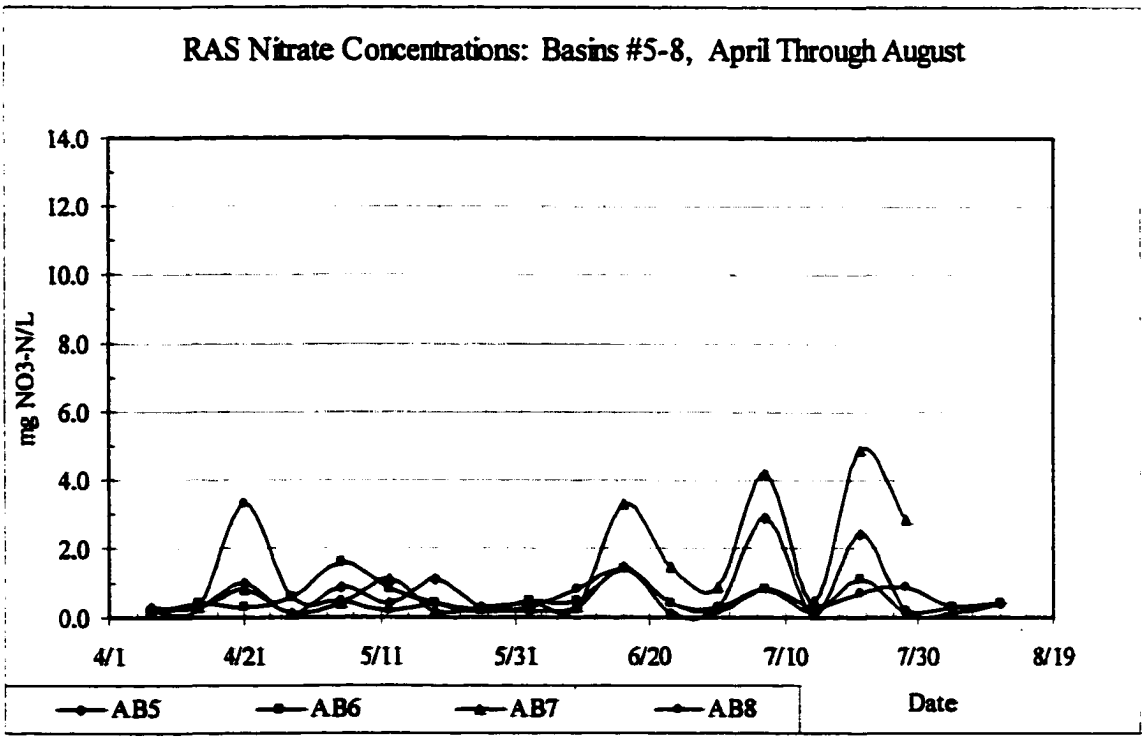

Figure 4.22 RAS Nitrate Concentrations, Basins #5-#8, April Through August

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Figures 4.23, 4.24 and Table 4.8 show the alkalinity data for the flow sequence in basin #4. The change in alkalinity in the anaerobic zones (Figure 4.23) is insignificant, since nitrification is not taking place due to a lack of oxygen. Once into the aerobic zones, the alkalinity decreases moderately, possibly due to the consumption of alkalinity by the nitrification process. The alkalinity continues to decrease as the water reaches the clarifier.

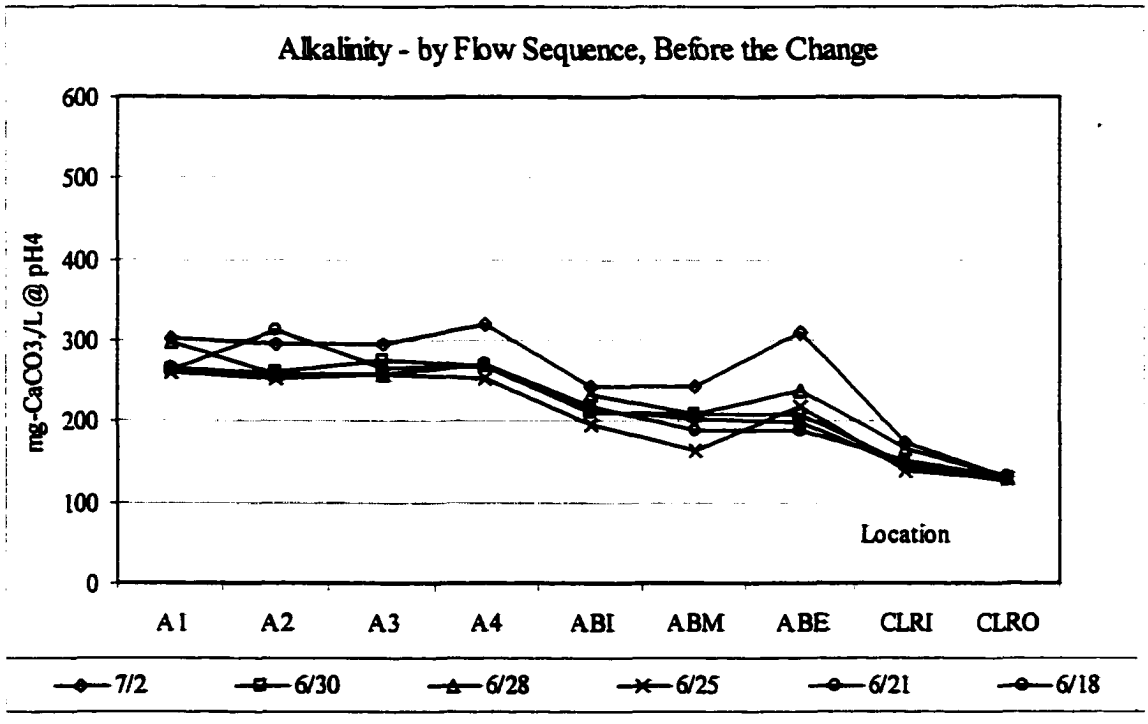

Figure 4.23 Alkalinity by Flow Sequence, Before the Change

As the Figures and Tables indicate, the alkalinity increased significantly in both the anaerobic and aerobic zones when the SRT was changed to 6.0 days. The anaerobic zones experienced an increase of about 30%, while the aerobic zones increased 56%. Alkalinity in the clarifier zones remained almost constant, changing less than 2%.

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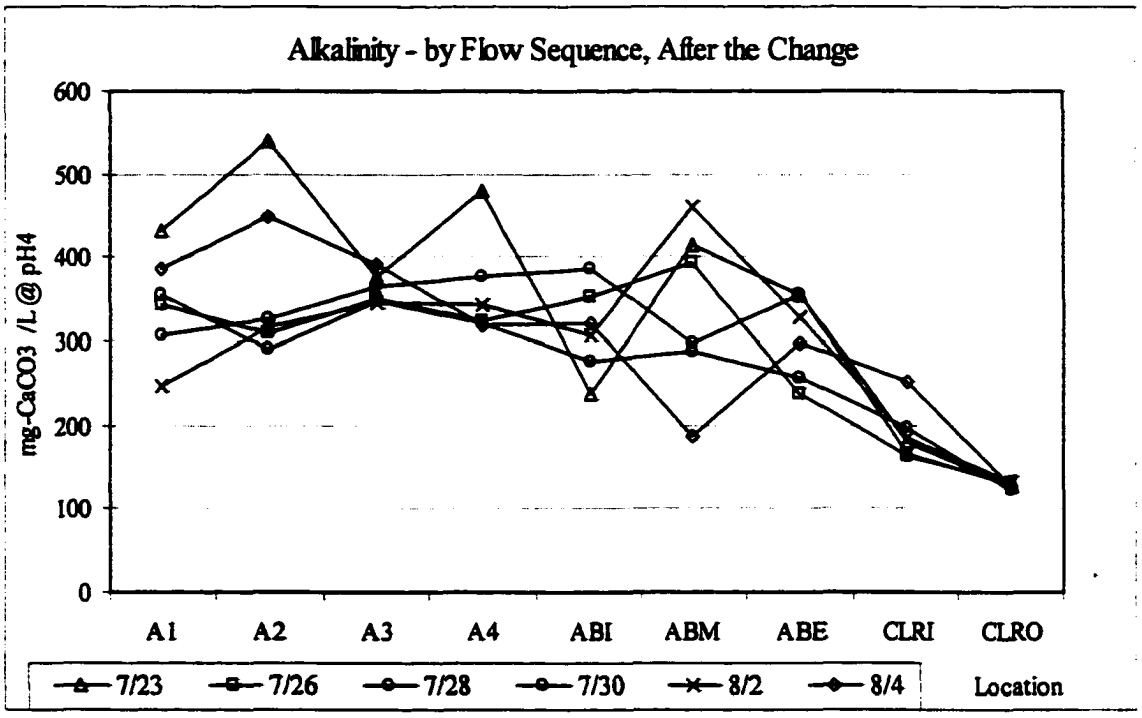

Figure 4.24 Alkalinity by Flow Sequence, After the Change

Table 4.8 Alkalinity, as mg-$CaCO_3$/L @ pH4								
	A1	A2	A3	A4	ABI	ABM	ABE	CLRO
Before					*mg/L*			
Average	286.1	277.1	271.5	285.7	218.9	200.5	220.2	129.0
Stdev	32.2	19.8	12.9	50.3	16.5	20.5	32.0	2.2
After					*mg/L*			
Average	343.8	380.6	363.3	372.7	328.4	349.0	317.5	131.0
Stdev	106.5	96.7	45.3	79.5	84.8	91.7	66.2	4.1
After/Before-1					*(the change)*			
Average	20.2%	37.3%	33.8%	30.4%	50.0%	74.0%	44.1%	1.6%
Entire Period					*mg/L*			
Average	306.0	328.9	325.7	326.7	275.3	275.2	267.8	130.9
Stdev	82.8	76.2	64.9	70.2	79.4	94.1	70.5	9.9

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4.2.5 Phosphorus Concentrations

In Figure 4.25, the concentrations of OP by flow sequence are shown. It can be seen that the OP increases slightly as the water goes from basin A1 to basin A4, a result of phosphorus release by the microbes in the anaerobic cells. As the flow passes through the aerobic zones, there is a sharp decrease in OP, which reaches a minimum at the clarifier effluent (CLRO). No major difference in OP concentrations throughout the basin was observed with the increase in SRT. The analysis of phosphorus for the data reported in Figures 4.25 and 4.26 was performed using unfiltered mixed liquor samples. Because of the high concentration of microbes and the time required to process these samples, the results shown do not reflect the soluble P in the wastewater.

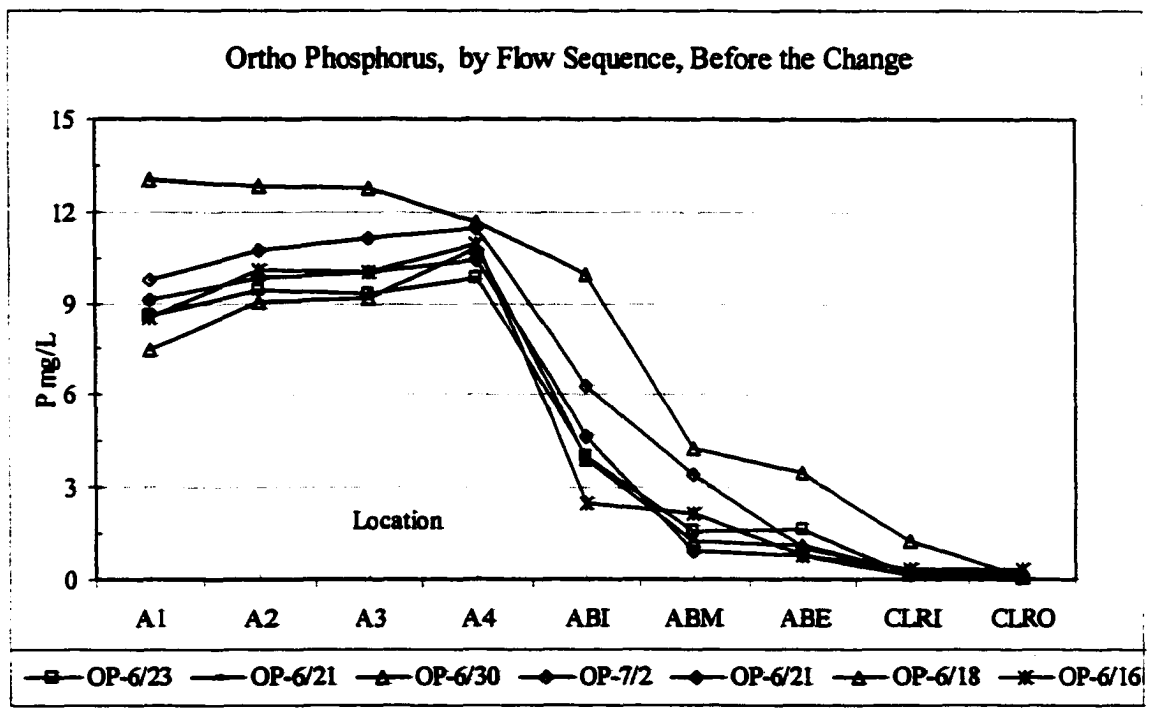

Figure 4.25 Ortho Phosphorus Concentrations, by Flow Sequence, Before the Change

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Figure 4.27 and Table 4.9 describe the soluble TP and OP concentrations as measured using filtered samples of the wastewater. Notice that when the soluble P results from a microbial connected release, the TP and OP concentrations from the same day are nearly the same (Legend, Figure 4.27). This indicates that OP is the major phosphate form released by the microbes. This Figure also shows very clearly, that the soluble phosphorus concentrations in the anaerobic zones increases as it travels from A1 to A4, this being the result of OP release by the PAOs. In addition, it shows that the phosphorus concentration decreases sharply in the aerobic zones, as it is taken up by the same PAOs from which it was released. A second important feature found in the Figure, is the TP/OP concentration in the RAS, which increases to levels higher than those of the aeration basin (ABE) and clarifier (CLRO) effluents. This is an indication that P release is taking place in the underflow of the clarifier, prior to reaching the anaerobic cell A1.

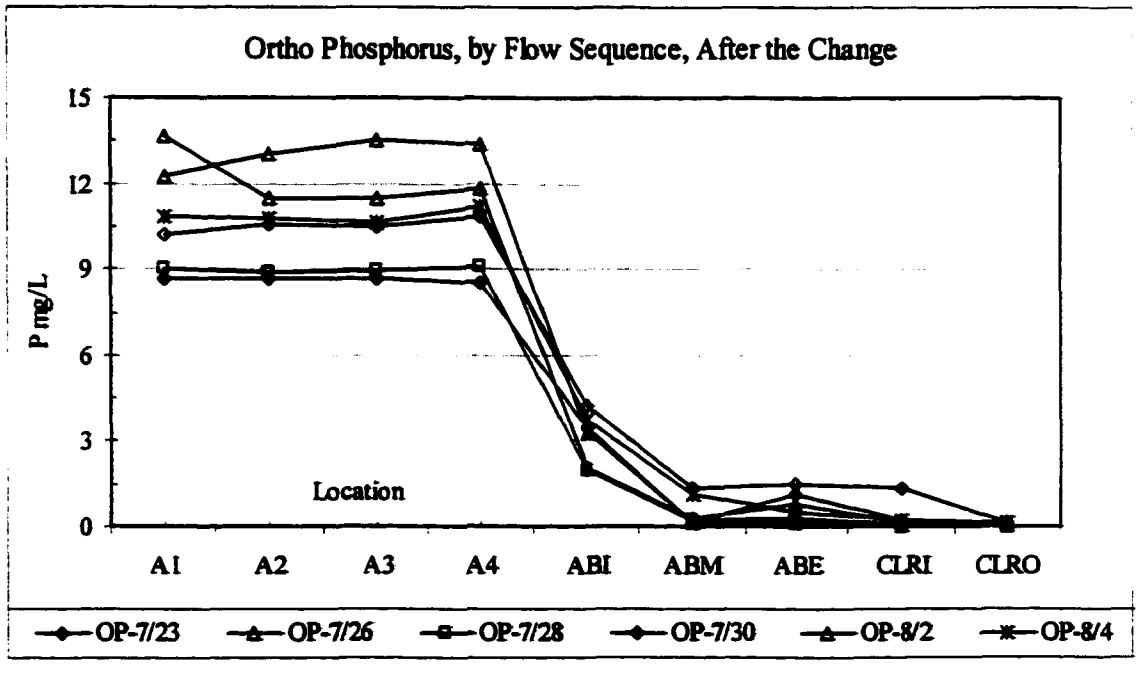

Figure 4.26 Ortho Phosphorus Concentrations, by Flow Sequence, After the Change

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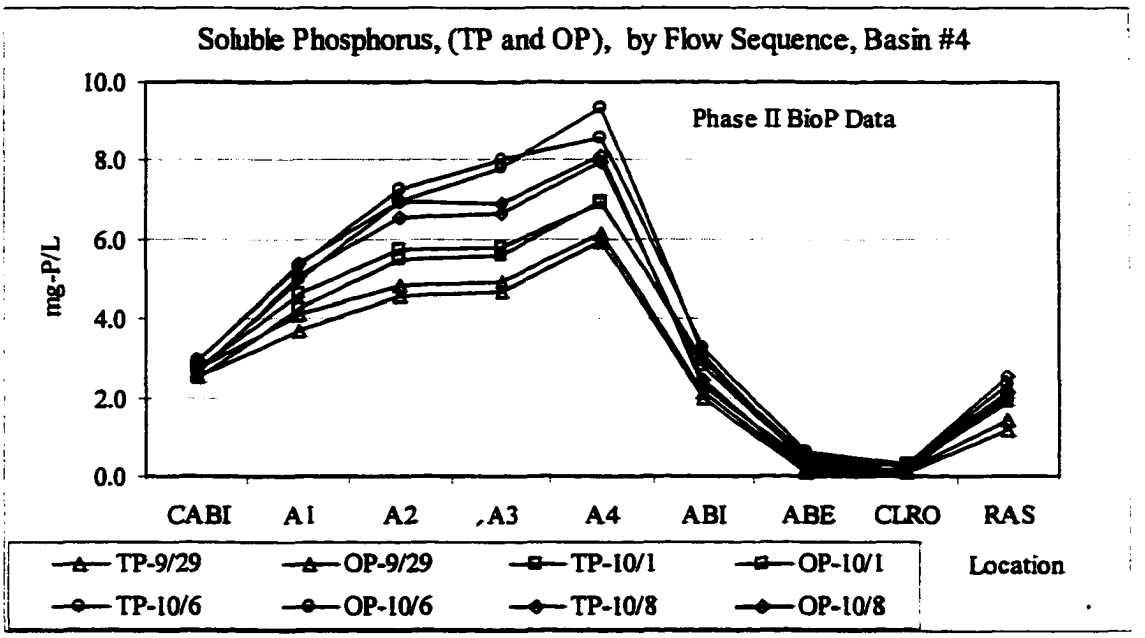

Figure 4.27 Soluble Phosphorus Concentration, (TP and OP), by Flow Sequence

Notice in Figure 4.27, that there is a slight uptake in P after the flow leaves the aeration basin (ABE) and becomes the clarifier (CLRO) effluent. P concentrations in the RAS are noticeably greater than in the clarifier effluent.

Table 4.9 TP, OP Average Concentrations, Basin #4, 9/29 - 10/8/99, Filtered Samples From Figure 4.27 *Units in mg/L*

	CABI	A1	A2	A3	A4	ABI	ABE	CLRO	RAS
TP	2.84	4.87	6.19	6.41	7.43	2.65	0.40	0.26	2.07
OP	2.57	4.51	5.89	6.17	7.55	2.59	0.27	0.18	1.84

Figures 4.28, 4.29, return to the experimental "before" and "after" periods, respectively. They show that there was a significant increase in total phosphorus concentration during the higher SRT.

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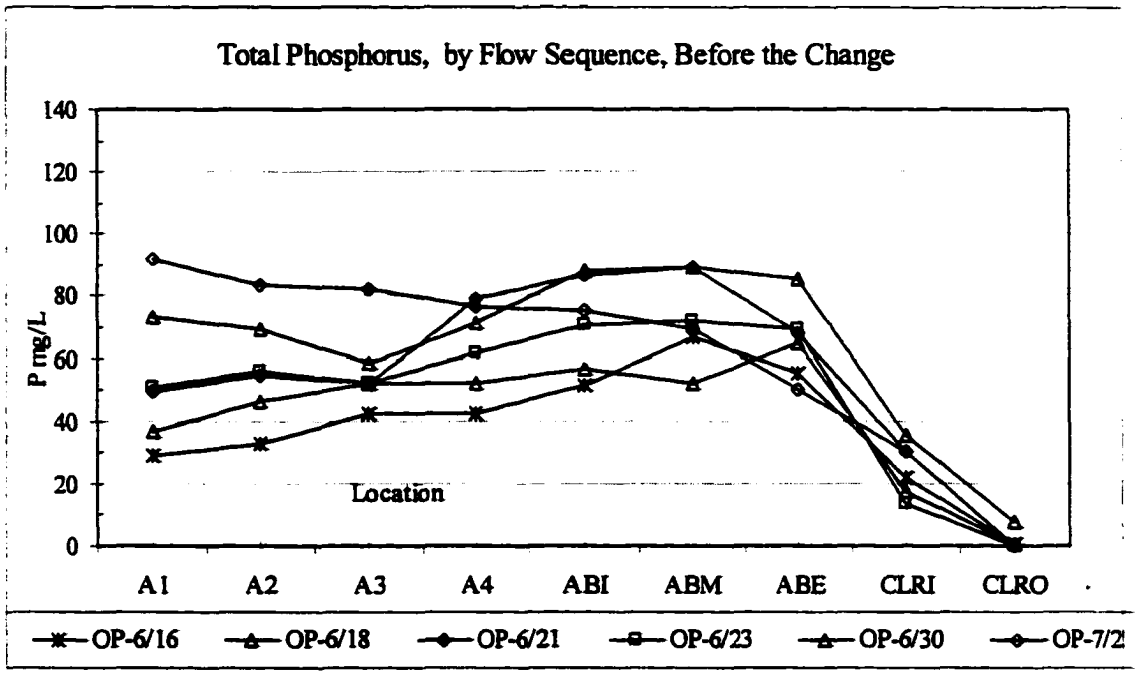

Figure 4.28 Total Phosphorus, by Flow Sequence, Before the Change

The reason for this is that return activated sludge concentration (RAS or WAS) increased during the "after" period, as indicated in Figure 4.3. The phosphorus concentrations for the anaerobic, aerobic and clarifier zones as a function of time and as measured during the entire experimental period, are shown in Appendix A.

Table 4.10 summarizes the statistics for the TP and OP concentrations in the anaerobic zones for the unfiltered samples, sample points of which are plotted in Figures 4.28 and 4.29. Table 4.11 summarizes the statistics for the TP and OP concentrations in the aerobic and clarifier zones for the unfiltered samples, sample points of which are also plotted in Figures 4.28 and 4.29.

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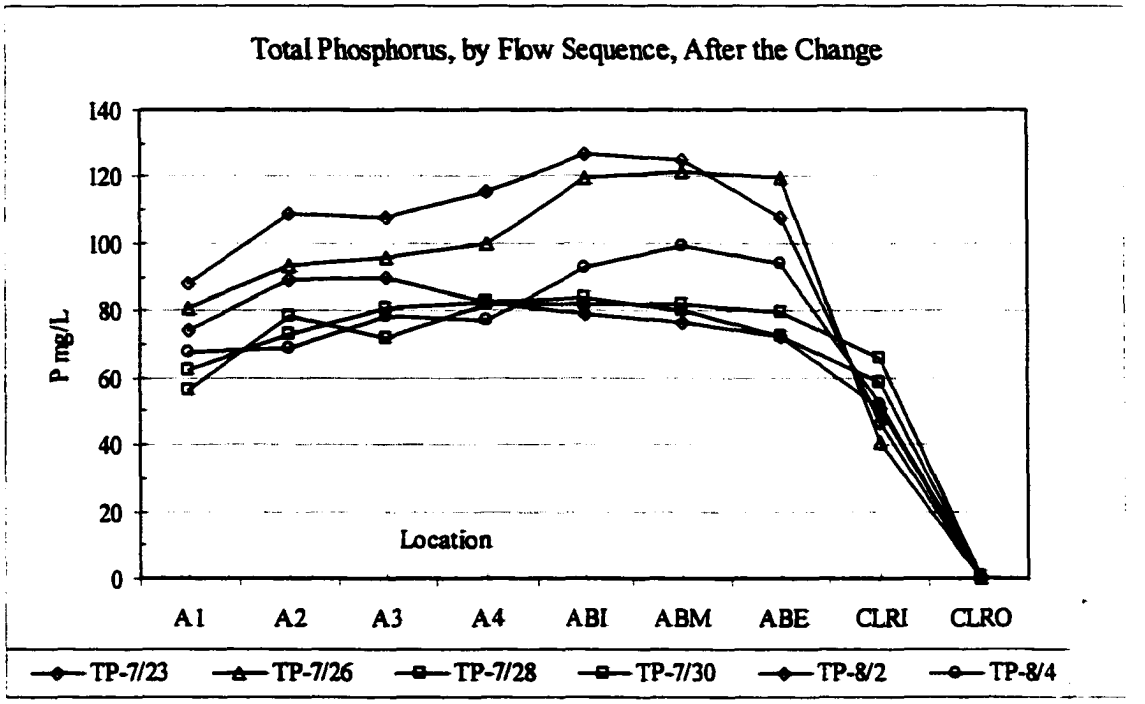

Figure 4.29 Total Phosphorus, by Flow Sequence, After the Change

Table 4.10 TP and OP Concentrations, Anaerobic Zones, Unfiltered Samples

	A1		A2		A3		A4	
	TP	OP	TP	OP	TP	OP	TP	OP
Before					*mg/L*			
Average	49.4	9.9	54.2	9.9	51.5	10.4	50.4	10.4
Stdev	29.5	2.1	24.2	1.3	21.8	1.6	21.6	1.2
After					*mg/L*			
Average	77.1	10.9	91.7	11.3	88.3	11.3	95.8	11.0
Stdev	15.6	1.8	17.1	2.9	18.9	2.7	14.8	2.7
After/Before-1					*(the change)*			
Average	56.2%	10.0%	69.1%	15.2%	71.6%	9.2%	90.2%	5.3%
Entire Period					*mg/L*			
Average	63.8	9.7	73.5	10.2	71.7	10.4	75.4	10.4
Stdev	24.4	2.3	24.8	2.6	24.8	2.4	26.3	2.3

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Table 4.11 TP and OP Concentrations, Aerobic and Clarifier Zones, Unfiltered Sample								
	ABI		ABM		ABE		CLRO	
	TP	OP	TP	OP	TP	OP	TP	OP
Before				*mg/L*				
Average	57.7	4.6	55.2	2.8	57.3	2.3	1.6	0.3
Stdev	26.3	1.9	25.7	1.9	24.5	1.1	2.5	0.3
After				*mg/L*				
Average	95.7	0.7	94.8	3.1	100.0	0.9	0.3	0.1
Stdev	21.1	0.7	25.7	1.6	16.7	0.5	0.1	0.0
After/Before-1				*(the change)*				
Average	65.9%	-84.4%	71.7%	11.5%	74.7%	-60.5%	-81.9%	-76.5%
Entire Period				*mg/L*				
Average	80.9	2.5	77.8	2.7	81.4	1.4	0.8	0.1
Stdev	29.8	2.6	28.9	1.7	27.4	1.1	1.7	0.2

4.2.6 Suspended Solids and COD

Figure 4.30 shows the COD for unfiltered samples by the flow sequence in basin #4. As can be seen, the COD seems to remain constant in the anaerobic zones, but decreases sharply in the settled effluent. Since this measurement includes contributions from the MLVSS, the disappearance of VFAs is difficult to see. However, if the COD is measured using filtered samples, the smaller, soluble fraction becomes very visible (Figure 4.31).

Figure 4.31 shows those soluble COD values, as measured from filtered samples taken during phase II of the BioP program. Observe that the soluble COD decreases from about 110 mg/L at the influent (CABI) to approximately 50 mg/L in cell A1. This is an indication that there is a large and immediate utilization of soluble COD within cell A1. From cell A1 to cell A4, there is a slow decrease in soluble COD.

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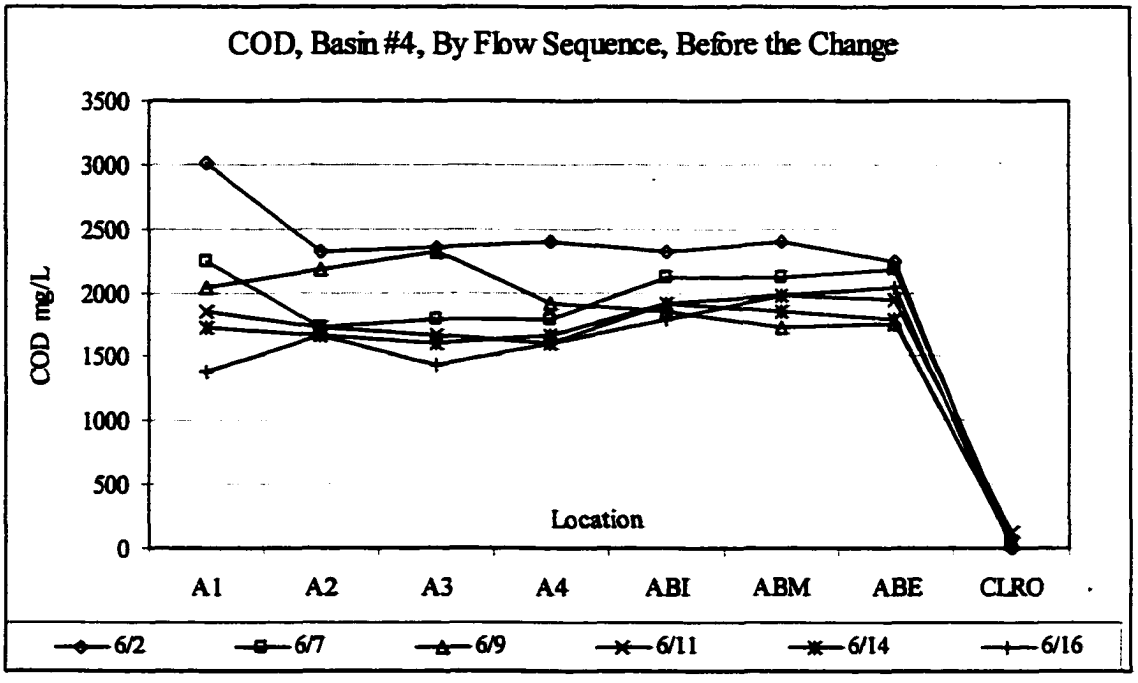

Figure 4.30 COD, Basin #4, by Flow Sequence, Before the Change

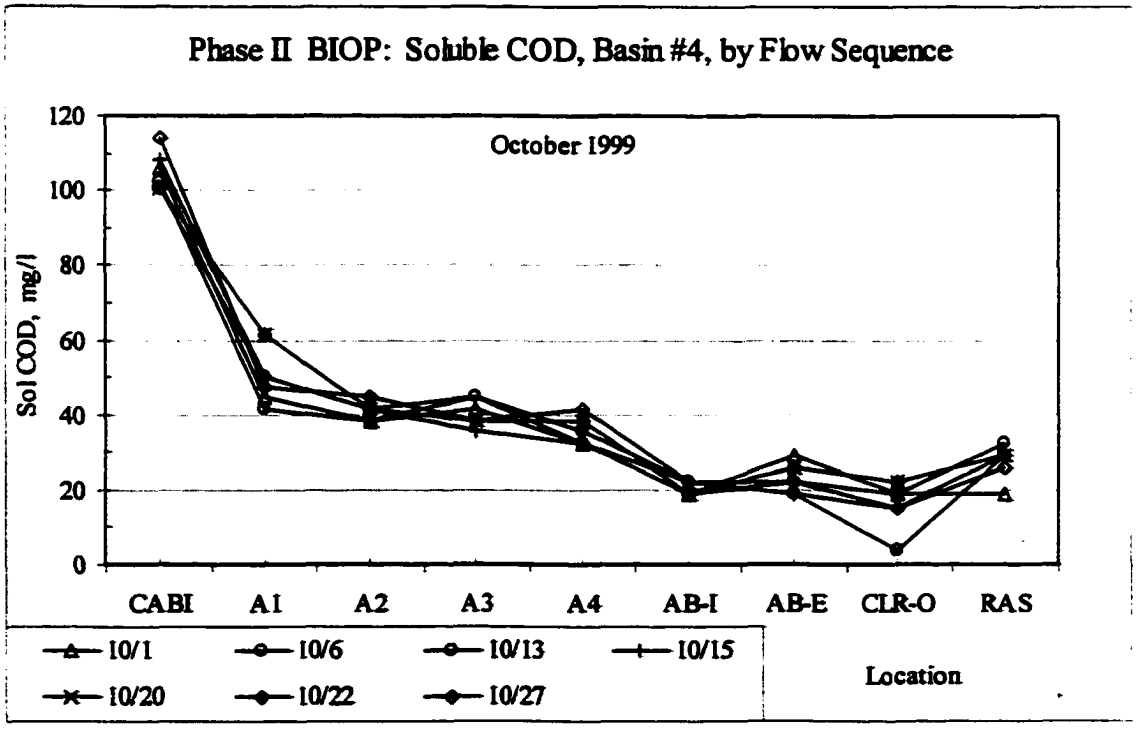

Figure 4.31 COD, Basin #4, by Flow Sequence, October 1999 (Phase II BIO-P)

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However, there is a sharp decrease in soluble COD after the flow enters the first aerated zone. The largest usage of soluble COD happens in cell A1 and in the ABI zone. In cell A1, the COD usage is related to biological phosphorus removal while in ABI (aerated) zone, it is related to carbonaceous BOD removal.

Figure 4.32 shows the volatile suspended solids (VSS) of basin #4 by flow sequence, during a few days in the phase II BIO-P program. The figure indicates that VSS increases very little in the anaerobic zones, but appears to rise more rapidly as the flow passes through the aerated zones.

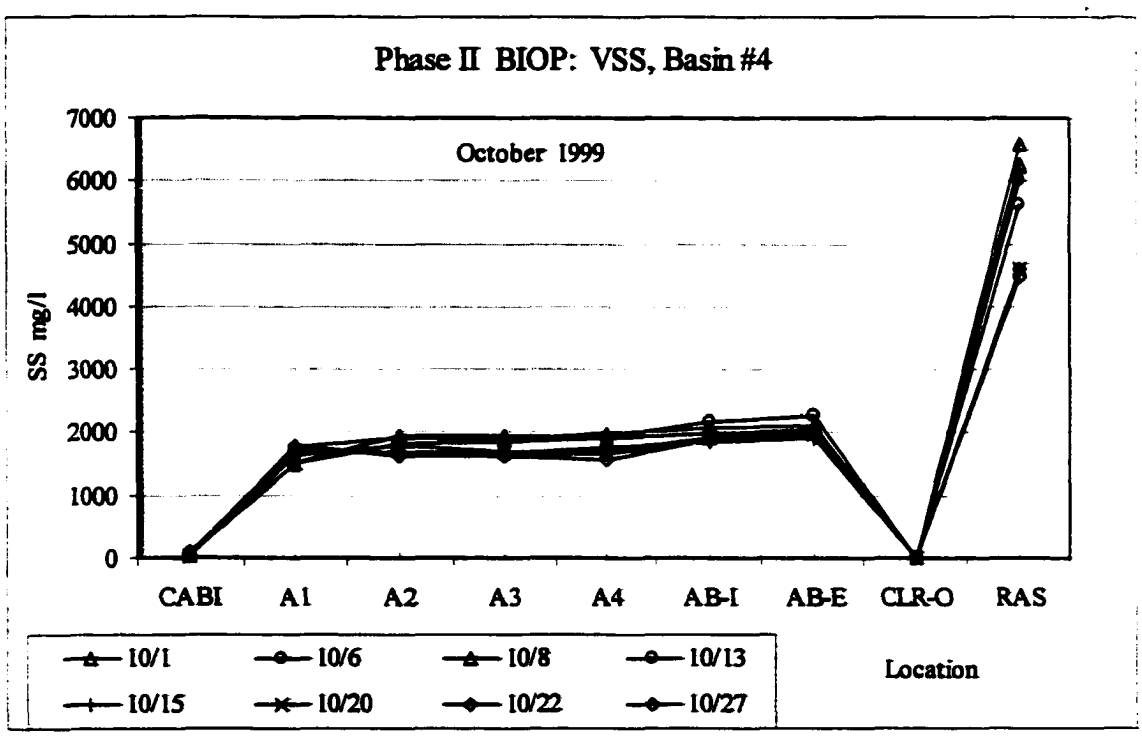

Figure 4.32 Volatile Suspended Solids (VSS), Basin #4, by Flow Sequence, Phase II

Averages, calculated from data used to plot the Figure, show that the VSS increases only 0.6 % (1779 to 1790 mg/L) while traveling from anaerobic cell A2 to A4,

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and increases 14.8 % (1790 to 2054 mg/L), while traveling from anaerobic cell A4 to the aeration basin effluent (ABE). Cell A1 is not used for reference because the mixing of the influents from the RAS and CABI flows may not be complete, as it is are by the time the flow has reached cell A2.

Figure 4.33 shows the combined behavior of the soluble COD (Figure 4.31) and soluble TP (Figure 4.27) for an unfiltered sample. Notice that in the anaerobic cells, the TP release increases with the flow sequence, while for the same sequence, the COD decreases. This confirms again, the relationship between P released and organic carbon usage in the anaerobic zones.

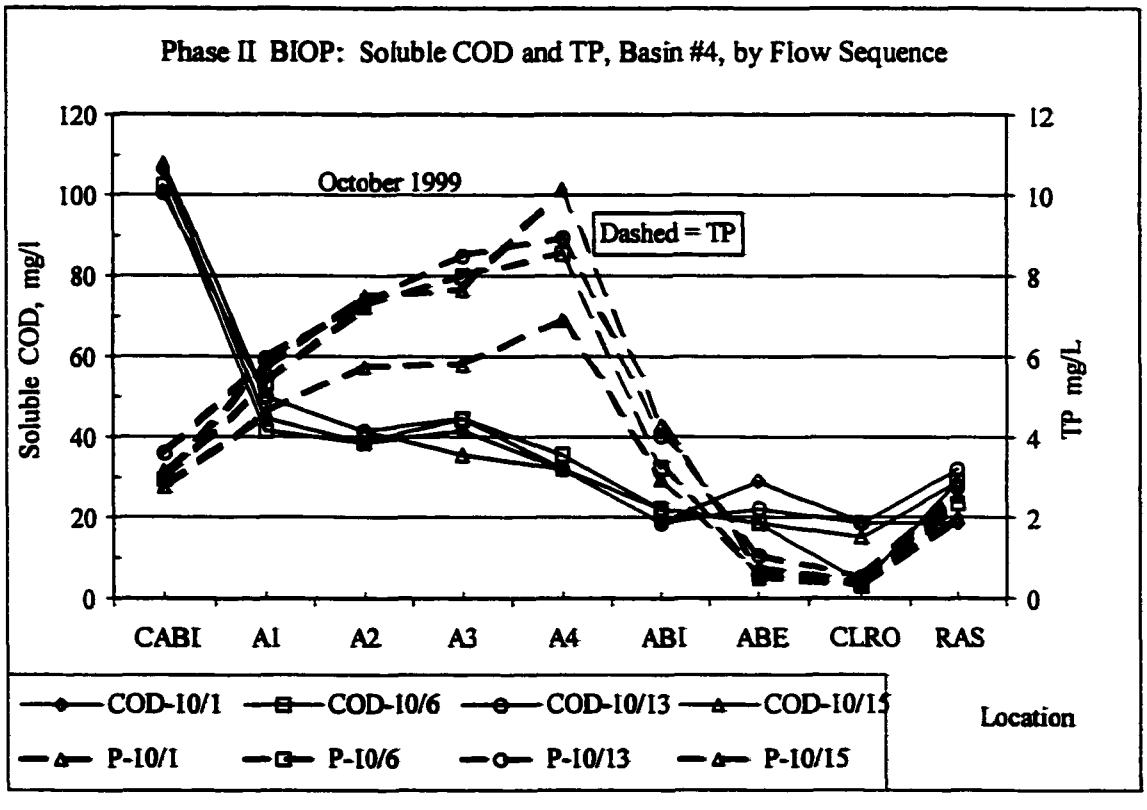

Figure 4.33 COD and Total P, Basin #4, by Flow Sequence, Phase II BIOP

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4.2.7 Microbiology, Basin #4

Figure 4.34 shows a Gram stained slide of a floc from cell A1. *Acinetobacter*, (Gram Negative) and *Nocardia* (Gram Positive) were identified as the major microorgainisms present. On the right, Acinetobacter appears as the plume shaped object, and at center and to the left are the filamentous *Nocardia* spp. Notice the large polyphosphate granules (dark, dotted points) inside the *Nocardia* filaments. This slide illustrates the abundance of polyphosphate stored within the PAOs at the beginning of the four anaerobic cells.

Figure 4.34 A Gram Stain Slide of PAOs From Anaerobic Cell A1, Basin #4, Using a Phase Contrast Lens of 100X, and Ocular Power of 10 X

Figure 4.35 shows a Gram stained slide of a floc from cell A4. Notice the Gram Negative and Gram Positive nature of the floc. Notice also, that some of the Noccardia

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filaments are free of polyP and appear almost transparent. This is an indication that polyP has been released and converted to OP.

Figures 4.36 and 4.37 show the composition of the microbial floc in cell A4. A cluster of Acinetobacter (Figure 4.36) and a cluster of Acinetobacter with extended *Nocardia* (Figure 4.37) are seen, reinforcing the fact that these two species are the most PAOs to be found in this process.

Figure 4.38 shows filaments of *Nocardia* spp. with polyP (dark granules) and chunks of PHA outside and inside the floc. Figure 4.39 shows that agglomerated PHA, that is found free in the media. These two Figures clearly demonstrate PHA formation by the time the flow has reached cell A4.

Figure 4.40 is a Gram stained slide of foam occasionally found at basin #4. Notice the overwhelming Gram Negative of the floc which has been identified as *Nocardia*. Therefore, Nocardia has a dual role in the biological process taking place in basin #4. On the one hand, *Nocardia* is a PAO microorganism, and therefore important in removing phosphorus from the effluent. On the other hand, *Nocardia* becomes a nuisance, causing foaming throughout the entire treatment unit. The investigation of conditions that promote foaming and the identification of possible remedial actions to solve this problem is the subject for another study.

All the slides shown this far prove that a true, biological phosphorus removal process is taking place at the Clark County Sanitation District.

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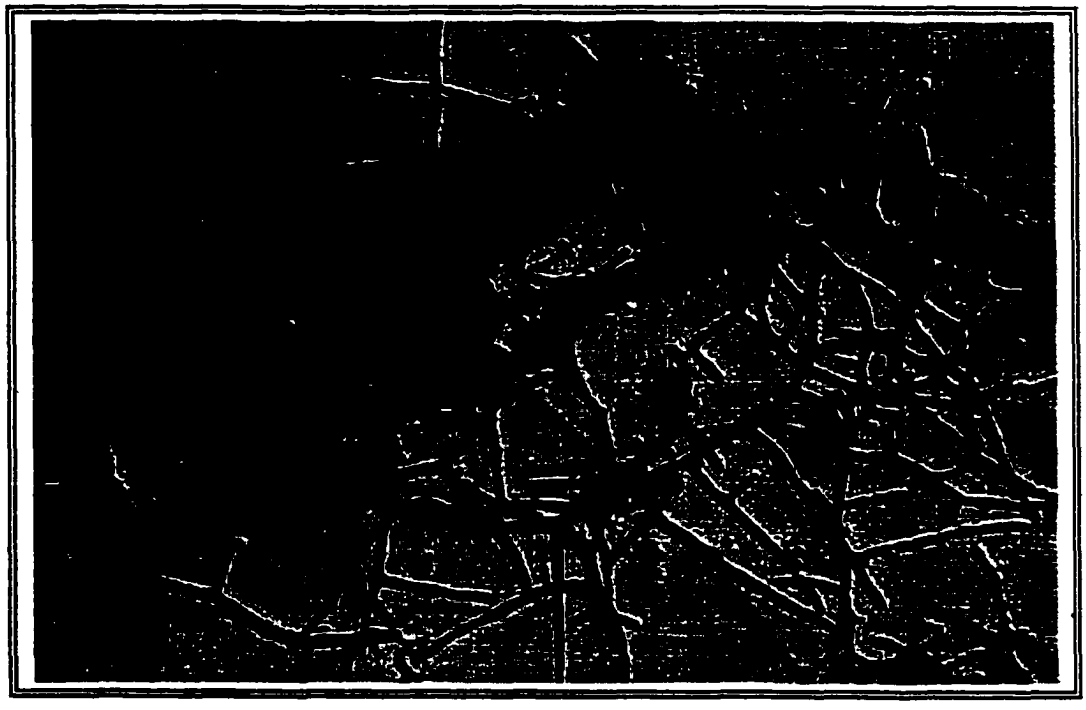

Figure 4.35 A Gram Stain Slide of PAOs From Anaerobic Cell A4, Basin #4, Using a Phase Contrast Lens of 100X, and Ocular Power of 10 X

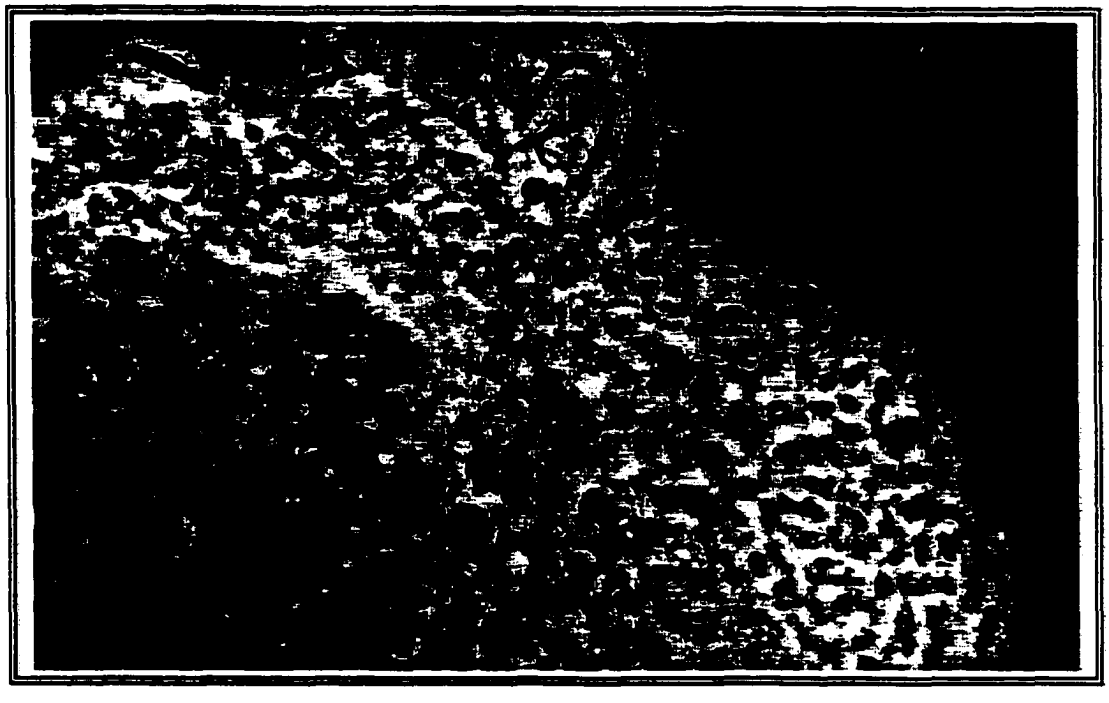

Figure 4.36 A Cluster of Acinetobacter From Anaerobic Cell A4, Basin #4, Using a Phase Contrast Lens of 100X, and Ocular Power of 10 X

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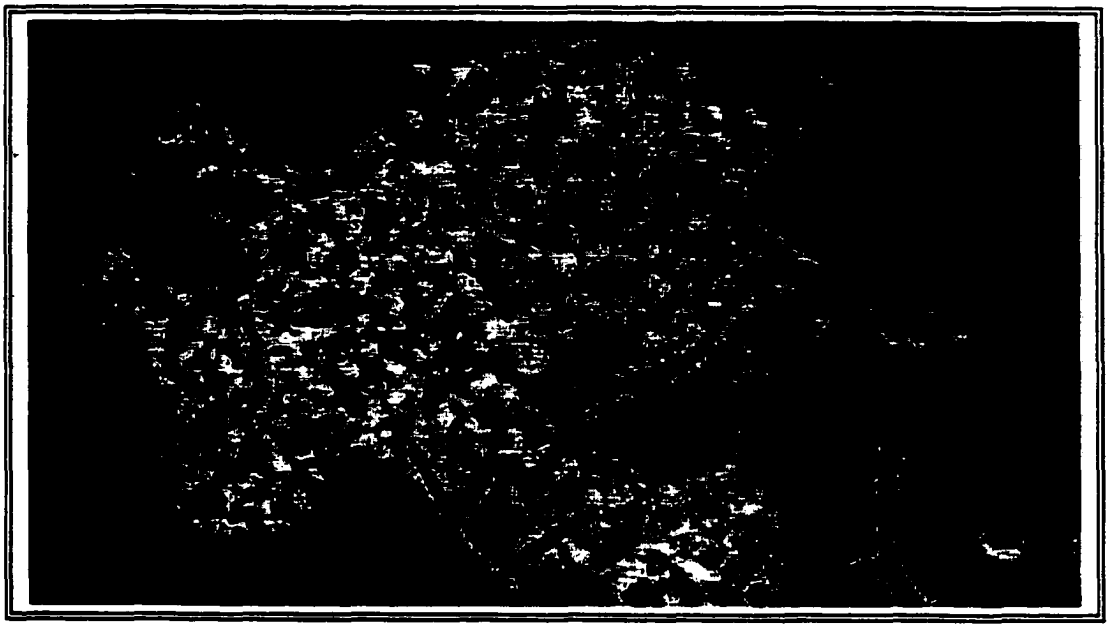

Figure 4.37 A Cluster of Extended Nocardia From Anaerobic Cell A4, Basin #4, Using a Phase Contrast Lens of 100X, and Ocular Power of 10 X

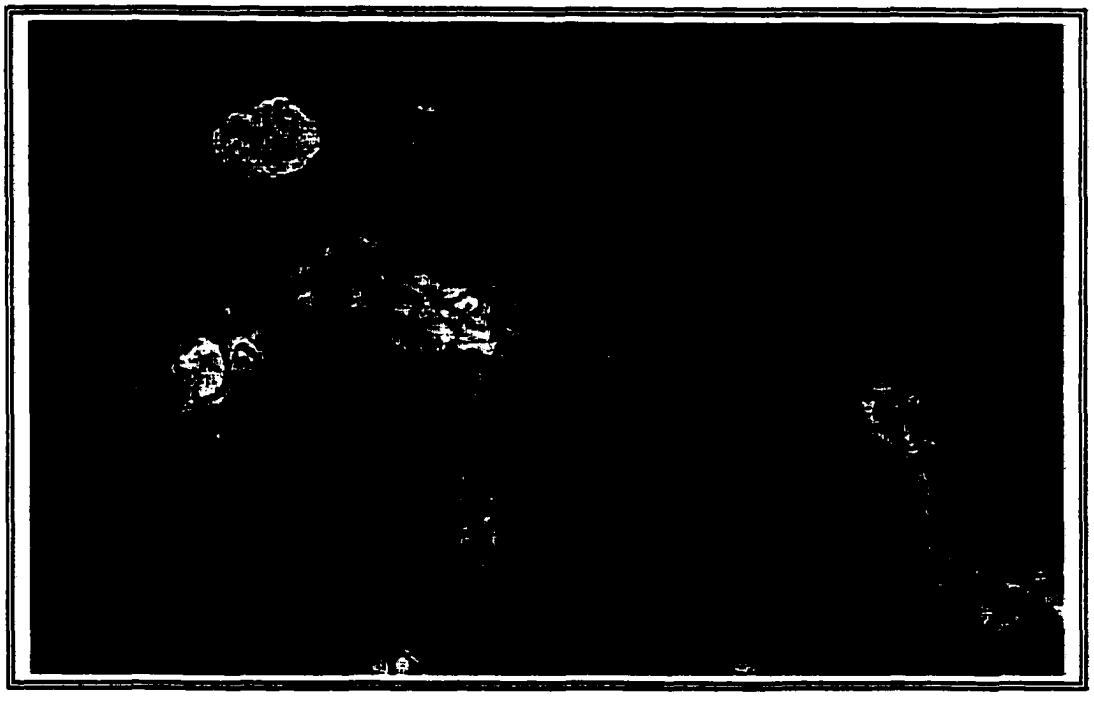

Figure 4.38 A Cluster of Nocardia and PHA Granule, From Anaerobic Cell A4, Basin #4, Using a Phase Contrast Lens of 100X, and Ocular Power of 10 X

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Figure 4.39 A Cluster of Nocardia From Anaerobic Cell A4, Basin #4, Using a Phase Contrast Lens of 100X, and Ocular Power of 10 X

Figure 4.40 A Gram Stain of Foam from Basin #4, Using a Phase Contrast Lens of 100X, and Ocular Power of 10 X

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4.3 Inter-Basin Measurements

This section evaluates and characterizes plant operating parameters during the experimental periods, and how they affect basin #4 performance.

4.3.1 Mass Balance of Phosphorus Throughout the Plant

This section evaluates the amount of phosphorus removed in the plant primaries, the combined (eight) plant basins, and basin #4 individually. Since the change in SRT took affect only in basin #4, the comparison of phosphorus removal between these unit processes places a perspective on the effluent measurements of basin #4 alone.

Figure 4.41 and Tables 4.12 and 4.13 summarize the overall mass balance in basin #4 and in the plant. Shown Figure 4.41, are the plant influent TP concentration, the TP concentration removed in the primaries, and the TP lost in basin #4.

The concentrations and losses, identified by their plant sampling location label, are calculated as follows:

Influent P concentration = PI (daily composite sample)

Loss in the primaries = PI-CABI (daily composite sample)

Loss in basin #4 = CABI-AB4 (daily plant and basin #4 composite sample)

Table 4.12 shows that the average influent TP concentration was 5.8 mg/L, and 6.07 in the "after" period. Table 4.13 shows average OP concentration in the effluent was 2.88 mg/L in the "before" period, and 2.66 mg/L in the "after" period. However, the changes are not statistically significant when compared to the standard deviations (Table 4.12 and 4.13).

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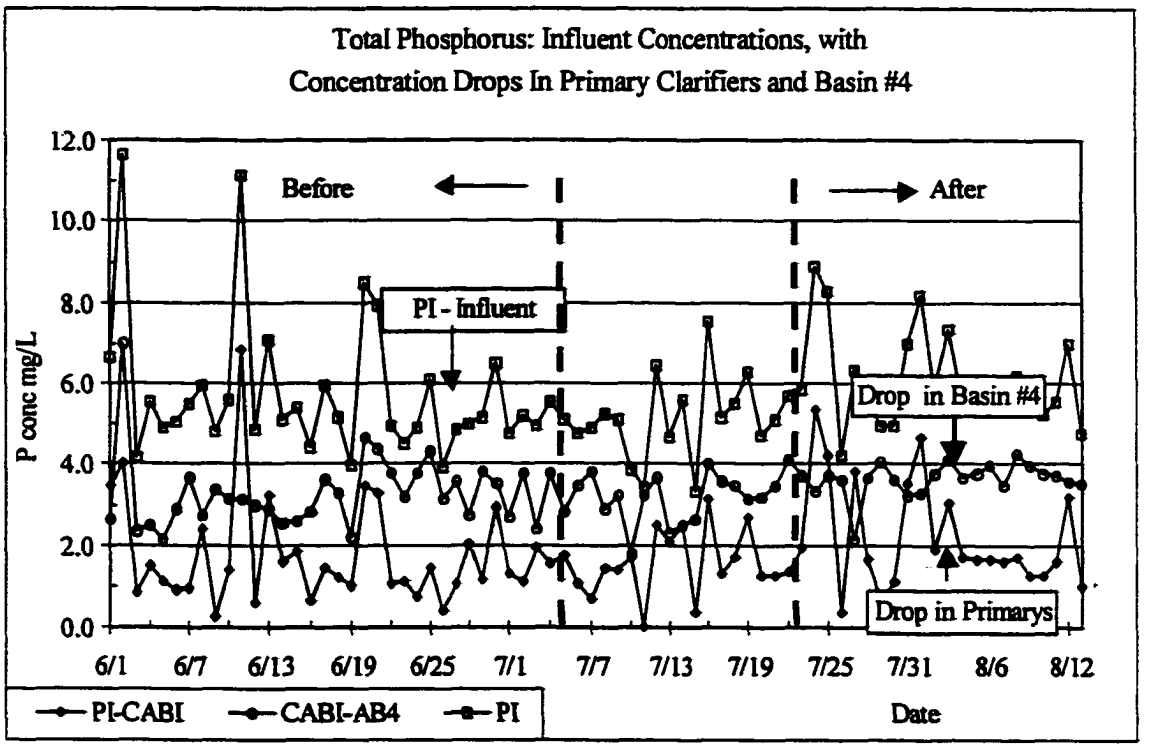

Figure 4.41 Absolute TP Concentrations Lost in Primary Clarifiers and Basin #4

Table 4.12 Total Phosphorus Concentrations Removed in Unit Processes						
	24 hour Composite					Grab
	Plant Inf	Basin Inf	Primaries	Plant	Basin #4	Basin #4
	PI	CABI	PI-CABI	CABI-CE	CABI-AB4	CABI -
Before	*mg/L*	*mg/L*	*mg/L removed*			
Average	5.83	3.99	1.84	3.68	3.29	3.30
Stdev	2.28	0.80	1.72	0.78	0.88	0.76
After	*mg/L*	*mg/L*	*mg/L removed*			
Average	6.07	3.90	2.17	3.70	3.65	3.61
Stdev	1.19	0.41	1.34	0.39	0.42	0.20
After/Before - 1		*(the change)*	*"+" means a greater loss for the*			
Average	4.3%	-2.3%	18.5%	0.7%	10.9%	9.5%
Entire Period	*mg/L*	*mg/L*	*mg/L removed*			
Average	5.77	3.87	1.91	3.62	3.36	3.38
Stdev	1.83	0.68	1.47	0.66	0.74	0.63

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Similarly, the changes in absolute phosphorus concentration lost in the primaries for the period under consideration were not statistically significant. For basin #4 however, a 10.9% increase in phosphorus lost was detected.

Table 4.13 Ortho Phosphorus Concentrations Removed in Unit Processes						
	24 hour Composite					Grab
	Plant Infl.	Basin Infl.	Primaries	Plant	Basin #4	Basin #4
	PI	CABI	PI-CABI	CABI-CE	CABI-AB4	CABI-
Before	*mg/L*	*mg/L*	*mg/L removed*			
Average	2.88	1.77	1.11	1.63	1.20	1.59
Stdev	0.29	0.24	0.40	0.20	0.34	0.24
After	*mg/L*	*mg/L*	*mg/L removed*			
Average	2.66	1.68	0.98	1.60	1.50	1.62
Stdev	0.22	0.27	0.41	0.27	0.26	0.32
After/Before-1		*(the change)*	*"+"means a greater loss for the differences*			
Average	-7.7%	-5.3%	-11.5%	-2.1%	25.2%	1.8%
All Periods	*mg/L*	*mg/L*	*mg/L removed*			
Average	2.725	1.63	1.09	1.52	1.26	1.50
Stdev	0.306	0.32	0.39	0.30	0.34	0.34

Figure 4.42 and Table 4.14 show the phosphorus removal in the (averaged) primary clarifiers and (averaged) aeration basins in terms of absolute efficiencies. The functions used to calculate absolute removal efficiency (relative to plant influent) are also given in Table 4.14 above each column of numbers. A five-day running average for each efficiency profile is also shown.

In other words, the maximum storage capacity of the microbes cells has not been reached, and additional amounts of phosphorus might be removed biologically in the basins. Availability of this resiliency uptake potential is essential to maintaining a low, effluent TP level, and it implies that less $FeCl_3$ could be used. However, further studies are needed to explore the ultimate limitations of the BioP removal system.

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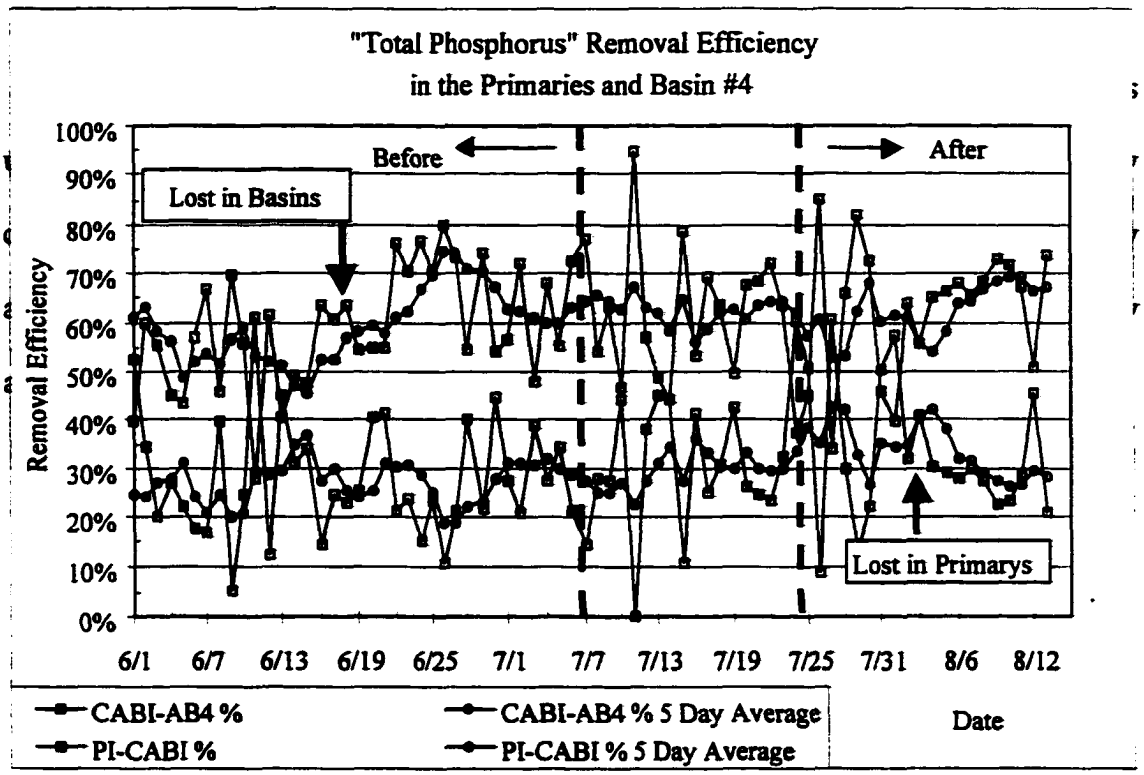

Figure 4.42 TP Absolute Removal Efficiencies in Primary Clarifiers and Basin #4

Table 4.14 shows that about 32% of the influent TP is removed in the primaries by $FeCl_3$ coagulation, while about 63% of the TP is removed biologically in the plant's basins. The Table also shows that P removal in basin #4 (56.5%) during the "before" period, was somewhat lower than the rest of the plant.

However, as the conditions became more stable, basin #4 began to operate like the rest of the plant. It is interesting to notice, that the phosphorus removal in basin #4, calculated from the 24 hour composite (AB4) and from the once a day grab data (CLRO), gives very similar results (Table 4.14).

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Table 4.14 Absolute Removal Efficiency (to PI Conc) for TP and OP								
	Primary (PI-CABI)/PI		Basins (Plant) (CABI-CE)/PI		Basin #4 (AB4) (CABI-AB4)/PI		Basin #4 (Grab) (CABI–CLRO)/PI	
	TP	OP	TP	OP	TP	OP	TP	OP
Before				*fraction of the total influent*				
Average	31.5%	38.5%	63.2%	56.7%	56.5%	41.5%	56.6%	55.3%
After				*fraction of the total influent*				
Average	35.8%	36.9%	61.0%	60.1%	60.1%	56.4%	59.5%	61.0%
After/Before-1				*(the change)*				
Average	13.6%	-4.1%	-3.5%	6.0%	6.3%	35.7%	5.0%	10.3%
All Periods				*fraction of the total influent*				
Average	33.0%	40.1%	62.6%	55.9%	58.2%	46.3%	58.6%	55.0%

Table 4.15 continues with the same theme of Figure 4.42 by displaying the relative removal efficiencies for the two SRT periods. The word 'Relative' means relative to the influent of the Unit process under scrutiny. The equations used for these calculations is given at the top of each column in the table. Table 4.15, column #2 also indicates that the (average) plant basin efficiency in removing TP began at about 92%. Notice that during the "before" period, basin #4 efficiencies were slightly less than the eight basin (plant) average, but during the "after" period, increased to nearly the same removal efficiencies as the rest of the plant. During that same period, basin #4 was prevented from becoming more efficient, because it had already reached the upper efficiency limits (section 4.3.3).

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Table 4.15 TP and OP Relative Removal Efficiency (to Influent Conc at PI)								
	Primaries		Basins (Plant)		Basin #4		Basin #4 (Grab)	
	1-CABI/PI		1-CE/CABI		1-AB4/CABI		1-CLRO/CABI	
	TP	OP	TP	OP	TP	OP	TP	OP
Before								
Average	31.5%	38.5%	92.3%	92.2%	82.5%	67.5%	86.8%	88.9%
After								
Average	35.8%	36.9%	95.0%	95.3%	93.6%	89.3%	93.0%	96.8%
After/Before – 1								
Average	13.6%	-4.1%	3.0%	3.4%	13.4%	32.3%	7.2%	8.9%
All Periods								
Average	33.0%	40.1%	93.5%	93.4%	86.9%	77.3%	90.3%	92.4%

4.3.2 Phosphorus Removal Efficiencies in Primaries, $FeCl_3$ Addition

Ferric chloride, $FeCl_3$, is used as a type II coagulant and added to the influent wastewater to improve primary sedimentation. It is added just above the two plant sampling points CPEI and CPWI, which are both above the primaries. Because phosphorus can also be removed from wastewater chemically by the addition of coagulants, such as $FeCl_3$ and aluminum sulfate ($Al_2(SO_4)_3$-14 H_20)), it was an objective of this research to determine what percentage of the influent P is removed chemically at the CCSD.

Figure 4.43 shows the $FeCl_3$ concentrations added above each primary group and the TP removal efficiency, relative to the influent P concentration at PI. As it can be seen, approximately 32% of the incoming TP is removed chemically in the primaries. Notice also that the addition of $FECL_3$ is relatively constant, despite the erratic nature of the P concentration chemically removed in the primaries. The reason can be seen in the erratic plant influent P concentrations at PI.

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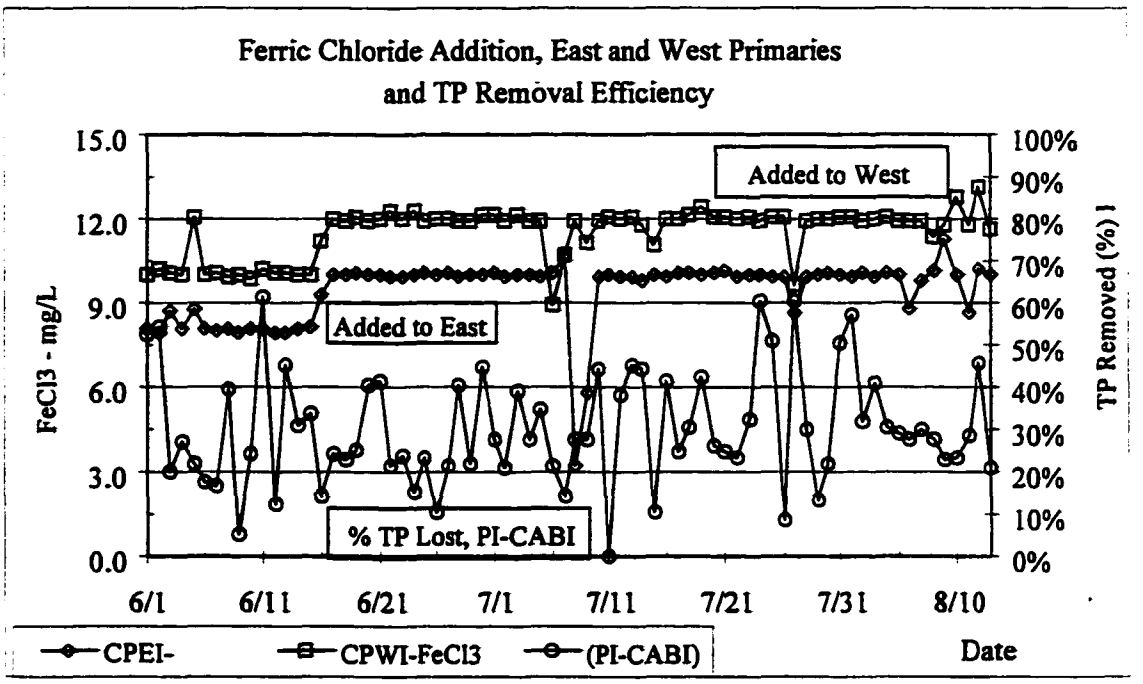

Figure 4.43 Ferric Chloride Addition to East and West Primaries, and TP Removal

Figure 4.44 shows the concentration of iron found in the water after the primaries (at CABI) and in the effluent of the plant basins (at CE). The two lines labeled CPWPE-After and CPEPE1-After represent the iron concentration measured in the effluent of the west and east primary groups, respectively.

The Figure indicates that most of the iron entering the primaries is taken out while passing through the coagulation and settling processes, leaving an exiting concentration of approximately 0.25 mg/L to enter the treatment basins. The average iron concentration leaves the aeration basins (CE) at about 0.1 mg/L, a removal of only 0.15 mg/L. This small loss of iron indicates that it does not contribute appreciably to chemical phosphorus removal in the basins.

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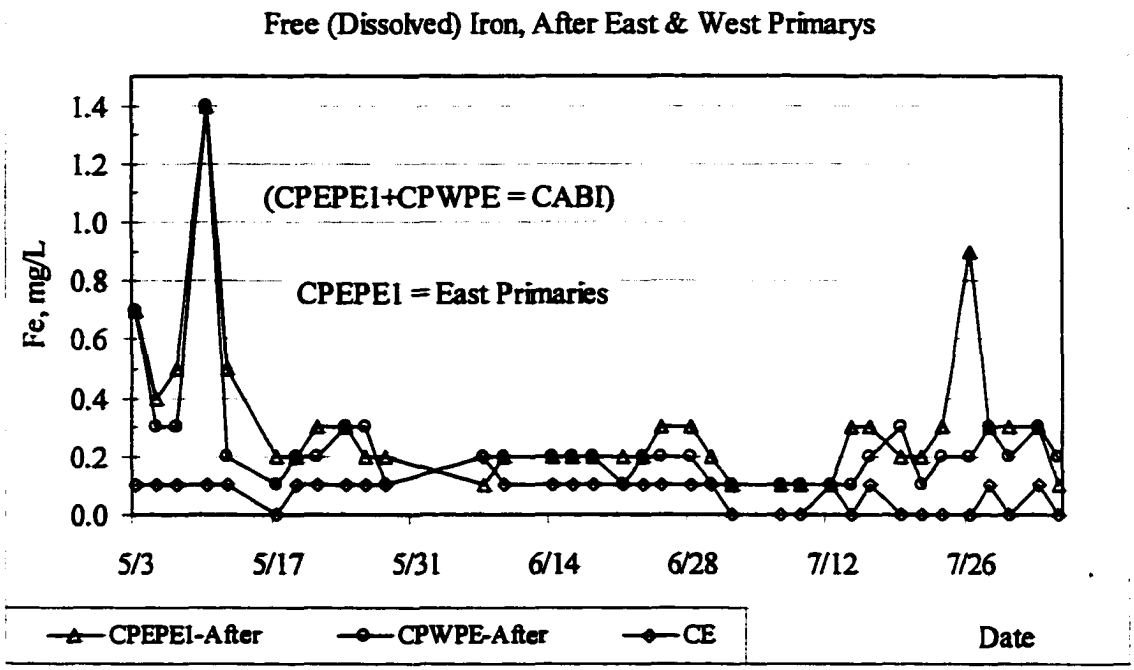

Figure 4.44 Dissolved Fe^{3+} Before and After the Primaries

4.3.3 Phosphorus Removal Efficiencies and BOD Concentrations

BOD supplies the energy necessary for uptake and storage of polyP. It also supplies energy for denitrification, and the catabolic and anabolic processes connected with carbonaceous BOD removal. After ten years of wastewater research, Qasim et. al., (1996) found a strong, statistical correlation between phosphorus removal and BOD_5 (the combined carbonaceous and nitrogenous five day oxygen demands). The two equations noted in section 2.2.3 are plotted in Figure 4.45 to illustrate this relationship.

Figure 4.46 displays the BOD_5_I (nitrogen inhibited, five day demand) and the BOD_5_U (nitrogen uninhibited, five day demand) taken from AWT Lab data at the influent to all plant aeration basins (CABI). The relative removal efficiency of basin #4, is also plotted and scaled on the right axis.

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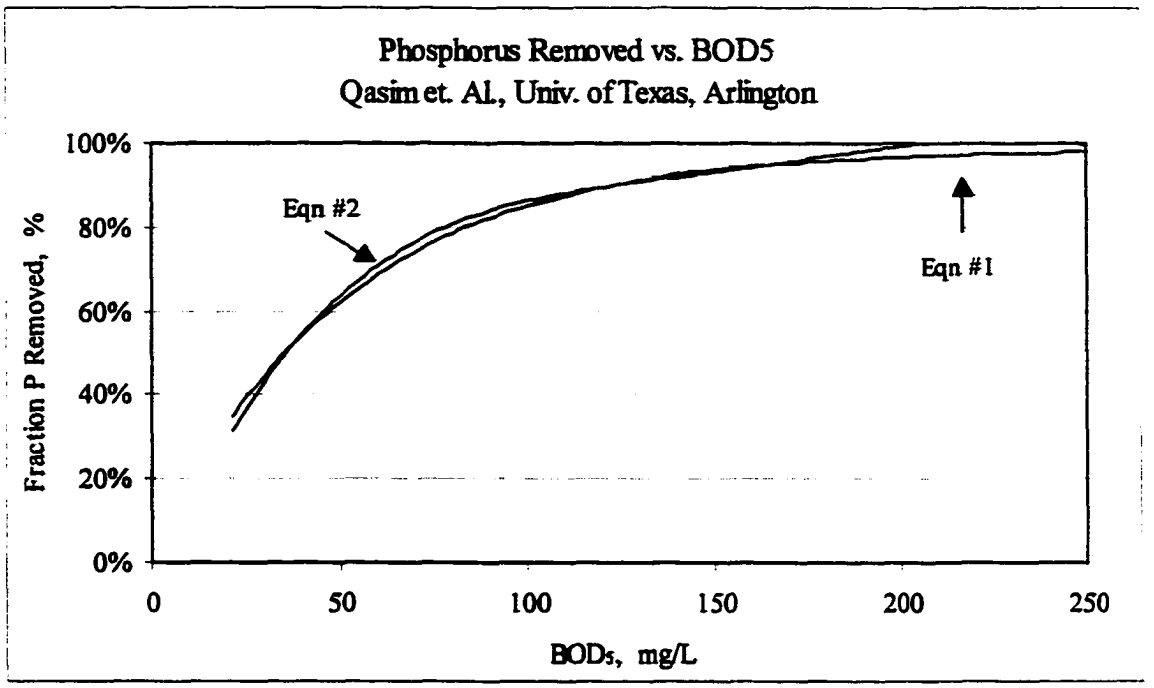

Figure 4.45 BOD_5 and P Removal Efficiency
From Qasim et. al., 1999

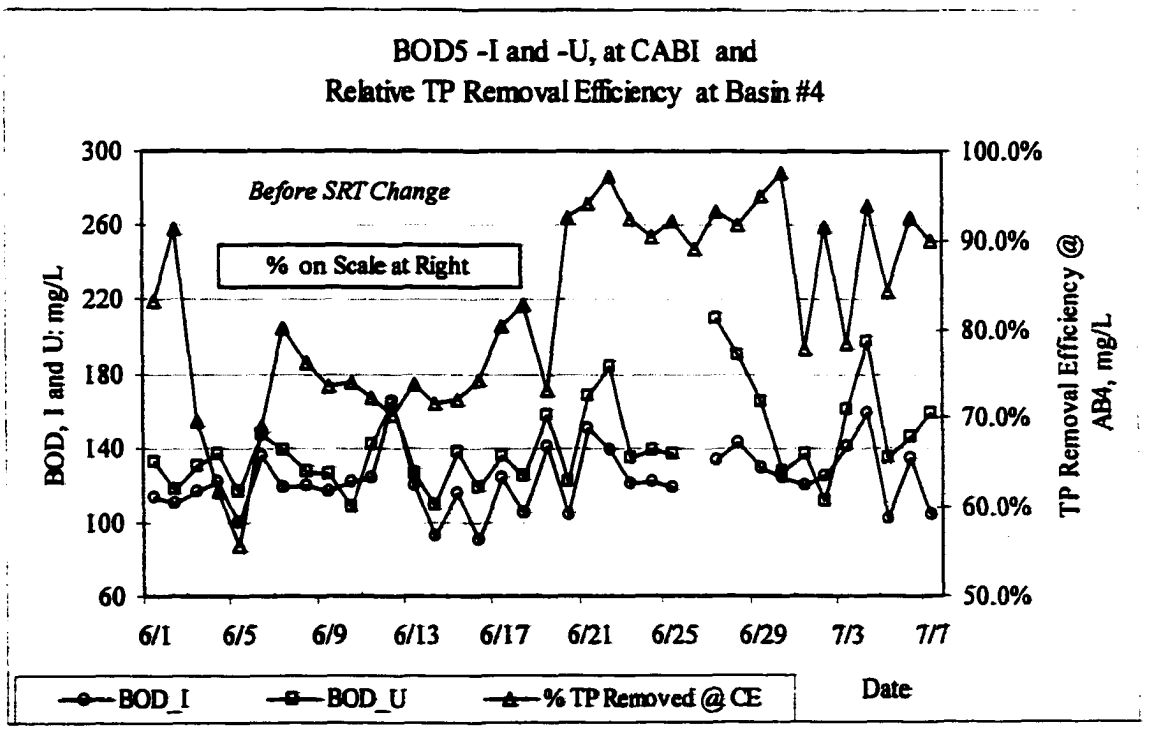

Figure 4.46 BOD_5_I, BOD_5_U, and TP Removal Efficiency, Before the Change

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As can be seen, basin #4 begins the "before" period with an efficiency somewhat lower than at the end of the "before" period, despite the fact that the BOD changed little over the entire period. Figure 4.47 profiles the same data during the "after" period. One clear observation is that removal efficiency is nearly constant and very high throughout the entire period.

Table 4.16 shows that the BOD_5-U at the basin influent decreased in basin #4 from 145.2 mg/L to 126.1 mg/L, while the TP removal efficiencies increased from 82.5% to 93.6% (Table 4.15). This shows that removal efficiencies can vary independently of BOD, even though long term relationships, such as those from Qasim (Figure 4.45), have been discovered.

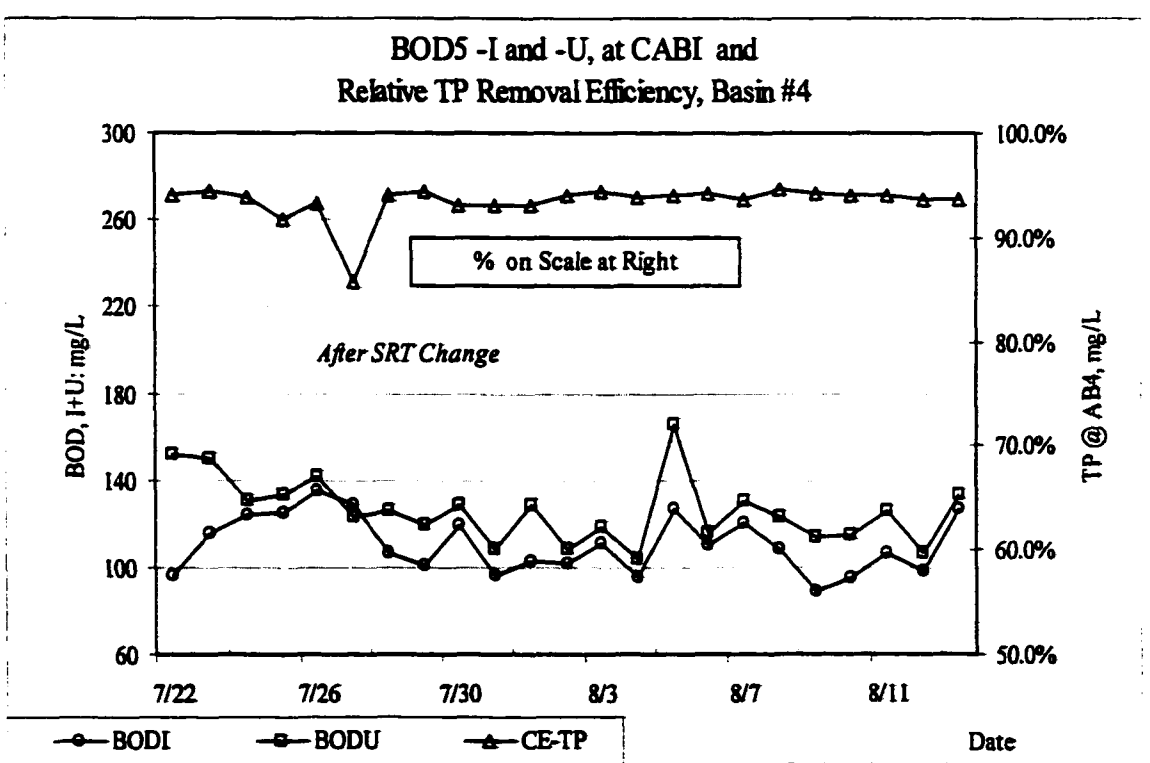

Figure 4.47 BOD_5_I, BOD_5_U, and TP Removal Efficiency, After the Change

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Table 4.16 SRT BOD_5-I, -U Concentrations in the Plant						
	CABI		CE Eff		(CABI – CE) Eff	
	BOD_5-I	BOD_5-U	BOD_5-I	BOD_5-U	BOD_5-I	BOD_5-U
Before			*mg/L*			
Average	122.8	145.2	5.8	10.3	113.9	109.5
Stdev	16.8	37.4	2.8	3.0	24.9	24.6
After			*mg/L*			
Average	110.3	126.1	5.2	8.7	105.1	101.7
Stdev	13.2	15.5	3.2	3.5	11.9	11.6
After/Before-1			*(the change)*			
Average	-10.1%	-13.2%	-9.3%	-16.0%	-7.7%	-7.1%
Entire Period			*mg/L*			
Average	115.4	142.6	5.3	9.3	108.6	104.7
Stdev	17.5	33.8	2.8	3.1	20.7	20.3

4.3.4 Phosphorus: Fractional Weight of the WAS

An indicator of success in the P removal process as cited in the literature, is the fractional weight of the phosphorus in the WAS. This parameter also assists in quantifying phosphorus concentrations found in the clarifier's effluent, which can be measured at CE, AB4 or CLRO.

Table 4.17 provides the equations used to calculate the fractional weight of P in the WAS, the P concentrations in the basin and RAS, the source of the data used, and the weight of WAS wasted each day.

The concentrations and additional parameters called out by the equations in Table 4.17 are taken from definitions identified by the control volume, shown in Figure 4.48 as a dotted line.

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Table 4.17 Fractional Weight Calculations, Phosphorus in WAS		
Description	Value, Units	Msmt Source
Microbe Conc, @AB4	MLSS, mg/L	SCADA
Wasted Sludge Conc, @AB4	WAS, mg/L	SCADA
Concentration of P Lost/Day	(CABI - AB4), mg/L	AWT, Plant Labs
Water Flow into @AB4	QAB4, in MGD	SCADA System
Weight of P Lost/Day	(CABI - AB4) * QAB4 * 8.34, lbs.	Calculation
WAS Flow/Day, @AB4	QWAS, MGD	SCADA System
Weight of WAS/Day	QWAS*WAS*8.34, lbs.	Calculation
Fractional Wt. of P in WAS	[(CABI - AB4) * QAB4]/[QWAS*MLSSWAS]	
Concentration of P in WAS	(Wt. of P Lost, lbs./Day)/(Wt. of QWAS, lbs./Day) mg/L	
Concentration of P in MLSS	(Concentration of P in WAS)*(MLSS/WAS) mg/L	

As an example, the Figure indicates that parameters using to calculate the quantity "Weight of P Lost/Day" is taken from the (daily) difference in concentrations between CABI and AB4, then multiplied by the daily (water) weight flow through basin #4. Internal flows and recycle flows of basin #4 are not taken into consideration. Therefore, the values calculated and presented in this section should be considered typical, rather then exact on a daily basis.

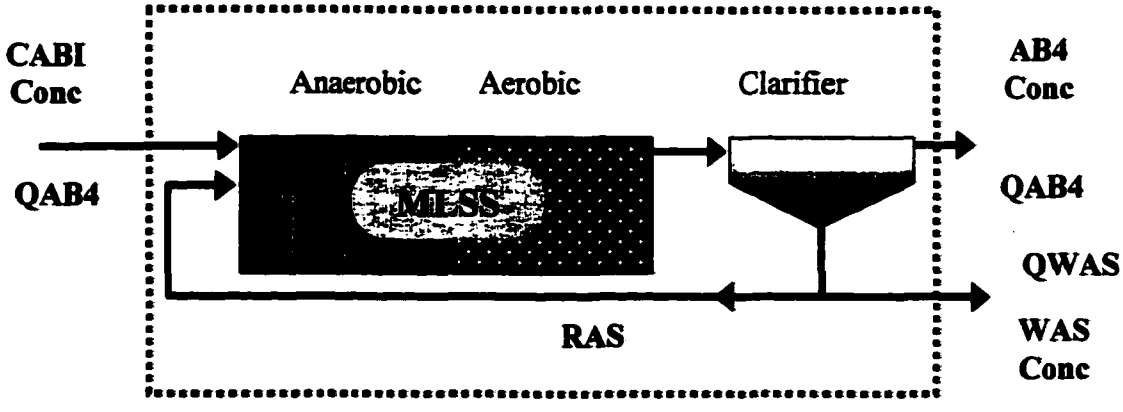

Figure 4.48 The Control Volume for Phosphorus Concentration Calculations

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Figures 4.49, 4.50, 4.51, and Table 4.18 describe the resulting fraction of TP and OP in the WAS that was calculated for the "before", transitional and "after" periods, relative to the SRT. Five day running averages were added to the Figures for reduction of uncertainties caused by the erratic, raw data. The Figures and Table indicate that the OP concentration is only about 25% of the TP value, whereas in the plant influent at PI, the OP was about 50% of the TP value. This indicates that about half of the OP at PI was converted into TP in the aeration basins by the biological phosphorus removal process, also pointing out that luxury uptake is occurring.

Figure 4.49 and 4.51, covering the "before" and "after" periods, show that the fractional weight of P can vary between 3% and 5.5% during periods when the SRT is stable.

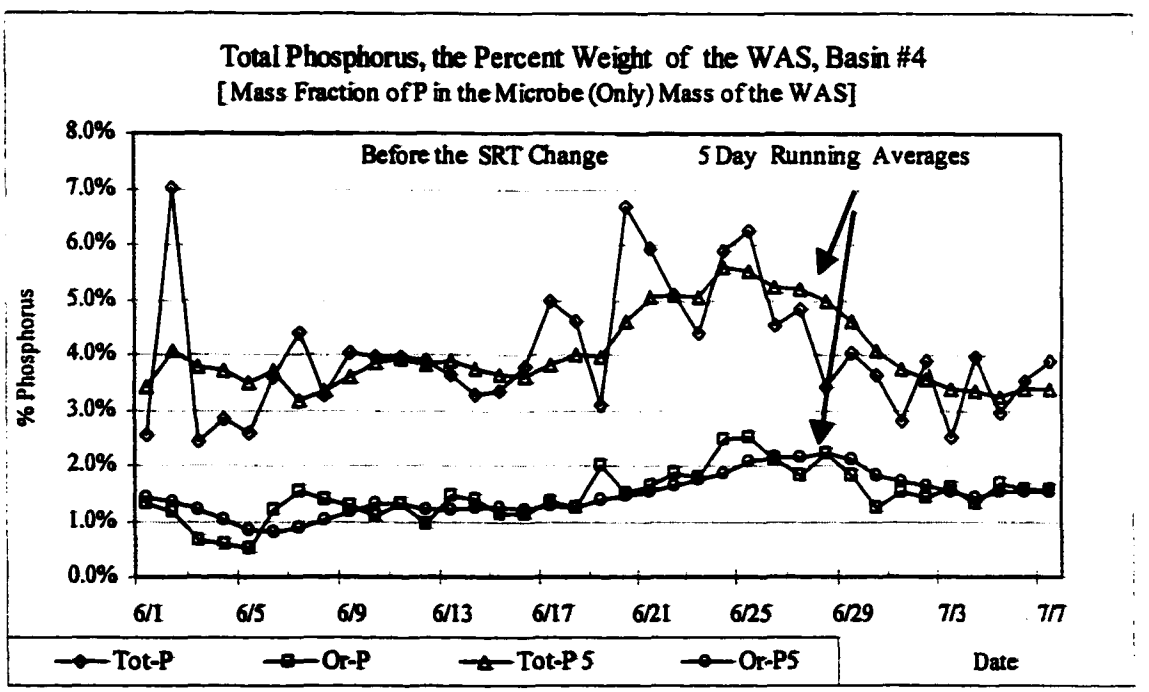

Figure 4.49 Fractional Weight of Phosphorus in the WAS, Before the Change

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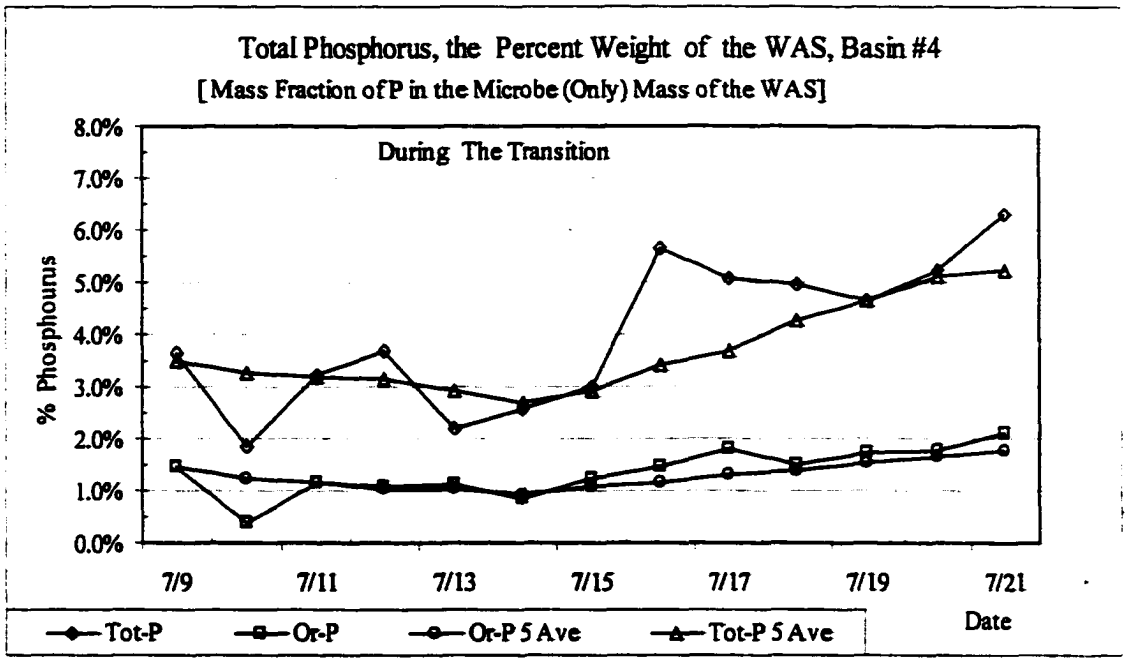

Figure 4.50 Total Phosphorus, the Percent Weight of the WAS, During Transition

These fractional weight levels are comparable to those found in other BIO-P removal systems described in the literature, and specifically by Matsuo et. al. (1994), Fukase et. al. (1984) and Liu et. al. (1997). A summary of fractional weight of P, evaluated by many researchers is also given in Table 2.3.

Table 4.18 verifies that the average fractional weight of P did not change significantly when the SRT was increased. Figure 4.50 plots the transition period from 7/12 to 7/21, and primarily illustrates the upward ramp in the fractional weight of P during this period. The fractional weight of P is shown to increase while the wasting rate of basin #4 was radically reduced, while increasing the MLSS concentration.

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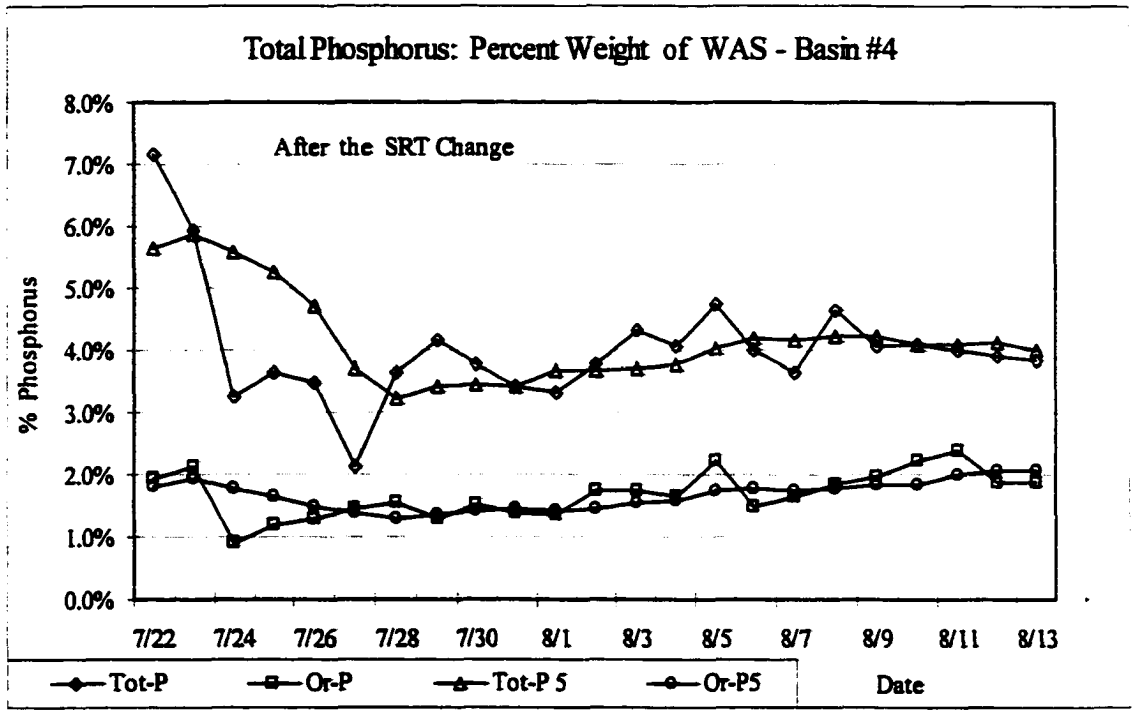

Figure 4.51 Total Phosphorus, Percent weight of the WAS, After the Change

Figure 4.51 shows that during the "after" period, the increased fractional weight of P returned quickly (within two days) to approximately the same value (4%) as that in the "before" period. For this reason, the WAS related calculations began on 7/24, rather than 7/22, considered to be the formal beginning for the higher SRT period.

Table 4.18 Summary: Fractional Weight of Phosphorus in the WAS					
	TP	OP		TP	OP
Before 6/1 – 7/7			*Entire Period 6/1 – 8/13*		
Average	4.04%	1.46%	Ave	4.03%	1.51%
Stdev	1.16%	0.46%	Stdev	1.13%	0.44%
After 7/22-8/13			*After/Before -1*		
Average	4.05%	1.68%	Ave	0.20%	14.8%
Stdev	0.97%	0.37%	Stdev	-16.8%	-18.8%

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Figure 4.52 displays the concentration of P in the WAS (mg/L) as calculated by equations given in Table 4.17. The Figure shows that the WAS concentration for both TP and OP increased 75% and 96%, respectively, during the "after" period. This increase in concentration corresponds roughly to the increased WAS concentration (5,000 mg/L to 12,000 mg/L), shown in Figure 4.38.

Figure 4.53 and Table 4.19 show that the increase of TP and OP concentrations in the MLSS (52.2% and 71.2%, respectively), experience a lower rate of increase as those in the RAS (75.5% and 96.1%, respectively). This is due to the fact that the MLSS concentration did not increase in the same proportion as the RAS concentration during the higher SRT period (Figure 4.3).

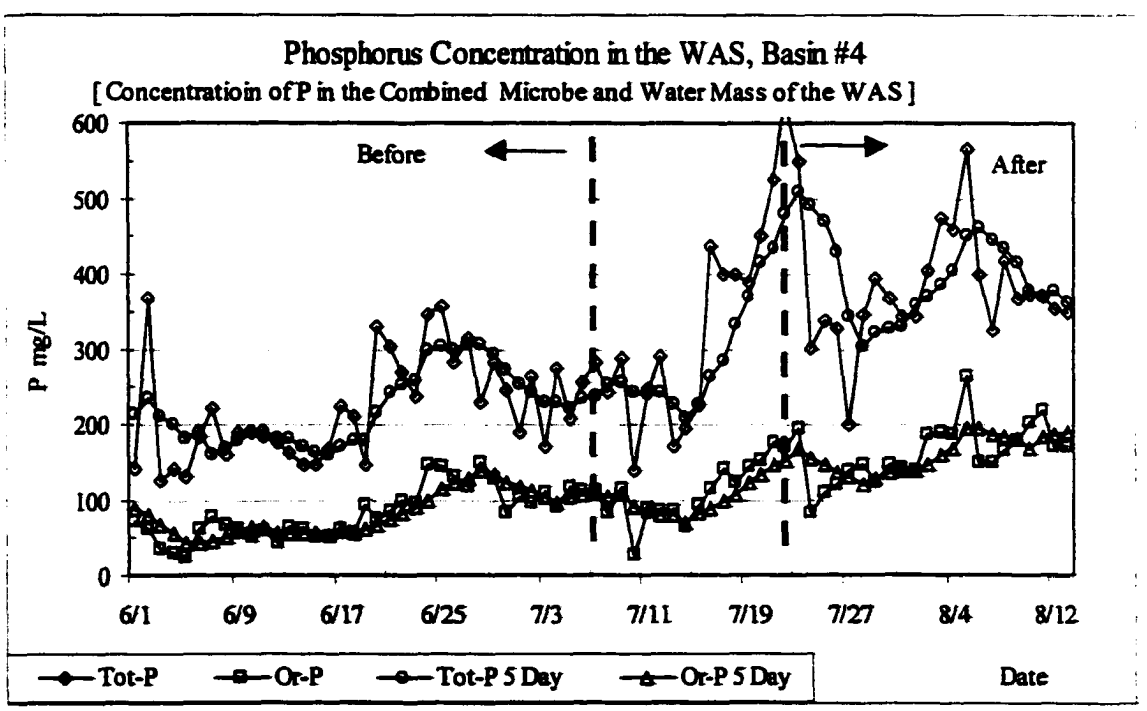

Figure 4.52 Phosphorus Concentration in the WAS, Basin #4

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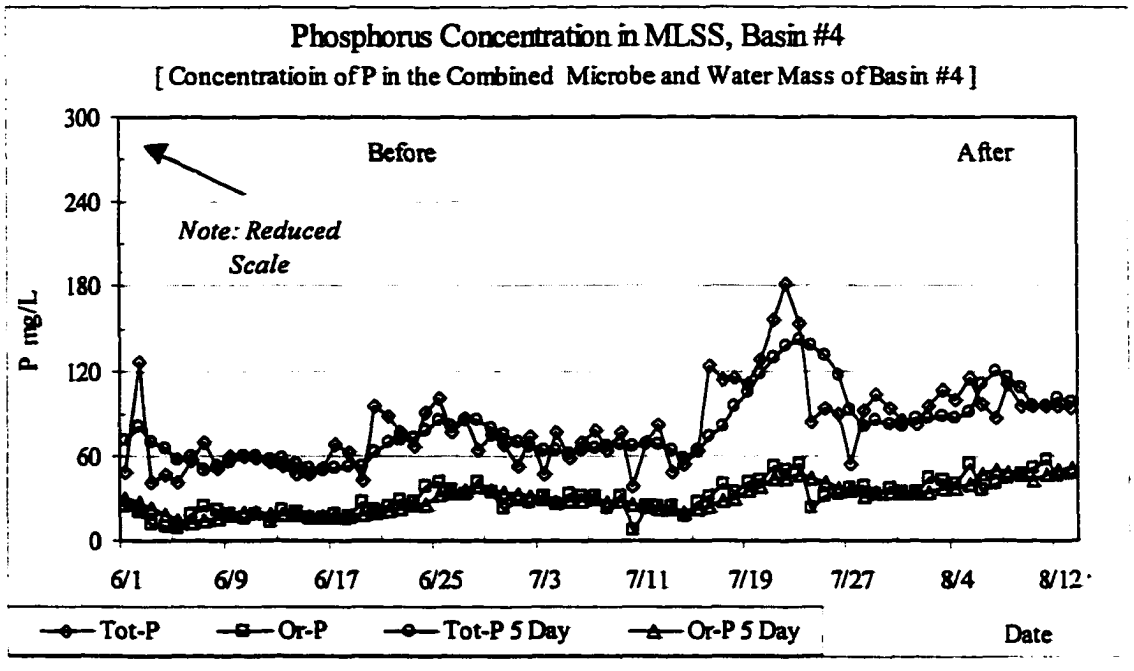

Figure 4.53 Phosphorus Concentration in Basin #4

Table 4.19 shows that the TP concentration in the MLSS is 65.7 mg/L during the "before" period, and rises to 100 mg/L during the "after" period.

Table 4.19 Statistics: Phosphorus Concentrations in the MLSS and WAS

	MLSS P Conc (calculated)		WAS P Conc (calculated)	
	TP	OP	TP	OP
Before		*mg/L*		
Average	65.7	24.2	223.3	83.1
Stdev	18.8	8.4	68.9	33.6
After		*mg/L*		
Average	100.0	41.4	391.8	163.0
Stdev	24.7	8.5	93.4	39.0
After/Before-1		*(the change)*		
Average	52.2%	71.2%	75.5%	96.1%
Entire Period		*mg/L*		
Average	80.8	30.6	293.0	112.4
Stdev	28.7	11.8	114.5	50.4

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These concentrations were also measured directly by the AWT Labs (Figures 4.28 and 4.29), and the results are nearly equal for both periods. This demonstrates that the method used to estimate the RAS and MLSS concentrations, and the fractional weight of P in the WAS, provide very similar values to those directly measured by the Labs.

4.3.5 Volatile Fatty Acids

Due to the reported influence of volatile fatty acids (VFAs) on biological phosphorus removal, the concentration of these acids was measured in several locations throughout the plant. The concentrations of acetic, propionic, isobutyric, butyric, isovaleric and valeric acids were initially investigated. At measurable levels, only acetic and propionic acids were detected at all locations except at the gravity thickener overflow (GTO) and the press filter overflow (PFO) where small concentrations of butyric and valeric acids were found.

Figure 4.54 and 4.55 show the concentrations of acetic acid at several locations in the plant. Notice that acetic acid concentrations are much higher at PFO (268 mg/L). This is expected, because of the opportunity for fermentation to take place in these Unit process. Although the acetic acid concentration at PFO is very high, the overall impact of this stream, which is returned just above CPEI, is not significant, due to its small flow.

The acetic acid concentration at CABI, the influent to the anaerobic cells, is about 16 mg/L. In several other locations throughout the plant, the acetic acid concentration is around 12 mg/L.

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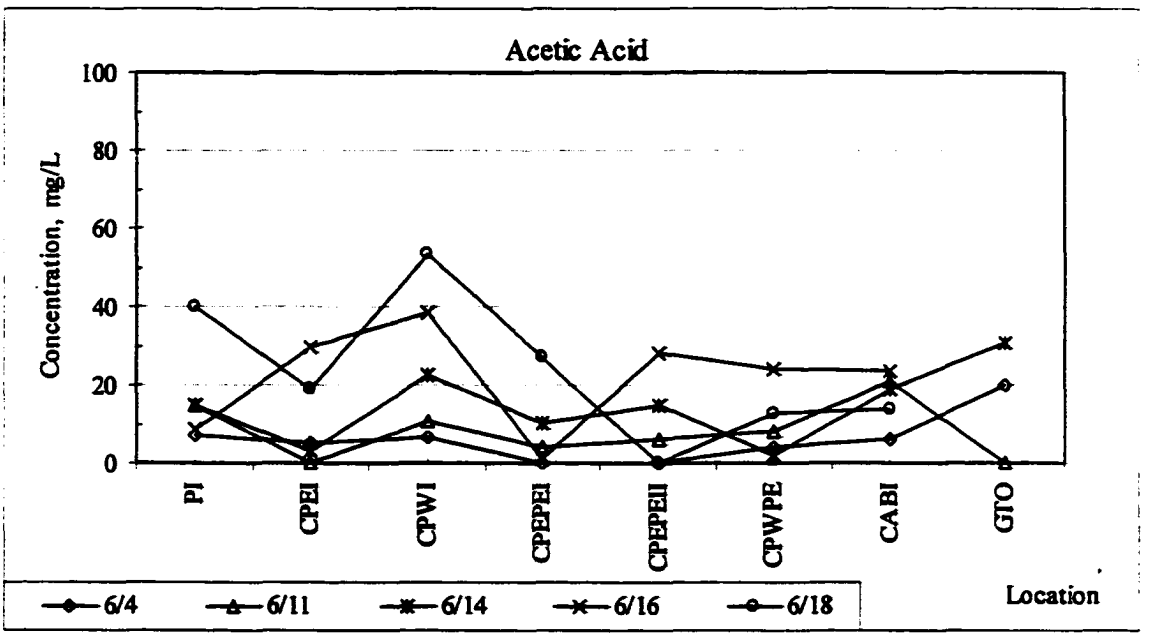

Figure 4.54 Acetic Acid Concentrations, Without the PFO Location

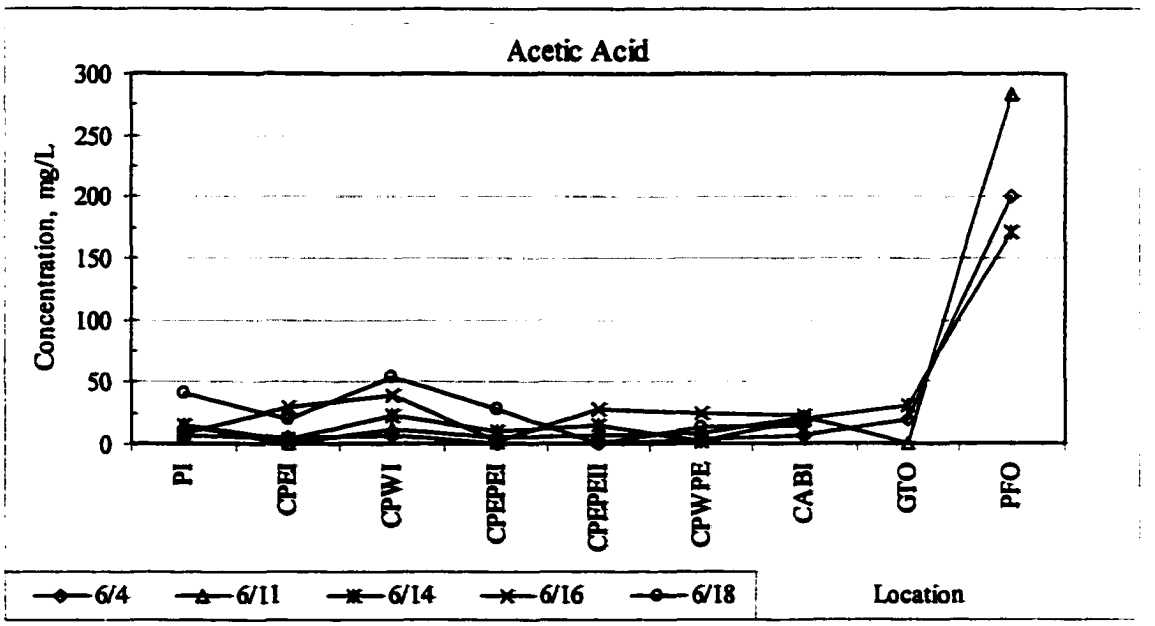

Figure 4.55 Acetic Acid Concentrations, With the PFO Location

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Figures 4.56 and 4.57 show the propionic acid concentration at several points within the plant. Notice that the propionic acid concentrations are much lower than the acetic acid concentrations. Again, PFO has the highest propionic concentration of all the locations, approximately ½ that of acetic acid. The propionic acid concentrations at CABI averages 3.9 mg/L, about 21% of the acetic acid concentration.

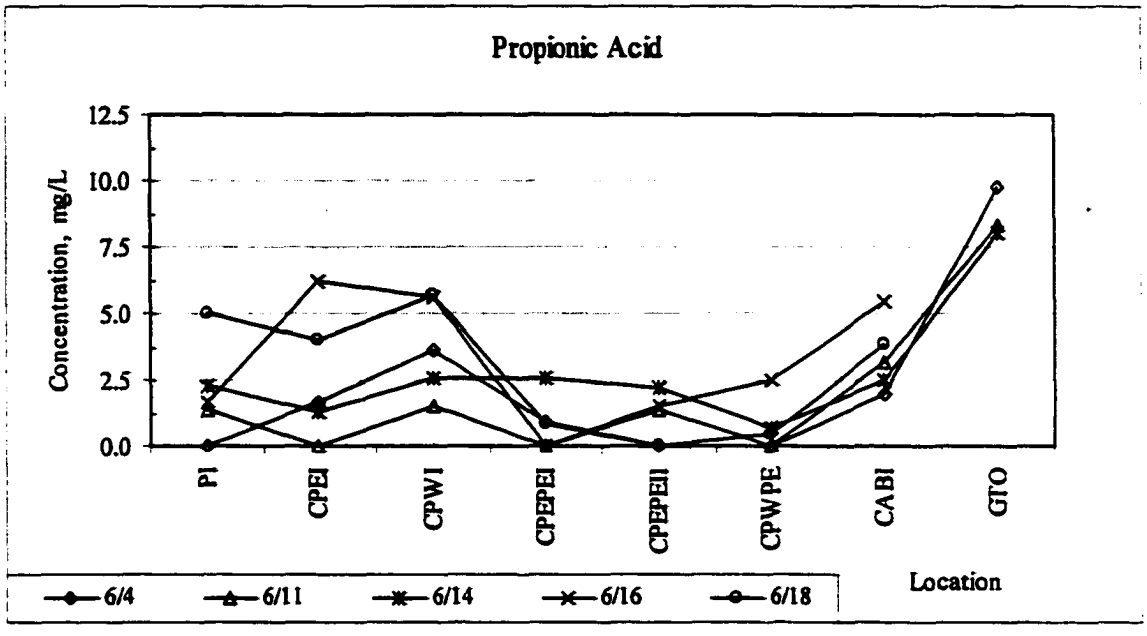

Figure 4.56 Propionic Acid Concentrations, Without the PFO Location

Table 4.20 gives the average values of acetic and propionic acids during the time period indicated in the legend of Figure 4.57.

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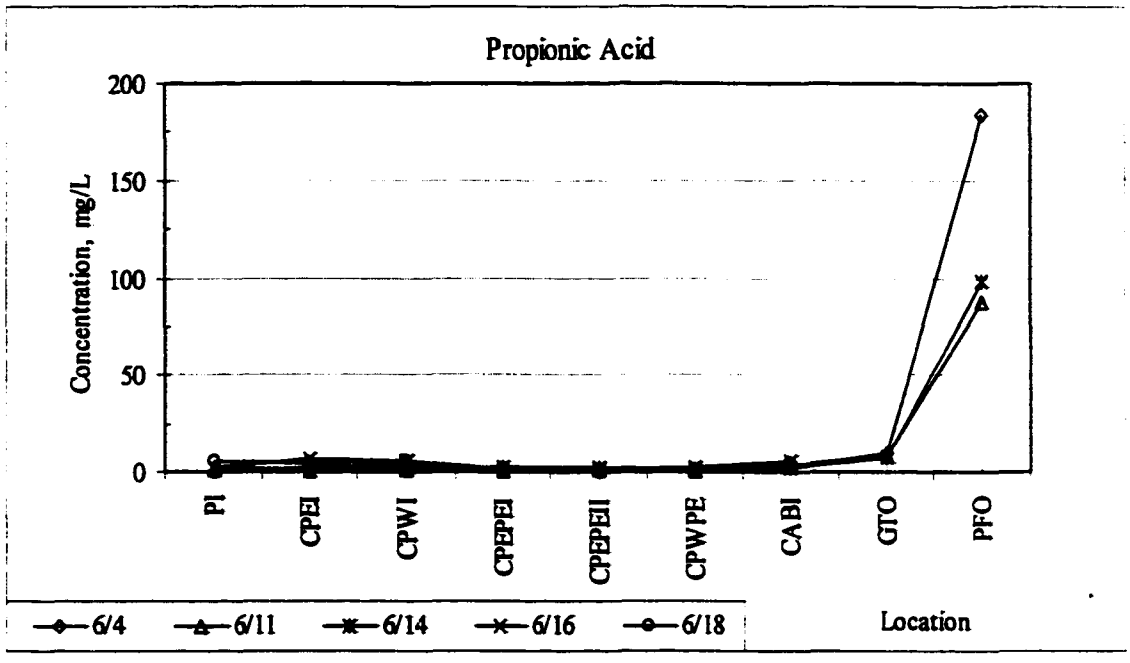

Figure 4.57 Propionic Acid Concentrations, With the PFO Location

Table 4.20 Acetic and Propionic Acid Concentrations in the CCSD Plant, in mg/L

	PI	CPEI	CPWI	CPEPE1	CPEPE2	CPWPE	CABI	GTO	PFO
Acetic	15.3	10.8	22.5	9.3	13.0	9.3	15.9	20.6	268.0
Propionic	2.0	2.2	3.3	1.1	1.8	0.6	3.4	12.0	127.5

4.3.6 Effluent Phosphorus Levels

Figure 4.58 shows the effluent P concentration in basin #4 (AB4) and the eight basin plant average (CE). Recall that AB4 are water samples measured by the plant process lab using Hach chemistry, and that CE is a mixture of effluent from all operating basins, measured by the AWT Labs. Notice the large excursions of phosphorus in the AB4 profiles between 6/3 and 6/20, are much higher than the plant average at CE.

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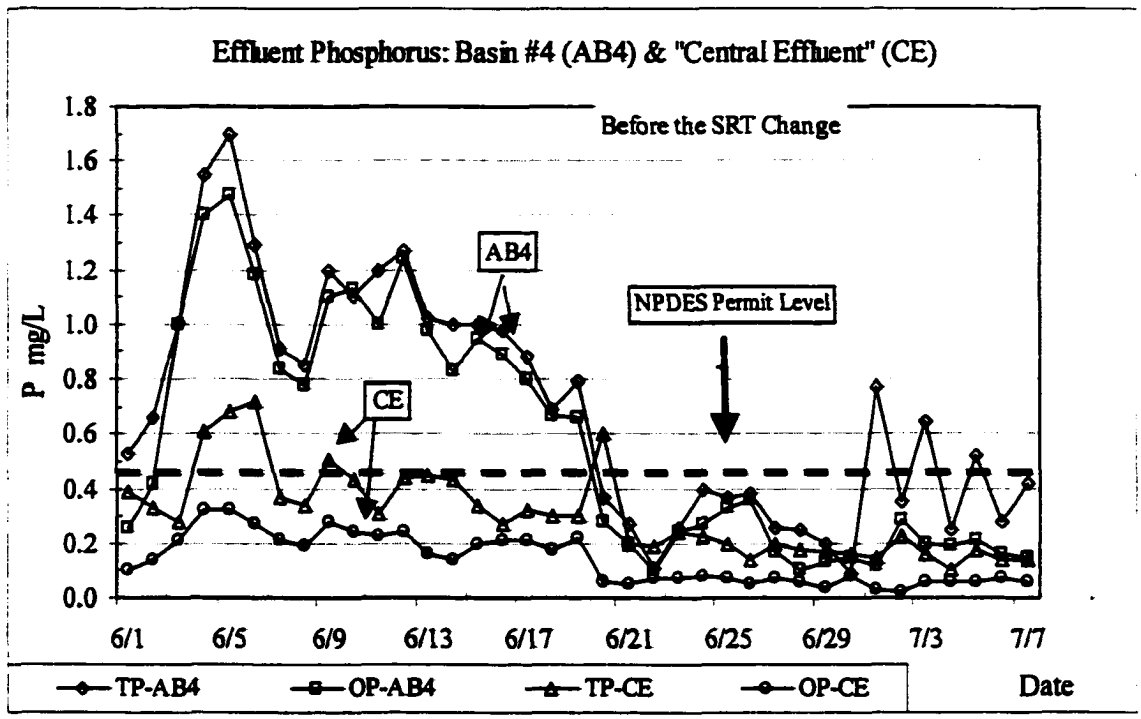

Figure 4.58 TP and OP Effluent Concentrations, AB4 and CE, Before the Change

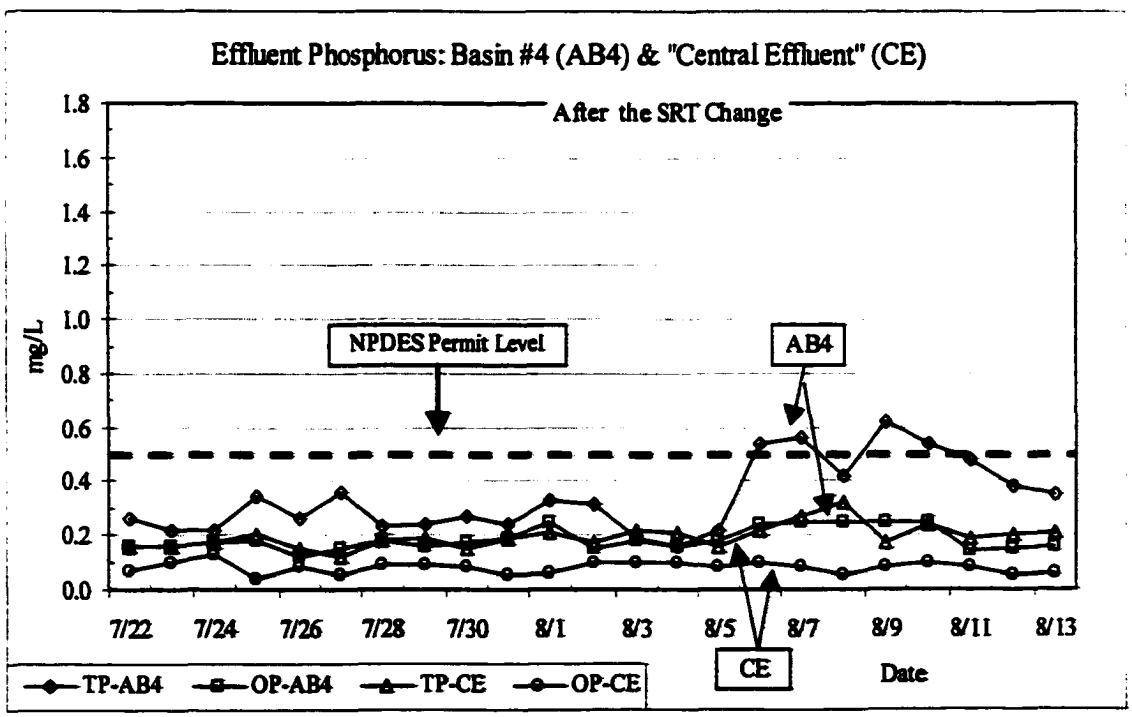

Figure 4.59 TP and OP Effluent Concentrations, AB4 and CE, After the Change

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This shows that the basin was performing less efficiently than the plant average, and that most of the reduction in effluent P concentration from basin #4 was experienced before the transition period was reached. Effluent phosphorus levels, similar to those in the "after" period, were reached by the end of the "before" period.

Figure 4.59 shows the effluent phosphorus concentrations for AB4 and CE during the "after" period. Here, basin #4 is performing nearly identical to the rest of the plant, except for the last eight days, where a small excursion of TP is noticeable at AB4.

Figures 4.60 and 4.61 and Table 4.21 summarize the effluent phosphorus concentrations based on the grab samples taken at CLRO (secondary clarifier effluent). The time at which all samples were taken was approximately 10:30 am, close to the maximum daily flow for the plant.

During this time of the day, the peak basin influent rate is approximately 14 MGD, exceeding the average design of 11 MGD by 27%. Including return flows of 40% influent, the true basin flow at this time is about 19.6 MGD or 78% greater than the average. The nature of the sampling creates a new measurement which is actually an indication of how the phosphorus removal is operating at a point in time when flows exceeding the design average.

Notice in Figure 4.60, 4.61 and Table 4.21, that independent of the type of sample taken (composite AB4, grab @ CLRO, and composite CE), the TP and OP in the effluent, both decreased in the "after" period. However, the decrease in OP concentration was much more prominent than that for TP.

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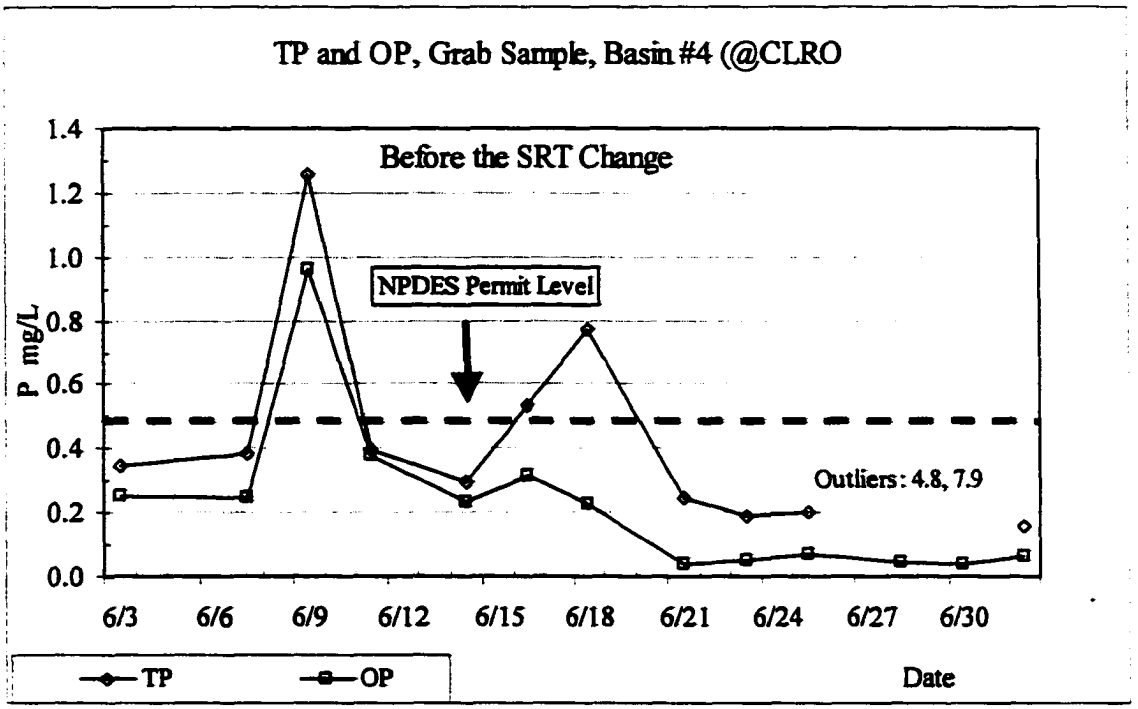

Figure 4.60 TP and OP Concentrations, Grab Sample, Basin #4, Before the Change

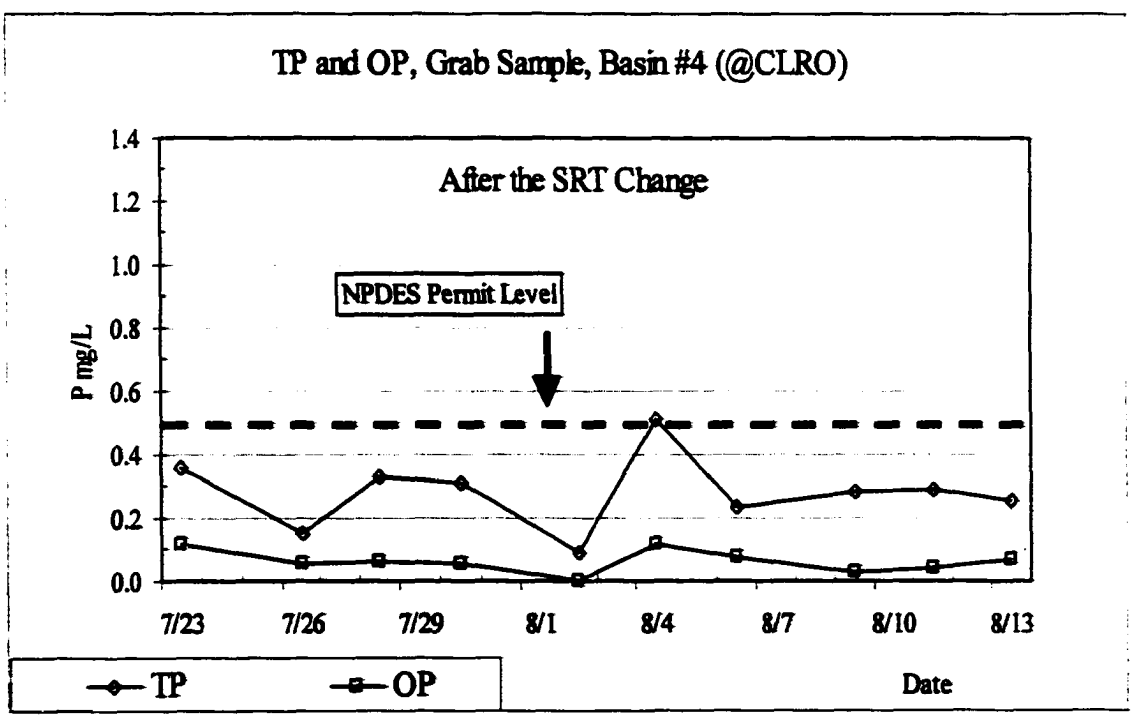

Figure 4.61 TP and OP Concentrations, Grab Sample, Basin #4, After the Change

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It appears as though increasing the SRT had a significant and beneficial response in basin #4, indicated by the significance "t" test performed and shown in Table 4.22. However, the basin was actually operating at a lower relative removal efficiency than the plant average during the "before" period (Table 4.14 and 4.15). A comparison of the phosphorus concentrations of the "before" and "after" period would not be a true representation of the effect of SRT changes in that basin.

Table 4.21 Total and Ortho Phosphorus, (Influent and) Effluent Concentrations								
	24 Hr Composite		24 Hr Composite		Grab Sample		24 Hr Composite	
	PI (Influent)		@ AB4		CLRO		CE	
	TP	OP	TP	OP	TP	OP	TP	OP
Before 6/1 - 7/7					*mg/L*			
Ave	5.84	2.89	0.698	0.575	0.433	0.224	0.309	0.139
Stdev	2.28	0.29	0.422	0.429	0.326	0.251	0.160	0.089
After 7/24 - 8/13					*mg/L*			
Ave	5.99	2.69	0.337	0.185	0.280	0.060	0.194	0.079
Stdev	1.19	0.18	0.132	0.041	0.114	0.041	0.043	0.023
Change (After/Before –1)				*"-" means lower concentration*				
Ave	2.6%	-7.0%	-51.8%	-67.8%	-35.3%	-73.1%	-37.2%	-42.9%

Hypothesis testing was performed on the difference between the two average effluent phosphorus concentrations, $(\bar{X}_1 - \bar{X}_2)$, to determine the numerical (statistical) significance of the change (Mendenhall, 1995). The test statistic used to evaluate the difference was a single tailed, students "t" with modifications to small-sample tests about $(\bar{X}_1 - \bar{X}_2)$ when the variances of the two independent data sets were not equal ($\sigma_1^2 \neq \sigma_2^2$). The resulting p-values are given in Table 4.22, and a description of the method used to compute the "t" Statistic and P-value (Mendenhall, 1995) are presented in

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Appendix C – Statistical Methods, Phase I, BIO-P Removal Study.

The Table shows that with the exception of TP measured from the grab sample, the information in support of the null Hypothesis is nearly zero. Thus, statistical evidence supports the claim that a change in concentrations definitely occurred.

Table 4.22 Phosphorus Values in Support of the Hypothesis: $(\bar{X}_1 - \bar{X}_2)$

	AB4		CLRO (grab)		Plant Ave @ CE	
	TP	OP	TP	OP	TP	OP
P value =	l.t. 0.001	l.t. 0.001	g.t. 0.1	l.t. 0.032	l.t. 0.003	l.t. 0.002
$(\bar{X}_1 - \bar{X}_2)$ =	0.361	0.390	0.153	0.164	0.115	0.06
t =	4.84	5.49	1.46	2.31	4.14	3.86
ν =	7	6	4	4	7	7

4.3.7 Vulnerability of Effluent Phosphorus Concentrations to P Micro-Release

It has been shown that nitrate concentrations in anaerobic cell A1 are (near) zero (Figures 4.18 and 4.19), also a suggestion that denitrification might take place in the sludge blanket of the secondary clarifier, before the RAS traveled to A1. Denitrification requires the same anaerobic conditions, found in the clarifier and cells A1 through A4, that are needed for release of polyP from PAOs.

The sludge blanket may contain a large amount of phosphorus, a small part of which may be released back into the secondary clarifier. To evaluate the fractional amount of P in the sludge blanket that would need to be released in order to raise the clarifier volume to a constant numerical value, the following assumptions and calculations were made:

1. Assume the P concentration in the sludge blanket is 300 mg/L (consistent with Figure 4.52 and Table 4.19). Calculate the total mass of P in the

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blanket.

2. Assume that the Clarifier and sludge blanket have the dimensions and characteristics, taken from plant specifications shown in Table 4.23.
3. Assume a P concentration in the clarifier effluent is 0.4 mg/L (0.1 mg/L below the NPDES permit level).
4. Calculate the mass of P released into the volume of water in the clarifier, that would result in a clarifier concentration of 0.4 mg-P/L.
5. Use the results from #4 to calculate the fraction of P to be released, using the equation below.

$$\text{Fraction} = \frac{\text{Dissolved Mass of P in Clarifier Water w/Conc} = 0.4\ \text{mg/L}}{\text{Mass of P Stored in Sludge Blanket, depth} = 1.5\ \text{ft., @300 mg/L}} \qquad \text{Eq. 4.2}$$

The results are shown in Table 4.23 demonstrating that only 0.55% of the total mass of P stored in the sludge blanket would have to be released to create a clarifier concentration of 0.4 mg-P/L under completely static conditions. A reduction in that fraction occurs if one considers that the hydraulic retention time of the sludge blanket is only 2.75 hours, as compared to an HRT of 4.0 hours for the clarifier overflow. The true mass fraction is reduced to about 0.38%.

The dimensions of the secondary clarifier in Table 4.23, and all other CCSD plant design specifications are given in Appendix D, CCSD Wastewater Plant Design Specifications.

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Table 4.23 Secondary Clarifier Release Parameters				
Cone Depth (1:12 slope)	5.83	ft		
Clarifier Diameter	140	ft		
Sludge Cone (Inverted) Volume, ft^3	38,089	ft^3	1,078,609	liters
Sludge Cylinder Volume, @ 1.5' height	23,091	ft^3	653,880	liters
Total Cone and Cylinder Volume	61,180	ft^3	1,732,489	liters
Cylindrical Volume of Clarifier, 14 ft high	215,404	ft^3	6,099,785	liters
Total Clarifier Cyliner and Cone Volume	253,493	ft^3	7,178,394	liters
Phosphorus Mass in the Sludge Blanket, @ P conc = 300 mg/L			519.8	kg
Phosphorus Mass in Clarifier, for P conc = 0.4 mg/L			2.87	kg
Mass Fraction P Released from Sludge in Blanket: Static Cnds			**0.55%**	
Effects from Non Equal Hydraulic Retention Times				
HRT of Sludge Blanket, Emptied by Recycle Flow (4.4 MGD)			2.75	hr
HRT of 2^0 Clarifier, Emptied by Basin Flow (11 MGD)			4.0	hr
Actual Mass Fraction P Released from Sludge in Blanket			**0.38%**	

This shows that excursions, far in excess of the NPDES permit, would occur even if only a small fraction of the P stored were to be released. Preventing only the smallest of fractions of P from being released as the sludge passes through the clarifier, is needed to prevent exceeding permit levels.

4.3.8 Denitrification Effects on Effluent Phosphorus Concentration

Measurements of nitrates and phosphorus in the RAS and clarifier effluent indicate that two main sources contribute to the concentration of phosphorus in the effluent, both of which are related to denitrification.

4.3.8.1 Phosphorus Release Under Weak to Moderate Denitrification

Figure 4.62 plots the same phosphorus concentration data of Figure 4.58, but with the addition of the (once a week) RAS nitrate measurements from basin #4, scaled

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on the right axis. The right axis maximum, 12 mg NO_3-N/L, represents the average nitrate concentration found in the effluent of the clarifier.

Notice in the Figure, that nitrate concentrations are relatively high when the phosphorus concentrations are high, and drop when the phosphorus concentrations decrease. The high nitrate concentrations range from 5 mg/L to 10.4 mg/L, while the lowered nitrate concentrations range from 0.2 mg/L to about 2.0 mg/L. Therefore, denitrification is taking place in the clarifier.

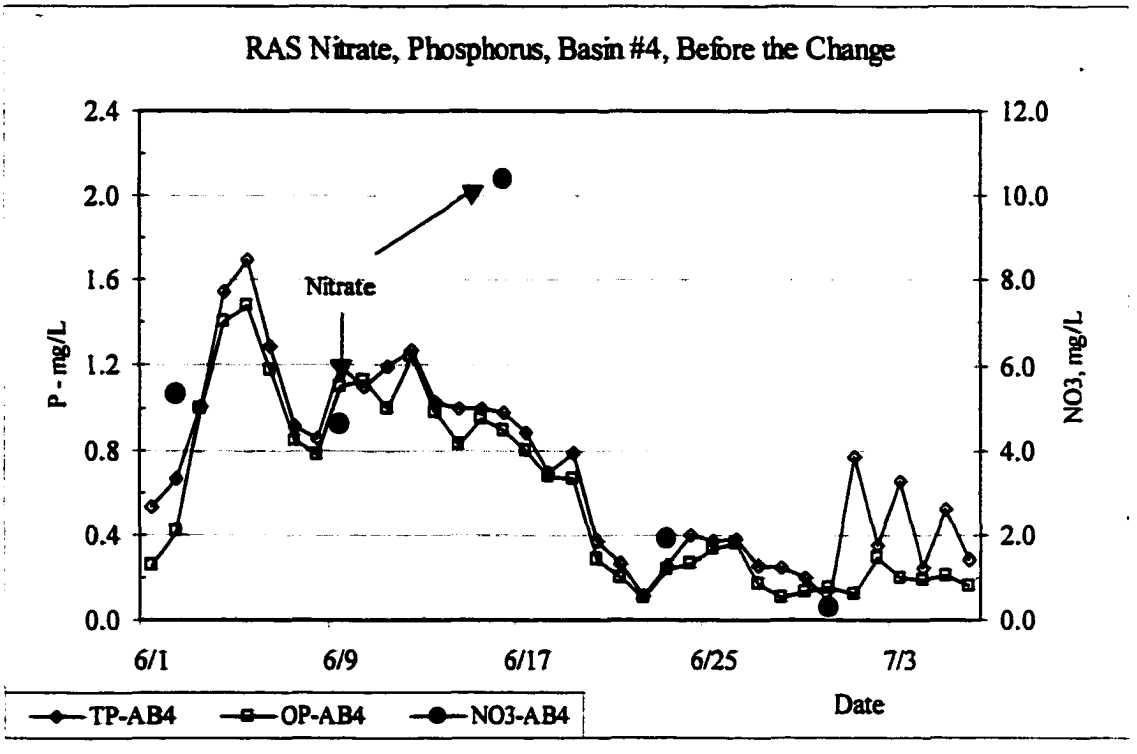

Figure 4.62 Nitrates in the RAS, Effluent Phosphorus, Basin #4, Before the Change

Also important to note, is that TP and OP are nearly the same value at most points sampled, regardless of their value. This is an indication that when nitrates are high (denitrification was weak), P release is significant, while when denitrification is

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moderate (low nitrates), P release is inhibited. This is the same competition between the denitrifiers and the PAOs that is known to exist in the anaerobic zones of biological phosphorus removal systems.

An indication that P excursions in the basin #4 effluent are the result of P release by the microbes, is that the OP and TP values are nearly the same. This is consistent with P release concentrations of OP and TP shown in Figure 4.27.

Figure 4.63 replaces the nitrate values of Figure 4.62 with TSS which is scaled on the right axis. The scale size was selected such that 10 mg-TSS/L would correspond to 0.4 mg-P/L, this corresponding to the 4% fractional weight of P found in the WAS (section 4.2.6). Arrows on the Figure scales indicate this proportion.

Important to note in Figure 4.63, is that TSS does not follow the TP/OP profiles during the period 6/4 to 6/21, when the P values are high. This further indicates that microbe cells containing phosphorus are not responsible for the high TP effluent levels shown when high nitrates occur. However, if this were the case, TP would be the dominant phosphate species found because of the stored polyP in the cells.

Figures 4.64 and 4.65 reinforce the same themes of Figures 4.62 and 4.63, but during the earlier months of April and May. Figure 4.64 shows that when nitrate levels are high, the effluent phosphorus levels are high, and nitrate levels drop when the phosphorus levels decrease.

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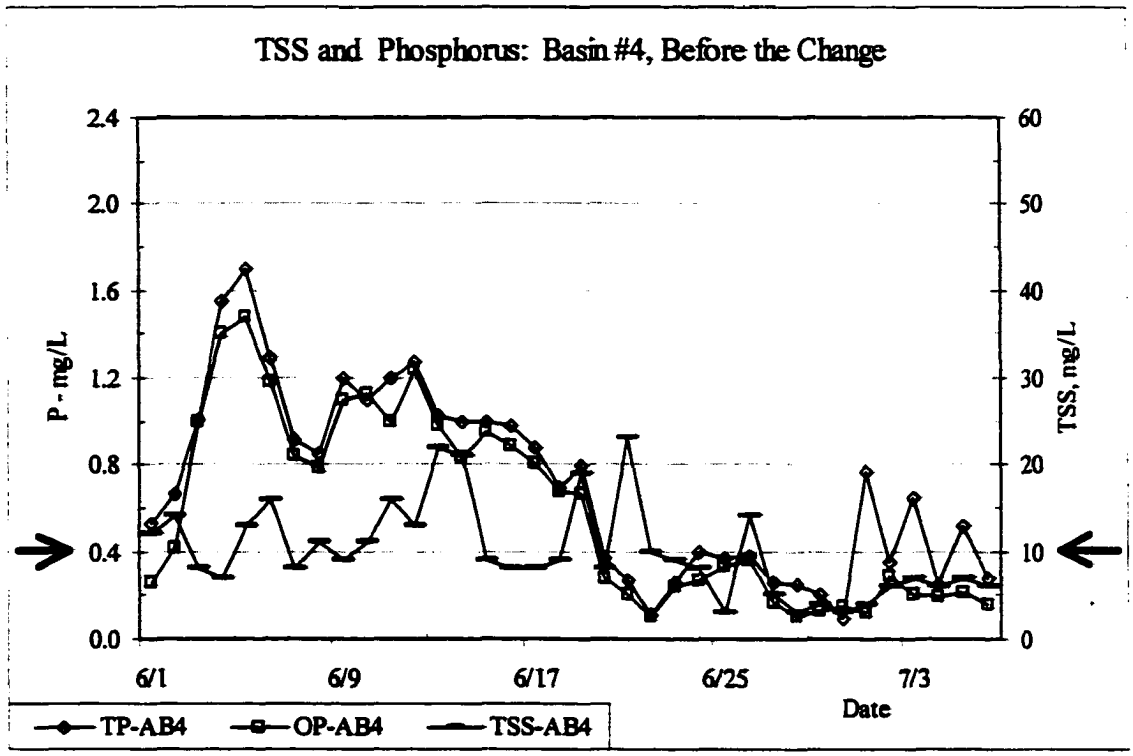

Figure 4.63 TSS and Effluent Phosphorus, Basin #4, Before the Change

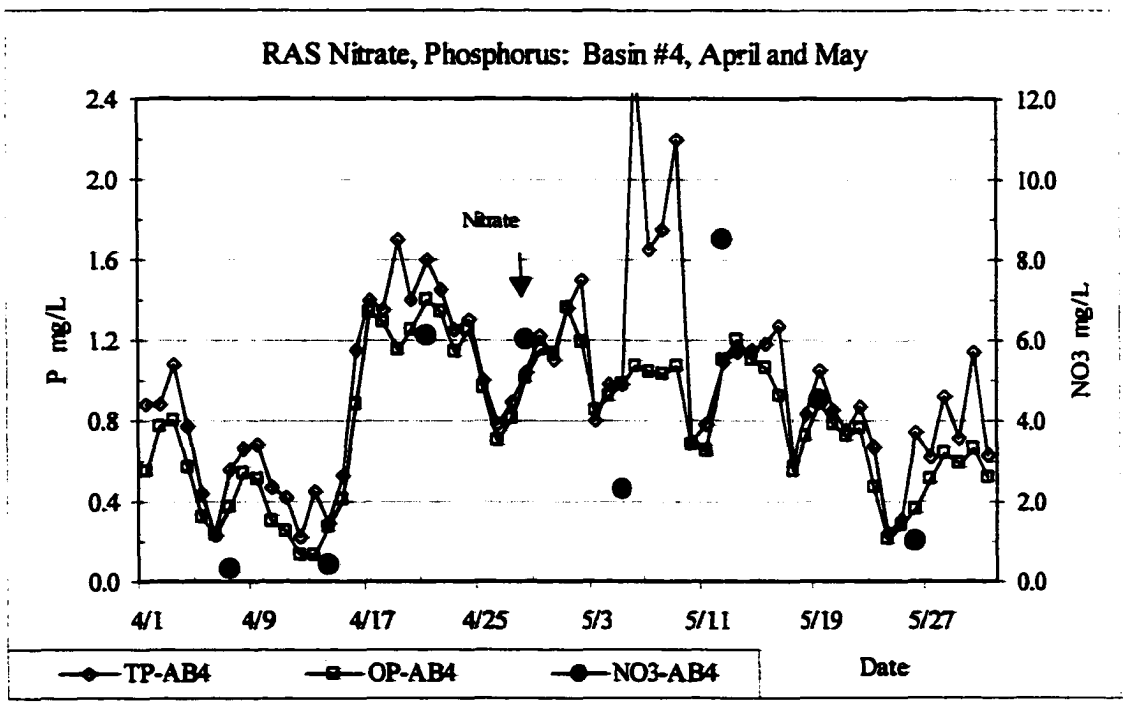

Figure 4.64 RAS Nitrates and Effluent Phosphorus, Basin #4, April and May

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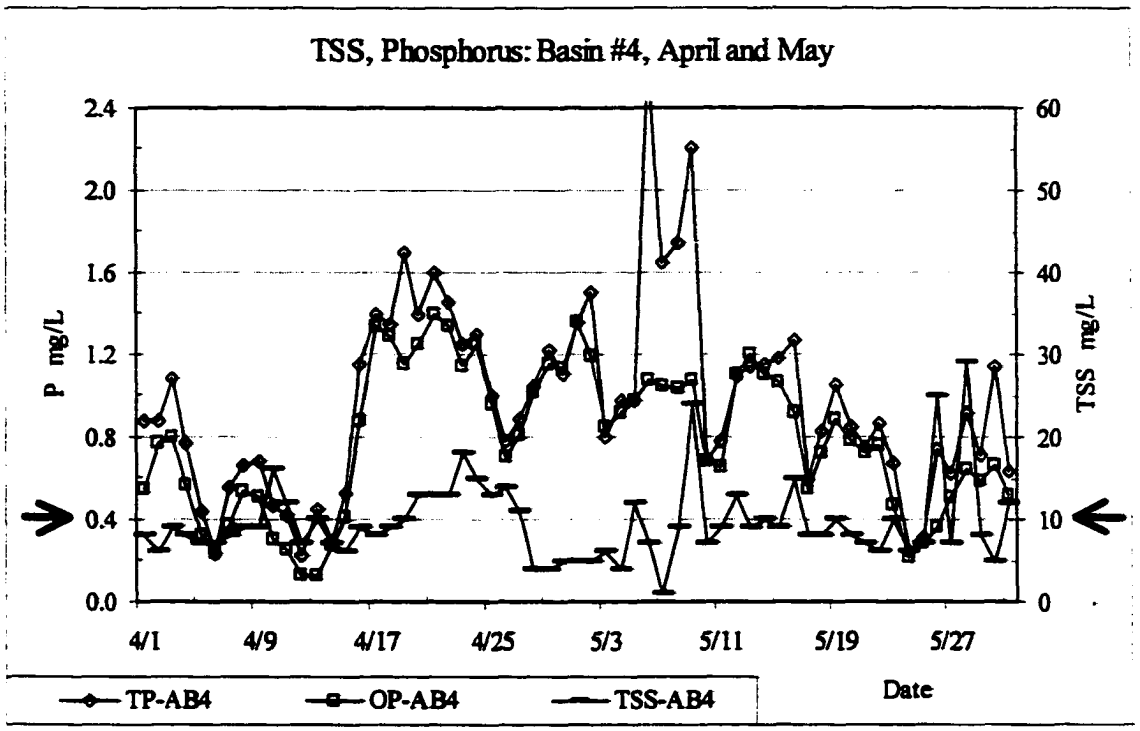

Figure 4.65 TSS and Effluent Phosphorus, Basin #4, April and May

The values of TP and OP are nearly the same throughout the entire period. This indicates that the phosphorus in the water was released by the microbes in the sludge blanket. In Figure 4.65, the TSS level is again scaled to equate 0.4 mg-P/L to 10 mg-TSS/L. It is clear that the TSS values do not follow the TP/OP profiles during most of the time period plotted. This again indicates that the phosphorus concentration results from a P re-release, originating from the polyP in the microbial cells. If the phosphorus in the cells were being measured, the TP values would be much larger than the OP.

All of the previous Figures (4.62, 4.63, 4.64 and 4.65), characterize what may result when weak to moderate levels of denitrification takes place. Weak denitrification corresponds to high nitrate levels, which are defined here as approximately 50% to 90%

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of the clarifier effluent level (12 mg NO_3–N/L). Also, the TP and OP levels are rather high, nearly equal to each other, and the TSS profile does not follow the P profiles. Moderate levels of denitrification correspond to nitrate levels approximately 10% to 50% of the clarifier effluent level, and the TSS and P concentrations are also very low. Moderate denitrification results in low amounts of P being released.

Denitrifying and polyP bacteria are strong competitors for VFAs and other sources of carbon, a behavior observed in the anaerobic cells. Being the stronger competitor, the denitrifiers are able to stall phosphorus release until all of the nitrates are consumed. This competitive behavior appears to be taking place in the sludge blanket and RAS of the secondary clarifier.

4.3.8.2 Total Phosphorus in the Effluent Under Strong Denitrification

Figure 4.66 characterizes a different relationship between nitrates and effluent P concentrations found in basin #6 during May and June. Basin #6 was chosen to represent this example, because basin #4 did not exhibit this behavior. Important to note in the Figure, is that TP and OP concentrations are not equal, and nitrate levels are consistently very low, averaging 0.67 mg NO_3–N/L or less than 10% of the clarifier effluent. Also, the TP values clearly lie above those of the OP.

Figure 4.67 plots TSS values in place of the nitrates in Figure 4.66. The TSS scale again equates 0.4 mg-P/L with 10 mg-TSS/L in the effluent, and the TSS profile is shown to follow the TP profile quite well, throughout the period shown.

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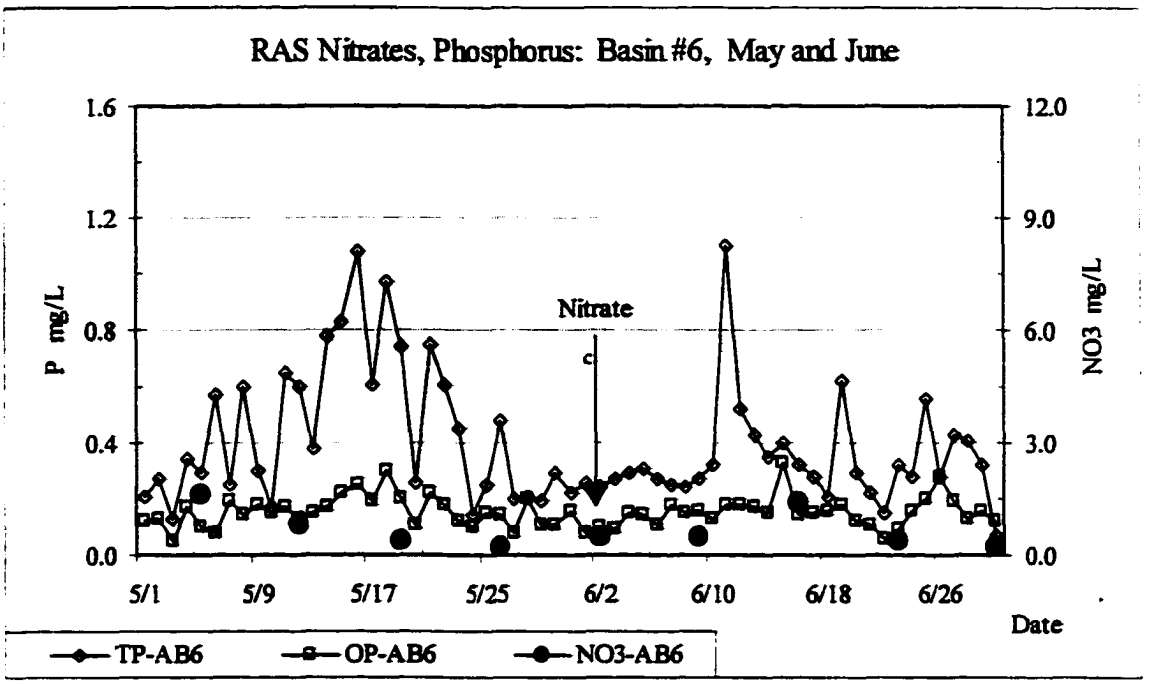

Figure 4.66 RAS Nitrates and Effluent Phosphorus, Basin #6, May and June

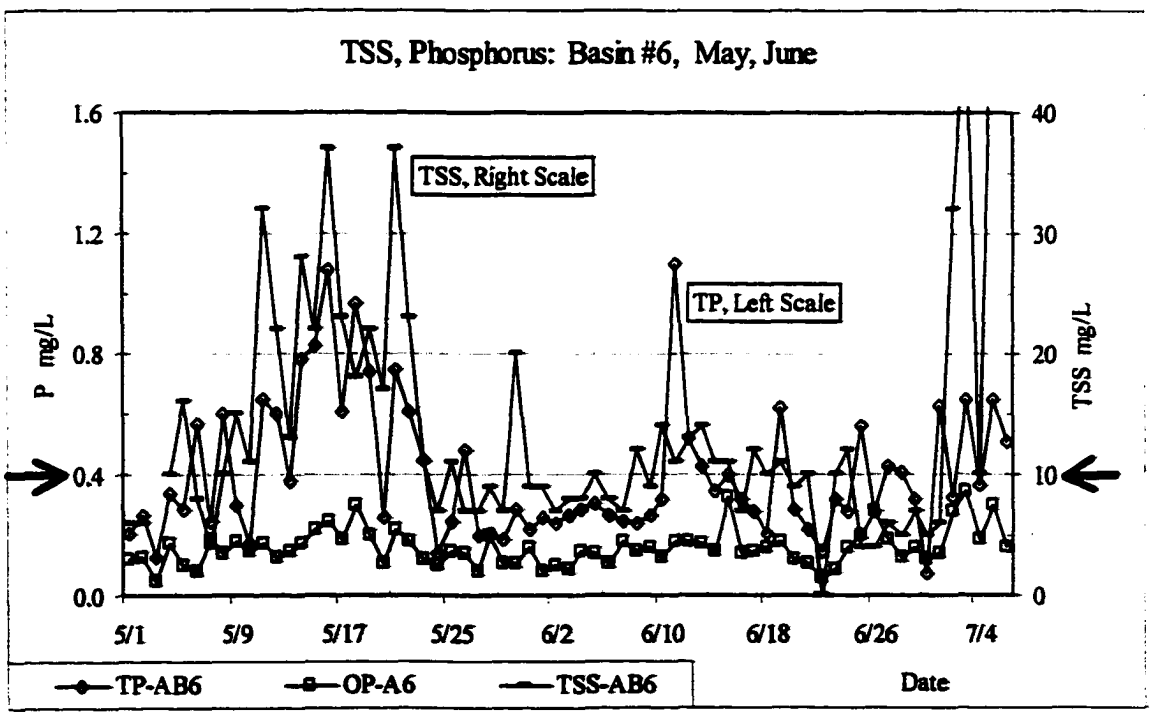

Figure 4.67 TSS and Effluent Phosphorus, Basin #6, May and June

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The scaling of the right axis is chosen to equate 0.4 mg-P/L with a 10 mg/L TSS concentration, a conditions consistent with P being 4% of the mass of the WAS cells. If the fractional weight of the WAS were greater than 4%, the TSS profile would lie above the TP profile. If the fraction were less than 4%, the TSS would lie below the TP profile.

Figures 4.68 and 4.69 reinforce the same theme as in Figures 4.66 and 4.67. Both of the previous Figures indicate that when the TP concentration is clearly higher than the OP, the nitrates remain extremely low and the TSS follows the TP profile.

Since polyP bacteria are not the only microbes present, the TSS profile will follow the TP profile, but still extend above the TP profile at times. The excursions of TSS at select points along the TP profile indicate additional varieties of microbes that are present in the TSS (Figures 4.68 and 4.69).

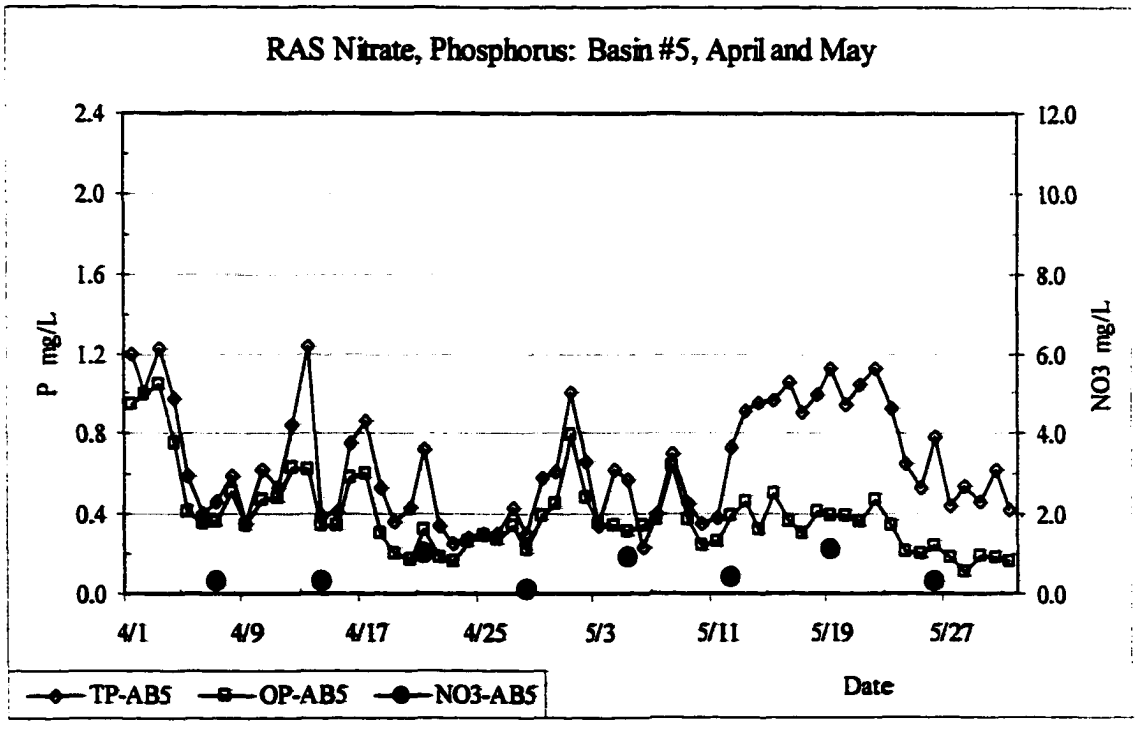

Figure 4.68 RAS Nitrates and Effluent Phosphorus, Basin #5, April and May

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Strong denitrification, identified by very low nitrate levels, produces large amounts of nitrogen gas that can potentially raise floc in the sludge blanket to the surface of the clarifier. Under these conditions, the TSS profile will to follow the TP profile.

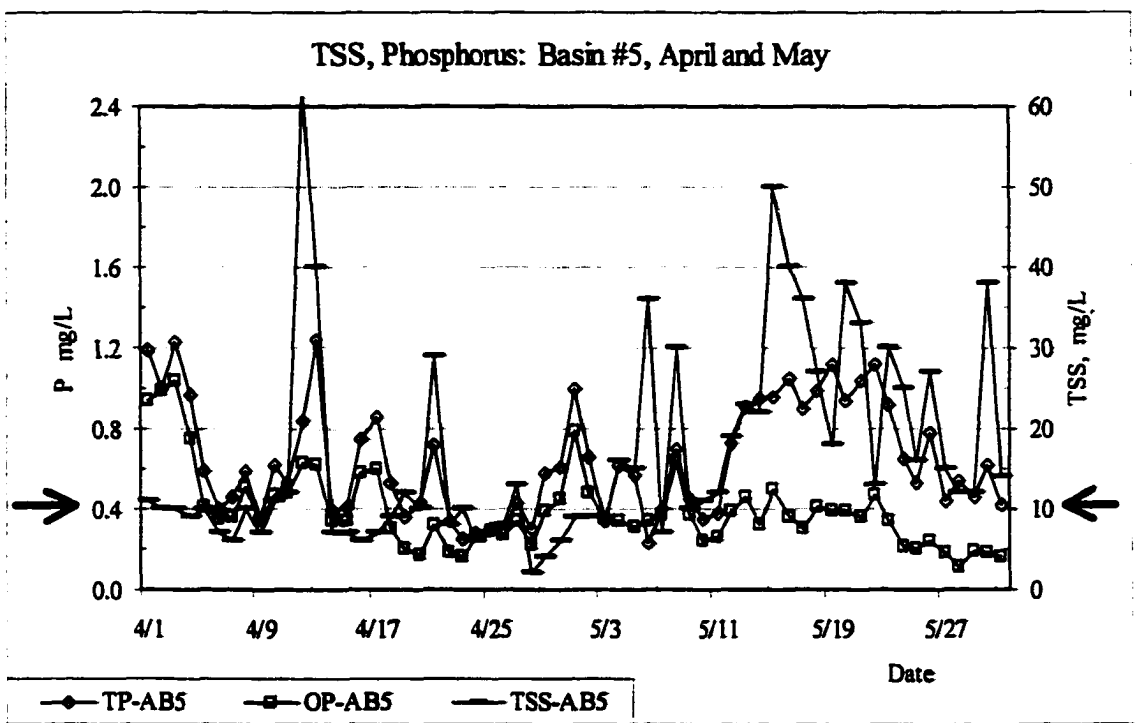

Figure 4.69 TSS and Effluent Phosphorus, Basin #5, April and May

4.3.8.3 Multiple Levels of Denitrification in Basin #4

Figures 4.70 and 4.71 plot the RAS nitrates and TSS of basin #4 along with effluent P levels in the secondary clarifier during the "after" period. These Figures show that during the days 7/22 to 8/1, the TP and OP levels are both low and approximately equal to each other, and the TSS level also remains low.

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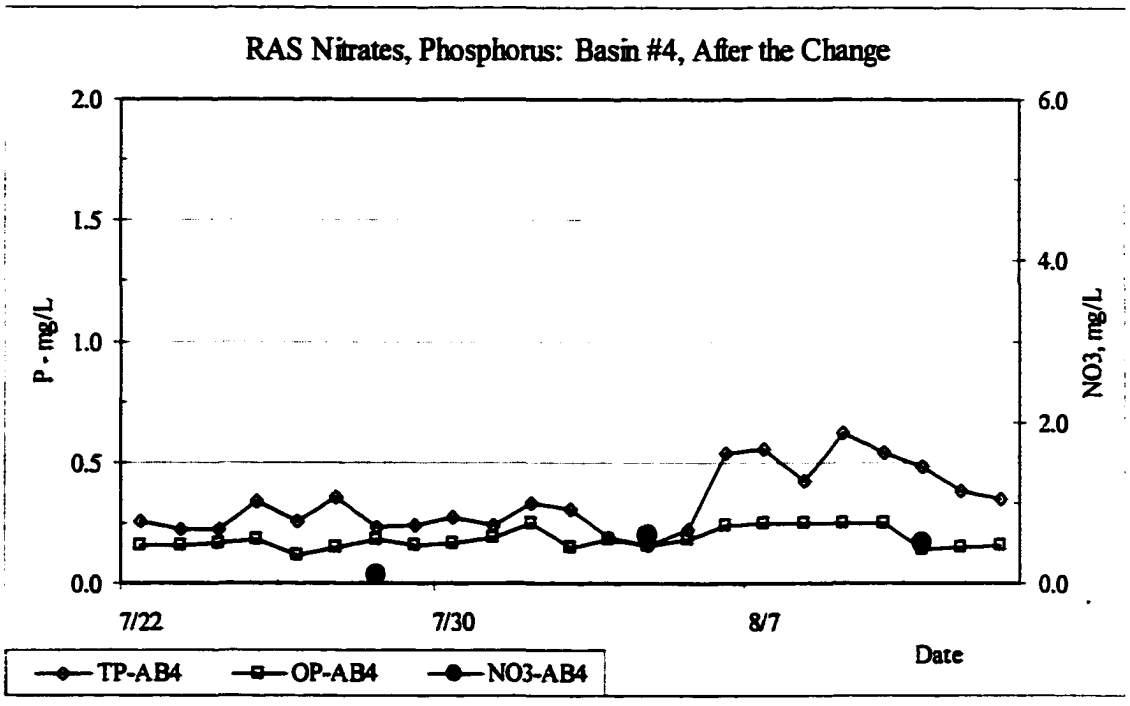

Figure 4.70 RAS Nitrates and Effluent Phosphorus, Basin #4, After the Change

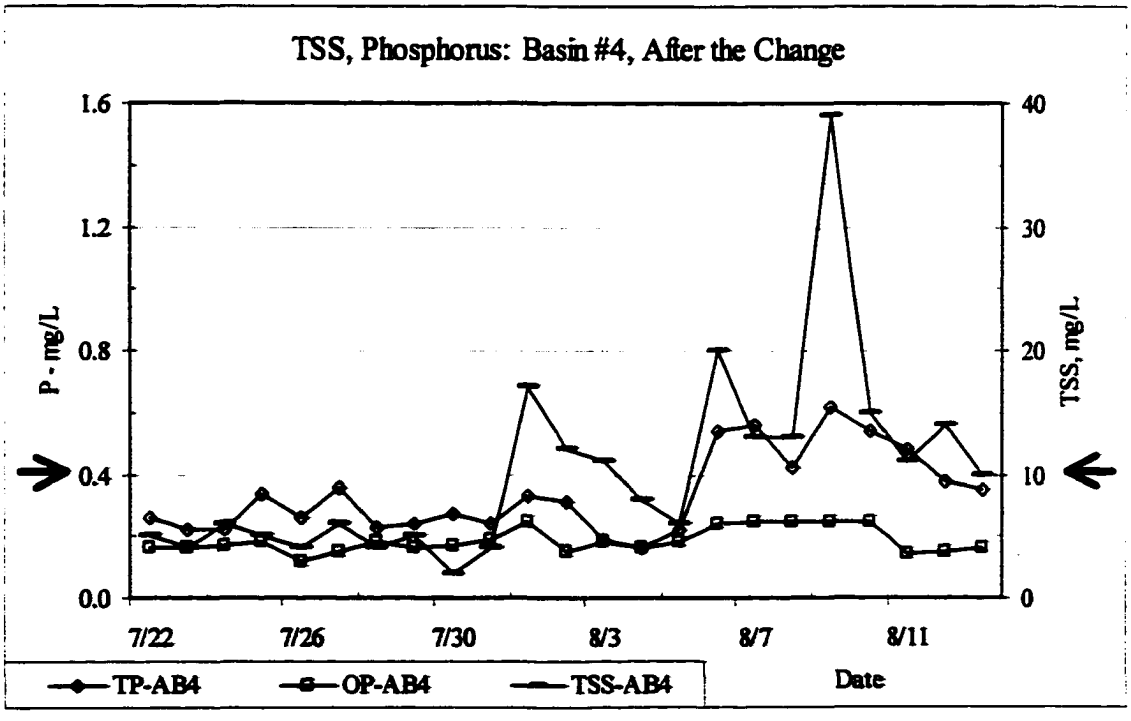

Figure 4.71 TSS and Effluent Phosphorus, Basin #4, After the Change

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Moderate denitrification appears to be taking place during this period, because the nitrate levels are low but the amount of nitrogen gas required to lift the floc is not yet being produced. Strong denitrification appears from 8/1 to 8/13, as the TP and OP levels separate and the TSS begins to emulate the TP profile.

Figure 4.72 shows the typical nitrate and phosphorus concentrations that were measured in the clarifier. The reduction of nitrates and the increase of phosphates with depth are the result of combined stratification caused by settling of the Activated Sludge, and anaerobiosis.

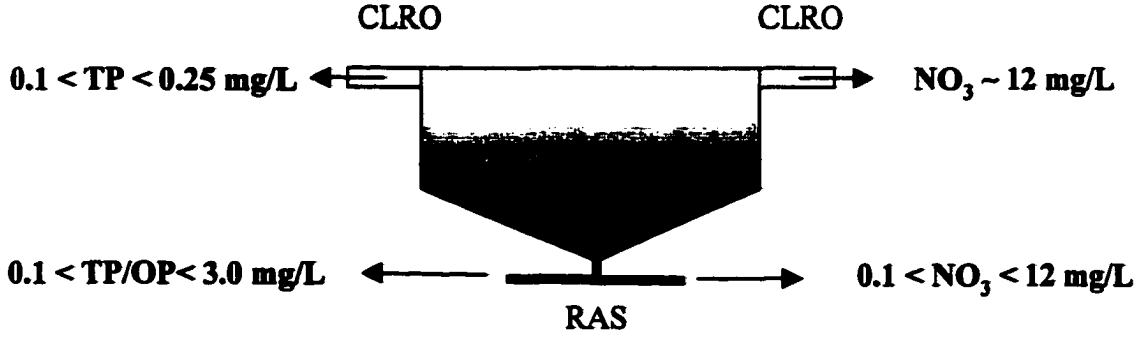

Figure 4.72 Nitrates and Phosphates Found in the Secondary Clarifier

It is not expected that the entire sludge blanket is contributing to P release or strong denitrification; this may occur only under specific conditions and in locations. Controlling denitrification so that it remains within moderate proportions, appears to prevent phosphorus release and phosphorus containing microbe cells, from raising the measured P concentrations in the secondary clarifier effluent concentration beyond acceptable limits.

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CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions are drawn from this research:

Intra-Basin Measurements-

1. The ORP values in the anaerobic zones of the basin drop continuously as the wastewater passes from cell A1 to A4. The values rise rapidly in the aeration zones. Low DO levels and lack of aeration in the clarifier zone do not decrease the ORP to values found in the anaerobic zones. The decrease in the ORP values during the "before" period, was probably the result of increased microbial activity, caused by an increase in temperature during that period.

2. The DO reaches levels (0.5 mg/L) in cell A1, and continues to drop as the water flows through each cell to A4. Similar DO levels are found in the clarifier. Changing the SRT did not significantly affect DO levels in the aerobic and anaerobic zones.

   A linear, functional relationship between DO levels and ORP was not found to exist for the studied basin.

3. Ammonia levels in the anaerobic zones remained nearly constant (15 mg/L), indicating that nitrification was not taking place. In the aerobic zones, ammonia

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levels dropped sharply and in less than half an hour, decreased to about 4 mg/L.

4. The change in SRT had no detectable effect on the nitrification process. Nitrate was not detected in any of the anaerobic cells, but formed quickly in the aeration zone, rising to nearly 8 mg/L in half an hour, and reaching 12 mg/L at the basin's effluent. Nitrate levels at the aeration basin and clarifier effluents were similar. Nitrate levels in the RAS, varied significantly, from near zero to the same values found in the aeration basin effluent (12 mg/L), indicating that denitrification takes place in the RAS on an inconsistent basis.

   The eastern four-basin cluster (basins #5-8) experienced much stronger denitrification than the western cluster (basins #1-4), for reasons yet unidentified.

5. The alkalinity in the basins decrease slightly with flow sequence through the anaerobic zones, and decrease faster once into the aerobic zones. The increased SRT brought about a large increase in alkalinity in all zones except the clarifier, where it remained nearly constant.

6. Ortho-phosphate (OP) concentrations by flow sequence on unfiltered water samples was not indicative of the soluble P in the wastewater. However, measurements of filtered samples, show a strong increase of OP within the anaerobic zones, indicating the release of polyphosphate by PAOs. The measurements also show a strong uptake of OP in the aerobic zones. The TP and OP concentrations for the same locations are nearly identical when the soluble P concentration originates the release of OP from stored polyP by the PAOs. P uptake continues as the water flows from the aeration basin to the clarifier, but is released again in the RAS.

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7. Soluble COD and suspended solids were difficult to assess using unfiltered samples, due to the mass of microbes present. Filtered samples, however, indicate that the soluble COD drops to about half the influent value (CABI) after entering cell A1. A slow decrease in COD continues through the anaerobic zones, and then drops sharply at the first aeration basin sampling point (ABI). VSS concentration in the anaerobic zones is constant (about 1785 mg/L), but rises to 14.8% (2054 mg/L) while traveling though the aerobic zones. Combined plots of soluble COD and P release confirms the relationship between P released and organic carbon usage in the anaerobic zones.

8. Microscope slides showing the microbiology from the basin's mixed liquor, indicate that the predominant PAOs found at CCSD are *Acinetobacter* spp. and *Nocardia* spp.. The photographs show polyphosphate granules stored in slides representing samples from anaerobic cell A1, and also show PHA being formed in samples from cell A4. This confirms that polyP stored in the aerobic zones is released in the anaerobic zones, while PHAs are formed in the anaerobic zones. In addition, photographs of scum sometimes found at CCSD shows that *Nocardia* is the foaming causing microorganism. Thus, *Nocardia* has a double role in this system; it is a PAO, but also a foam causing microorganism.

Inter-Basin Measurements-

9. Analysis of the WAS concentrations, WAS flow (QWAS) and MLSS revealed that the SCADA System kept the basin operating at exactly the proper SRT values that were designated for the two periods. The wasting rate was shown to

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increase during the "after" period, but this was an anomalous, transient condition that originated from plant operations. As a result of this condition, the F/M ratio dropped more than kinetic theory would require.

10. A mass balance performed on the average TP concentration as it passed through the plant, indicated that TP concentrations varied erratically on a daily basis. A second evaluation of the same mass balance using absolute removal efficiency as the comparative parameter revealed that the aeration basins compensated for any decrease in TP removal efficiency that occurred in the primaries. The removal efficiencies indicated that basin #4 was not operating as efficiently as the remainder of the basins in the plant during the "before" period (56.3% for basin #4, and 63.2% TP removal efficiency).

11. Evaluation of chemical removal of TP in the primaries showed that about 35% of the P entering the plant is removed chemically in the primaries. The erratic variations of the TP concentration leaving the primaries is not due to fluctuations in the amount of $FeCl_3$ added. A very small amount of iron leaves the primaries and it does not influence phosphorus removal in the basin. Therefore, phosphorus removal in the basins is exclusively biological.

12. Investigation of the effects of BOD on TP removal during the two SRT periods, show that despite the well documented relationships between the two parameters, removal efficiencies can still vary independently of BOD.

13. The fractional weight of phosphorus in the mass of the WAS was calculated to be about 4% during the entire experimental period, and was not altered by the larger SRT. Subsequent calculations were made on the P concentration in the

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WAS mixed liquor and MLSS mixed liquor. Measurements of P made on the MLSS by the AWT Labs were in close agreement with the predictions made from the calculations.

14. Measurements of volatile fatty acids found that acetic and propionic acids are the major acids found throughout the plant. An exception to this occurred at the gravity thickener overflow (GTO) and the press filter overflow (PFO) where small concentrations of butyric and valeric acids were found. Acetic and propionic acid concentrations found at the GTO and PFO were the highest recorded in the plant.

15. During the period of higher SRT, TP and OP for all measurement types (CE, AB4 and CLRO) decreased. At the first glance, the SRT seemed to produce an improvement in removal efficiencies, because an evaluation involving hypothesis testing of the difference of two means, demonstrated that statistically, a change had occurred. In reality, basin #4 was found to be operating at removal efficiencies less than the plant average before the SRT was increased. The basin continued to improve its performance, approaching plant performance levels in terms of effluent phosphorus concentration toward the end of the "before" period. As a result, quantifying the extent to which the role of SRT played in the improvement of P removal was difficult.

16. The DO levels of the secondary clarifier are similar to the anaerobic zones where P release takes place. Calculations show that a fractional release of only 0.38% of the total mass of P, passing through the sludge blanket in the secondary clarifier during the HRT of the clarifier overflow, would raise the P

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concentration in the effluent to 0.4 mg/L.

17. When denitrification is weak, P release takes place in the sludge blanket. Indicators of P release are high nitrates in the RAS, an OP concentration equal to a TP concentration, and TSS varying independently from the TP profile.

    Moderate levels of denitrification prevent P release from taking place due to competition between the polyP and denitrifying microbes. A similar competition occurs in the anaerobic cells. Indicators of moderate denitrification are low nitrates in the RAS, low OP and TP concentrations, and low TSS concentrations in the clarifier effluent, which do not correlate with either the OP or TP concentrations.

    Strong denitrification produces enough nitrogen gas to lift the phosphorus bearing microbes into the effluent. Indicators of this are very low nitrates in the RAS, a TP concentration that is noticeably higher then the OP concentration and a TSS profile that correlates with the TP profile in the clarifier effluent. The TSS profile will overlay the TP profile when the fractional weight of P in the WAS is matched with the respective TSS concentration.

18. Controlling denitrification such that it remains within moderate proportions appears to prevent phosphorus release from the sludge blanket during weak denitrification, and also the formation of nitrogen gas during strong denitrification that lifts the P bearing microbe cells into the clarifier effluent. P release and P microbes with stored polyP are responsible for most of the P concentration excursions in the effluent. The introduction of controls on denitrification will allow CCSD to operate at considerably higher influent plant

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flows and remain below the maximum concentrations dictated by the NPDES permit.

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APPENDIX A

AWT LABORATORY DATA, PHASE I, BIO-P REMOVAL STUDY

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APPENDIX A - AWT LABORATORY DATA

DATE	Loc	ALK mg/L	TOT-P mg P/L	OR-P mg P/L	NH4 mg N/L	NO2 mg N/L	NO3NO2 mg N/L	TKN mg N/L	PH siu
5/17	A2	303.0	43.50	8.19	15.86	0.08	0.08	125.4	
5/17	A3	326.9	61.08	8.42	15.36	0.08	0.08	157.4	
5/17	A4	277.2	46.12	9.77	14.86	0.08	0.10	147.2	
5/17	ABI	207.2	78.33	0.92	0.63	0.08	11.26	128.1	
5/17	ABM	326.5	67.77	2.87	4.17	0.323	8.89	125.4	
5/17	ABE	248.9	74.82	1.11	0.60	0.08	12.06	89.4	
5/17	CLRI	147.0	15.35	0.35	0.14	0.08	12.55	50.5	
5/17	CLRO	123.5	0.34	0.24	0.08	0.08	12.43	0.7	
5/19	A2	264.2	66.68	7.43	16.26	0.08	0.08	93.0	
5/19	A3	313.6	65.86	6.92	13.60	0.08	0.08	173.3	
5/19	A4	320.4	61.26	8.87	13.52	0.08	0.08	123.0	
5/19	ABI	169.9	79.66	0.39	0.78	0.08	11.98	111.5	
5/19	ABM	269.7	76.07	1.73	2.62	0.135	10.05	77.2	
5/19	ABE	385.3	77.90	0.33	0.55	0.08	12.34	218.5	
5/19	CLRI	197.9	23.82	0.43	0.19	0.08	13.34	18.4	
5/19	CLRO	120.7	0.55	0.35	0.08	0.08	13.01	2.4	
5/21	A2	247.3	60.68	8.03	13.91	0.08	0.08	173.1	
5/21	A3	284.8	60.54	8.06	13.88	0.08	0.08	106.6	
5/21	A4	265.0	46.99	9.14	13.88	0.08	0.08	159.6	
5/21	ABI	230.5	87.18	0.42	0.30	0.08	11.54	200.0	
5/21	ABM	229.1	79.36	3.73	3.01	0.471	9.00	138.1	
5/21	ABE	256.0	71.61	0.51	0.26	0.095	11.78	184.9	
5/21	CLRI		30.76	6.71	0.08	0.08	9.95	77.4	
5/21	CLRO	117.9	0.35	0.20	0.08	0.08	12.37	3.4	
5/24	A2	266.8	62.81	12.27	14.96	0.08	0.08	163.7	7.5
5/24	A3	259.5	66.41	12.11	15.47	0.08	0.08	217.6	7.48
5/24	A4	413.5	81.40	13.13	15.20	0.08	0.08	103.4	7.5
5/24	ABI	292.3	55.88	6.16	4.95	0.376	7.75	218.3	7.27
5/24	ABM	261.4	67.43	2.45	0.27	0.177	11.41	195.1	7.27
5/24	ABE	173.0	75.97	2.52	0.34	0.08	11.41	211.8	7.22
5/24	CLRI	155.9	17.11	0.13	0.13	0.08	11.22	31.8	7.14
5/24	CLRO	129.3	0.17	0.10	0.08	0.08	11.43	0.7	7.23

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APPENDIX A - AWT LABORATORY DATA

DATE	Loc	ALK mg/L	TOT-P mg P/L	OR-P mg P/L	NH4 mg N/L	NO2 mg N/L	NO3NO2 mg N/L	TKN mg N/L	PH siu
5/26	A2	282.6	65.46	9.36	16.39	0.08	0.08	159.1	7.44
5/26	A3	304.3	70.56	9.73	16.24	0.08	0.08	147.7	7.43
5/26	A4	278.3	50.05	9.92	16.19	0.08	0.08	189.0	7.42
5/26	ABI	239.5	75.98	3.83	5.16	0.08	8.08	145.6	7.17
5/26	ABM	208.2	78.44	2.34	0.40	0.108	11.97	218.5	7.15
5/26	ABE	194.6	78.27	1.71	0.25	0.08	12.32	212.2	7.15
5/26	CLRI	154.2	23.95	0.38	0.11	0.08	11.69	55.3	7.12
5/26	CLRO	124.2	0.20	0.10	0.08	0.08	12.07	1.3	7.14
5/28	A2	274.2	85.75	10.97	14.11	0.08	0.08	203.8	7.44
5/28	A3	271.0	78.49	12.00	14.10	0.08	0.08	109.4	7.44
5/28	A4	268.9	87.03	11.72	13.81	0.08	0.08	212.5	7.44
5/28	ABI	113.8	94.32	2.08	1.82	0.439	8.48	202.5	7.18
5/28	ABM	235.9	96.56	0.35	0.50	0.084	9.81	188.9	7.04
5/28	ABE	209.9	91.03	0.07	0.29	0.199	10.64	218.1	7.1
5/28	CLRI	214.0	23.15	0.20	0.08	0.08	11.56	50.7	7.14
5/28	CLRO	126.4	0.36	0.24	0.08	0.08	11.97	1.4	7.25
5/31	A2	306.3	60.09	13.54	16.90	0.08	0.08	113.2	7.49
5/31	A3	329.9	64.66	13.63	16.58	0.08	0.08	212.1	7.47
5/31	A4	288.4	65.34	13.88	16.22	0.08	0.08	181.1	7.46
5/31	ABI	224.7	73.01	6.60	3.21	0.082	9.87	165.7	7.21
5/31	ABM	207.3	79.38	4.68	0.50	0.08	12.09	190.0	7.33
5/31	ABE	248.1	62.07	4.64	0.91	0.08	6.98	115.8	7.32
5/31	CLRI	159.5	26.44	0.49	0.08	0.08	12.18	85.5	7.25
5/31	CLRO	122.2	0.18	0.20	0.08	0.08	12.87	0.9	7.33
		Begin the "Before" Period, SRT = 4.85 Days							
6/2	A2	305.2	67.51	10.73	20.49	0.08	0.08	366.6	7.55
6/2	A3	278.4	56.20	10.03	21.52	0.08	0.08	1.4	7.49
6/2	A4	274.6	63.92	11.49	20.27	0.08	0.08	258.9	7.47
6/2	ABI	247.0	67.24	3.65	5.42	0.442	10.02	188.4	7.32
6/2	ABM	187.3	48.47	2.18	0.46	0.175	12.47	203.4	7.21
6/2	ABE	216.8	68.95	2.59	0.63	0.08	13.09	233.6	7.46
6/2	CLRI	147.7	27.06	0.61	0.27	0.08	12.98	49.2	7.33
6/2	CLRO	125.2	0.34	0.25	0.08	0.08	12.32	1.0	7.33

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APPENDIX A - AWT LABORATORY DATA

DATE	Loc	ALK mg/L	TOT-P mg P/L	OR-P mg P/L	NH4 mg N/L	NO2 mg N/L	NO3NO2 mg N/L	TKN mg N/L	PH siu
6/7	A2	261.2	47.17	10.32	15.66	0.08	0.08	139.9	7.51
6/7	A3	260.1	42.07	10.03	15.57	0.08	0.08	141.0	7.5
6/7	A4	255.9	48.10	11.05	14.99	0.08	0.08	95.2	7.49
6/7	ABI	207.9	43.76	3.86	0.90	0.121	10.24	152.0	7.42
6/7	ABM	190.5	47.36	6.18	3.85	0.316	7.18	150.7	7.3
6/7	ABE	218.0	60.31	3.64	0.82	0.103	10.31	147.6	7.3
6/7	CLRI	144.4	7.04	0.67	0.08	0.08	10.95	55.3	7.32
6/7	CLRO	130.0	0.38	0.24	0.08	0.08	11.32	0.7	7.3
6/9	A2	279.3	65.58	8.03	23.50	0.08	0.08	151.9	7.55
6/9	A3	280.8	67.06	8.02	23.37	0.08	0.08	165.8	7.53
6/9	A4	275.6	45.11	7.93	22.47	0.08	0.08	146.2	7.55
6/9	ABI	205.9	57.43	3.45	6.17	0.32	10.07	129.5	7.35
6/9	ABM	181.6	58.72	2.28	0.79	0.08	13.06	124.8	7.37
6/9	ABE	189.2	56.77	2.17	0.53	0.16	13.59	126.7	7.46
6/9	CLRI	138.5	22.21	1.28	0.18	0.08	13.02	50.5	7.33
6/9	CLRO	127.7	1.26	0.96	0.08	0.08	12.52	2.4	7.33
6/11	A2	281.2	17.09	8.78	17.04	0.08	0.08	160.0	7.56
6/11	A3	287.6	17.86	9.09	17.14	0.08	0.08	209.0	7.54
6/11	A4	316.4	17.11	10.06	16.50	0.08	0.08	122.9	7.54
6/11	ABI	229.3	14.41	5.32	4.86	0.286	7.62	147.3	7.3
6/11	ABM	209.3	13.10	1.34	0.50	0.08	11.36	159.9	7.33
6/11	ABE	214.5	13.96	1.92	0.47	0.08	11.44	148.2	7.38
6/11	CLRI	143.1	7.93	0.71	0.40	0.08	11.68	32.0	7.3
6/11	CLRO	127.4	0.40	0.38	0.08	0.08	12.48	4.4	7.3
6/14	A2	277.3	15.51	9.79	13.52	0.08	0.24	132.6	7.54
6/14	A3	269.6	14.19	10.46	13.78	0.08	0.08	121.0	7.5
6/14	A4	264.9	15.64	11.45	13.22	0.08	0.08	144.5	7.5
6/14	ABI	212.3	14.37	6.56	1.55	0.335	8.93	159.5	7.28
6/14	ABM	208.0	11.05	3.47	0.16	0.08	10.94	138.3	7.22
6/14	ABE	208.1	12.86	3.65	0.21	0.08	10.62	156.2	7.25
6/14	CLRI	144.8	5.28	0.89	0.08	0.08	11.19	33.8	7.22
6/14	CLRO	131.4	0.29	0.23	0.08	0.08	11.73	0.8	7.27

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APPENDIX A - AWT LABORATORY DATA

DATE	Loc	ALK mg/L	TOT-P mg P/L	OR-P mg P/L	NH4 mg N/L	NO2 mg N/L	NO3NO2 mg N/L	TKN mg N/L	PH siu
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
6/16	A2	264.3	32.93	10.07	16.02	0.08	0.08	117.0	7.52
6/16	A3	259.7	42.56	10.05	16.33	0.08	0.08	114.6	7.51
6/16	A4	262.1	42.10	10.92	15.42	0.08	0.08	122.4	7.51
6/16	ABI	208.3	51.57	0.78	3.74	0.101	8.19	148.8	7.36
6/16	ABM	201.9	66.87	0.32	0.79	0.08	10.96	164.0	7.41
6/16	ABE	205.0	55.23	2.52	0.69	0.08	11.07	149.0	7.51
6/16	CLRI	152.4	21.69	2.17	0.34	0.08	11.97	32.2	7.3
6/16	CLRO	129.7	0.54	0.31	0.08	0.08	12.67	0.5	7.29
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
6/18	A2	312.1	45.93	9.04	14.60	0.08	0.09	138.1	7.54
6/18	A3	264.4	52.08	9.15	14.69	0.08	0.08	225.0	7.53
6/18	A4	268.9	51.73	10.80	14.40	0.335	0.08	136.3	7.52
6/18	ABI	214.3	56.36	3.90	4.45	0.08	7.21	124.9	7.33
6/18	ABM	204.0	52.02	1.21	0.23	0.08	10.84	147.0	7.37
6/18	ABE	197.8	65.06	1.10	0.28	0.08	10.86	134.0	7.47
6/18	CLRI	144.8	17.29	0.28	0.10	0.08	11.69	32.4	7.31
6/18	CLRO	126.7	0.77	0.23	0.08	0.08	12.42	0.6	7.28
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
6/21	A2	259.1	54.80	9.85	16.58	0.08	0.08		7.56
6/21	A3	259.0	51.70	10.00	16.67	0.08	0.08		7.55
6/21	A4	269.7	78.80	10.40	15.69	0.08	0.08		7.54
6/21	ABI	219.0	86.60	4.62	5.74	0.241	6.66		7.33
6/21	ABM	189.1	68.20	0.91	0.29	0.098	10.79		7.5
6/21	ABE	188.2	89.50	0.79	0.29	0.08	11.01		7.43
6/21	CLRI	151.8	30.30	0.12	0.09	0.08	11.31		7.33
6/21	CLRO	132.4	0.24	0.04	0.08	0.08	11.82		7.37
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
6/23	A2	264.8	55.63	9.46	14.92	0.08	0.08		7.61
6/23	A3	266.9	52.25	9.29	14.91	0.08	0.08		7.59
6/23	A4	290.0	61.75	9.80	14.28	0.08	0.08		7.57
6/23	ABI	229.2	70.59	4.00	4.94	0.265	7.01		7.41
6/23	ABM	216.8	72.21	1.56	0.24	0.102	11.28		7.4
6/23	ABE	223.4	69.64	1.63	0.25	0.08	11.33		7.41
6/23	CLRI	136.2	13.43	0.13	0.13	0.08	11.75		7.37
6/23	CLRO	128.3	0.19	0.05	0.08	0.08	12.43		7.3

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DATE	Loc	ALK mg/L	TOT-P mg P/L	OR-P mg P/L	NH4 mg N/L	NO2 mg N/L	NO3NO2 mg N/L	TKN mg N/L	PH siu
6/25	A2	253.7	70.23	9.15	15.44	0.08	0.08	167.6	7.47
6/25	A3	258.3	66.29	9.65	15.36	0.08	0.08	139.3	7.46
6/25	A4	251.9	71.90	10.23	15.21	0.08	0.08	146.1	7.45
6/25	ABI	196.2	75.80	3.77	5.08	0.314	7.18	190.7	7.25
6/25	ABM	162.5	58.78	1.28	0.37	0.193	11.37	148.5	7.26
6/25	ABE	217.6	84.02	0.63	0.56	0.081	11.45	151.4	7.26
6/25	CLRI	138.1	27.27	0.17	0.14	0.08	11.84	58.9	7.23
6/25	CLRO	128.0	0.20	0.07	0.08	0.08	12.31	1.0	7.33
6/28	A2	258.7	81.59	8.94	16.30	0.08	0.08	134.2	7.57
6/28	A3	257.7	77.30	13.60	16.74	0.08	0.08	187.8	7.55
6/28	ABI	233.5	93.24	5.26	3.88	0.33	8.37	278.6	7.33
6/28	ABM	208.7	82.65	5.77	0.44	0.08	11.90	153.4	7.47
6/28	ABE	237.4	76.58	2.15	0.54	0.108	12.25	256.4	7.43
6/28	CLRI	165.8	42.82	0.58	0.23	0.08	12.06	67.2	7.3
6/28	CLRO	131.9	4.78	0.04	0.08	0.08	11.89	2.0	7.41
6/30	A2	261.0	69.58	12.82	14.88	0.08	0.08	185.3	7.54
6/30	A3	274.9	48.64	12.79	15.03	0.08	0.08	147.5	7.52
6/30	A4	267.4	71.39	8.66	14.61	0.08	0.08	215.4	7.5
6/30	ABI	211.2	90.72	7.98	3.98	0.437	8.14	283.3	7.33
6/30	ABM	208.4	93.09	3.23	0.44	0.107	11.73	150.0	7.48
6/30	ABE	209.1	85.68	3.67	0.44	0.08	11.61	204.1	7.41
6/30	CLRI	146.2	35.02	1.24	0.20	0.08	11.93	51.6	7.3
6/30	CLRO	128.9	7.95	0.04	0.08	0.08	12.20	1.8	7.38
7/2	A2	294.6	83.37	10.74	13.46	0.08	0.08	132.1	7.55
7/2	A3	295.6	81.91	11.11	13.41	0.08	0.08	136.4	7.54
7/2	A4	419.7	76.67	11.46	13.76	0.08	0.08	161.1	7.5
7/2	ABI	242.6	69.50	6.27	4.24	0.357	7.32	208.3	7.35
7/2	ABM	243.5	75.30	3.40	0.28	0.083	11.68	212.9	7.43
7/2	ABE	309.3	50.37	1.08	0.29	0.118	11.77	170.9	7.49
7/2	CLRI	172.3	30.27	0.28	0.08	0.08	11.97	71.2	7.4
7/2	CLRO	131.7	0.16	0.06	0.08	0.08	12.39	0.8	7.4

End the "Before" Period, SRT = 4.85 Days

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APPENDIX A - AWT LABORATORY DATA

DATE	Loc	ALK mg/L	TOT-P mg P/L	OR-P mg P/L	NH4 mg N/L	NO2 mg N/L	NO3NO2 mg N/L	TKN mg N/L	PH siu
7/7	A2	312.9	71.12	14.55	15.20	0.08	0.08	192.0	7.55
7/7	A3	337.4	76.88	14.41	15.03	0.08	0.08	187.8	7.55
7/7	A4	281.9	74.37	14.49	15.18	0.08	0.08	253.3	7.54
7/7	ABI	251.4	78.40	8.80	3.38	0.335	8.89	232.4	7.37
7/7	ABM	210.6	75.81	0.47	0.17	0.14	11.95	193.6	7.43
7/7	ABE	211.4	86.97	1.10	0.22	0.122	11.99	206.3	7.42
7/7	CLRI	154.1	34.54	0.19	0.08	0.08	11.99	81.9	7.32
7/7	CLRO	130.5	2.00	-0.04	0.08	0.08	12.22	1.2	7.43
7/9	A2	355.2	92.09	6.65	13.68	0.08	0.08	189.9	7.6
7/9	A3	418.9	79.46	6.87	13.69	0.08	0.08	205.7	7.58
7/9	A4	373.1	84.87	7.55	13.41	0.08	0.08	250.5	7.57
7/9	ABI	213.7	90.16	2.32	4.99	0.08	6.27	249.1	7.36
7/9	ABM	248.2	95.21	0.57	0.44	0.08	11.37	233.3	7.3
7/9	ABE	275.9	91.60	0.47	0.50	0.08	11.28	347.9	7.31
7/9	CLRI	135.6	16.28	0.16	0.22	0.08	10.70	80.7	7.27
7/9	CLRO	112.0	0.08	0.09	0.08	0.08	10.99	1.1	7.32
		Begin the Transition Period							
7/12	A2	329.0	67.90	4.66	19.57	0.08	0.08	199.0	7.27
7/12	A3	278.0	61.44	5.28	19.55	0.08	0.08	207.2	7.26
7/12	A4	327.0	59.05	5.87	19.11	0.08	0.08	283.4	7.26
7/12	ABI	288.0	67.98	0.47	5.34	0.08	11.43	232.1	7.05
7/12	ABM	242.0	76.96	0.16	0.48	0.08	10.82	226.7	6.94
7/12	ABE	211.0	68.14	0.29	0.50	0.08	12.43	254.3	6.89
7/12	CLRI	172.0	41.67	0.11	0.21	0.08	13.10	105.6	6.93
7/12	CLRO	130.0	0.20	0.09	0.08	0.08	11.42	1.1	7.05
7/14	A2	290.4	78.98	9.84	12.83	0.08	0.08	151.6	7.61
7/14	A3	483.7	73.78	9.35	13.06	0.08	0.08	93.9	7.59
7/14	A4	368.8	79.09	9.96	12.70	0.08	0.08	287.5	7.57
7/14	ABI	460.4	103.30	0.60	0.40	0.08	13.14	290.3	7.4
7/14	ABM	463.7	85.68	2.58	4.63	0.08	11.22	368.7	7.4
7/14	ABE	434.4	96.00	1.73	0.55	0.08	11.42	268.0	7.45
7/14	CLRI	148.8	15.85	0.08	0.22	0.08	10.83	25.9	7.32
7/14	CLRO	175.7	0.07	0.00	0.08	0.08	12.59	2.6	7.4

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APPENDIX A - AWT LABORATORY DATA

DATE	Loc	ALK mg/L	TOT-P mg P/L	OR-P mg P/L	NH4 mg N/L	NO2 mg N/L	NO3NO2 mg N/L	TKN mg N/L	PH siu
7/16	A2	351.1	76.70	8.32	13.65	0.08	0.08	214.6	7.6
7/16	A3	412.5	76.24	9.51	13.58	0.08	0.08	159.3	7.59
7/16	A4	323.4	83.08	9.48	14.14	0.08	0.08	290.5	7.56
7/16	ABI	288.3	97.56	0.22	0.56	0.08	11.22	179.9	7.4
7/16	ABM	313.1	92.31	3.83	3.54	0.08	8.00	284.9	7.36
7/16	ABE	254.0	99.76	0.68	0.54	0.08	11.42	241.8	7.4
7/16	CLRI	147.6	16.52	0.20	0.40	0.08	12.21	69.9	7.39
7/16	CLRO	129.6	0.06	0.00	0.08	0.08	12.03	0.5	7.38
7/19	A2	293.8	89.31	10.15	14.00	0.08	0.08	199.5	7.59
7/19	A3	287.8	89.56	9.82	14.54	0.08	0.08	189.2	7.58
7/19	A4	295.8	91.79	11.10	14.21	0.08	0.08	292.4	7.56
7/19	ABI	263.2	93.38	0.18	0.57	0.08	11.19	253.8	7.43
7/19	ABM	269.4	101.05	2.22	4.45	0.08	6.60	248.8	7.45
7/19	ABE	268.3	109.40	0.29	0.67	0.08	11.51	243.3	7.43
7/19	CLRI	147.2	19.01	0.05	0.24	0.08	11.44	67.7	7.42
7/19	CLRO	130.8	0.14	0.03	0.08	0.08	11.92	1.2	7.49
7/21	A2	420.5	67.10	8.60	12.98	0.08	0.08	210.0	7.65
7/21	A3	281.5	99.91	8.69	13.38	0.08	0.08	255.4	7.64
7/21	A4	265.9	102.21	9.35	12.66	0.08	0.08	172.3	7.64
7/21	ABI	249.8	142.13	0.23	0.39	0.08	12.08	335.5	7.47
7/21	ABM	261.6	97.33	3.39	3.54	0.08	0.08	240.6	7.57
7/21	ABE	246.1	98.44	0.73	0.38	0.08	8.50	348.0	7.52
7/21	CLRI	149.1	54.26	0.14	0.32	0.08	12.07	61.6	7.62
7/21	CLRO	127.0	0.38	0.04	0.08	0.08	11.81	1.2	7.67
		Begin the "AFter" Period, SRT = 6.0 Days							
7/23	A2	540.0	88.87	10.60	14.32	0.08	0.08	122.2	6.77
7/23	A3	376.7	65.81	10.48	14.33	0.08	0.08	245.6	6.76
7/23	A4	480.3	89.77	10.83	13.62	0.08	0.08	115.6	6.74
7/23	ABI	236.6	76.73	1.37	0.76	0.08	12.51	166.6	6.49
7/23	ABM	414.7	72.31	4.21	4.27	0.08	4.70	107.6	6.53
7/23	ABE	355.0	82.83	1.50	0.40	0.08	12.17	127.8	6.5
7/23	CLRI	179.6	51.07	1.33	0.22	0.08	12.56	100.6	6.51
7/23	CLRO	126.9	0.36	0.12	0.08	0.08	12.56	0.7	6.53

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APPENDIX A - AWT LABORATORY DATA

DATE	Loc	ALK mg/L	TOT-P mg P/L	OR-P mg P/L	NH4 mg N/L	NO2 mg N/L	NO3NO2 mg N/L	TKN mg N/L	PH siu
7/26	A2	309.5	93.42	11.45	15.84	0.08	0.08	329.5	6.71
7/26	A3	350.4	95.60	11.45	16.58	0.08	0.08	285.0	6.7
7/26	A4	323.1	99.82	11.82	16.02	0.08	0.08	150.6	6.7
7/26	ABI	353.0	119.93	0.28	0.71	0.08	10.88	349.0	6.54
7/26	ABM	394.0	121.75	2.05	4.24	0.08	8.41	133.0	6.52
7/26	ABE	236.9	123.80	0.77	0.74	0.08	11.41	311.2	6.53
7/26	CLRI	162.5	40.75	0.12	0.33	0.08	11.53	120.4	6.53
7/26	CLRO	131.7	0.15	0.05	0.24	0.08	11.43	1.1	6.56
7/28	A2	326.3	78.24	8.85	14.52	0.08	0.08	223.5	6.75
7/28	A3	365.9	71.86	8.92	14.62	0.08	0.08	407.5	6.73
7/28	A4	377.9	81.68	9.10	14.35	0.08	0.08	294.6	6.71
7/28	ABI	386.0	82.09	0.24	0.19	0.163	12.62	410.2	6.55
7/28	ABM	296.9	79.28	1.99	3.52	0.332	8.52	148.0	6.53
7/28	ABE	356.2	81.93	0.29	0.18	0.08	12.63	132.0	6.52
7/28	CLRI	165.5	65.79	0.08	0.13	0.08	11.07	130.6	6.52
7/28	CLRO	130.1	0.33	0.06	0.08	0.08	12.63	0.5	6.52
7/30	A2	290.5	73.25	8.64	15.91	0.08	0.08	329.5	6.85
7/30	A3	347.9	80.89	8.64	15.31	0.08	0.08	316.2	6.79
7/30	A4	322.3	82.71	8.54	15.41	0.08	0.08	251.5	6.78
7/30	ABI	276.6	72.22	0.13	0.63	0.08	12.99	167.6	6.65
7/30	ABM	288.7	80.04	3.47	3.27	0.08	9.57	274.8	6.58
7/30	ABE	256.1	83.47	1.14	0.56	0.08	13.91	421.2	6.66
7/30	CLRI	197.4	58.74	0.23	0.29	0.08	14.13	116.9	6.61
7/30	CLRO	123.2	0.31	0.06	0.08	0.08	14.56	2.5	6.6
8/2	A2	317.2	108.66	13.01	15.14	0.08	0.08	191.9	6.8
8/2	A3	345.4	107.40	13.54	15.19	0.08	0.08	180.9	6.89
8/2	A4	344.3	115.72	14.36	15.65	0.08	0.08	244.2	6.78
8/2	ABI	307.2	126.82	0.11	0.64	0.08	10.82	327.3	6.59
8/2	ABM	459.7	125.10	3.30	3.98	0.08	7.05	131.0	6.56
8/2	ABE	329.6	107.94	0.13	0.54	0.08	11.31	293.5	6.57
8/2	CLRI	184.3	46.58	-0.01	0.17	0.08	11.53	5.5	6.61
8/2	CLRO	132.7	0.09	-0.02	0.08	0.08	11.61	1.2	6.62

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APPENDIX A - AWT LABORATORY DATA

DATE	Loc	ALK mg/L	TOT-P mg P/L	OR-P mg P/L	NH4 mg N/L	NO2 mg N/L	NO3NO2 mg N/L	TKN mg N/L	PH siu
[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
8/4	A2	448.8	78.08	10.80	14.86	0.08	0.08	206.0	
8/4	A3	390.2	69.07	10.65	15.42	0.08	0.08	200.9	
8/4	A4	320.1	92.71	11.21	15.10	0.08	0.08	238.8	
8/4	ABI	321.7	77.45	0.47	0.39	0.092	12.49	306.2	
8/4	ABM	187.8	52.04	0.21	0.29	0.08	12.15	133.4	
8/4	ABE	298.7	99.22	1.14	0.45	0.08	12.54	354.0	
8/4	CLRI	252.0	93.75	3.72	4.05	0.294	8.04	319.7	
8/4	CLRO	128.0	0.51	0.12	0.08	0.08	12.59	0.7	
[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
8/6	A2	304.8	76.53	10.38	15.76	0.08	0.08	190.0	6.76
8/6	A3	290.7	80.45	10.40	15.50	0.08	0.08	233.1	6.77
8/6	A4	299.7	85.09	10.47	15.43	0.08	0.08	228.8	6.72
8/6	ABI	230.1	91.66	1.31	0.68	0.08	12.54	200.5	6.62
8/6	ABM	248.0	93.84	5.01	4.34	0.08	8.63	117.5	6.6
8/6	ABE	237.9	94.43	1.42	0.82	0.08	12.53	211.3	6.6
8/6	CLRI	177.1	65.35	0.29	0.37	0.08	12.19	70.0	6.58
8/6	CLRO	131.2	0.24	0.08	0.08	0.08	12.36	1.3	6.6
[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
8/9	A2	299.9	123.55	13.43	14.36	0.08	0.08	319.5	6.83
8/9	A3	468.3	121.05	14.05	14.83	0.08	0.08	366.5	6.81
8/9	A4	306.9	115.50	9.66	14.85	0.08	0.08	229.0	6.8
8/9	ABI	270.9	120.74	0.15	0.53	0.08	12.20	23.7	6.8
8/9	ABM	333.7	116.51	2.29	4.47	0.08	6.94		6.67
8/9	ABE	384.8	117.47	0.09	0.62	0.08	12.15	444.6	6.74
8/9	CLRI	152.6	22.63	0.04	0.16	0.08	11.11	49.5	6.71
8/9	CLRO	137.6	0.28	0.03	0.08	0.08	11.18	0.6	6.7
[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
8/11	A2	486.5	86.31	8.30	16.32	0.08	0.08		6.82
8/11	A3	340.5	82.14	8.33	16.08	0.08	0.10	162.4	6.81
8/11	A4	529.1	79.56	7.17	16.48	0.08	0.08	355.0	6.8
8/11	ABI	506.2	81.15	0.80	0.57	0.08	12.60	243.2	6.63
8/11	ABM	439.6	82.47	2.94	3.44	0.08	9.02	237.2	6.67
8/11	ABE	435.0	87.11	1.41	0.72	0.08	11.95	178.5	6.74
8/11	CLRI	135.3	8.72	0.04	0.13	0.08	12.30	16.0	6.72
8/11	CLRO	134.6	0.29	0.04	0.08	0.08	11.80	0.8	6.7

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APPENDIX A - AWT LABORATORY DATA

DATE	Loc	ALK mg/L	TOT-P mg P/L	OR-P mg P/L	NH4 mg N/L	NO2 mg N/L	NO3NO2 mg N/L	TKN mg N/L	PH siu
8/13	A2	482.8	110.08	18.04	15.12	0.08	0.08	253.9	6.88
8/13	A3	357.3	108.81	16.71	15.15	0.08	0.08	248.1	6.86
8/13	A4	423.5	115.46	16.39	14.72	0.08	0.08	248.2	6.83
8/13	ABI	396.2	107.95	2.37	0.50	0.094	12.19	195.5	6.64
8/13	ABM	427.1	124.57	5.60	4.28	0.243	7.90	234.3	6.67
8/13	ABE	284.5	121.87	1.14	0.56	0.122	12.13	328.1	6.71
8/13	CLRI	133.5	74.51	0.89	0.17	0.08	12.21	72.8	6.67
8/13	CLRO	133.8	0.25	0.07	0.08	0.085	12.21	1.3	6.68
			End the "AFter" Period, SRT = 6.0 Days						
8/16	A2	432.1	74.38	9.81	16.82	0.08	0.08	274.9	6.94
8/16	A3	569.5	88.03	9.76	16.76	0.08	0.08	222.5	6.92
8/16	A4	431.8	68.56	9.86	16.62	0.08	0.08	159.9	6.88
8/16	ABI	391.1	92.15	1.60	0.61	0.08	11.30	399.6	6.8
8/16	ABM	429.5	102.74	3.90	5.11	0.093	6.06	178.2	6.79
8/16	ABE	431.9	87.54	1.74	0.68	0.08	11.72	320.9	6.79
8/16	CLRI	239.0	59.16	0.33	0.25	0.08	11.76	31.1	6.79
8/16	CLRO	135.4	0.38	0.11	0.08	0.08	11.66	1.0	6.76
8/18	A2	423.1	84.87	7.89	16.84	0.08	0.08	316.4	
8/18	A3	338.3	86.23	7.97	18.32	0.08	0.08	390.0	
8/18	A4	350.4	79.97	8.38	16.71	0.08	0.08	257.3	
8/18	ABI	258.5	76.70	0.08	0.66	0.08	11.98	152.7	
8/18	ABM	288.4	88.53	0.79	5.08	0.183	6.49	250.1	
8/18	ABE	356.4	97.05	0.08	0.63	0.08	12.07	148.9	
8/18	CLRI	272.6	61.36	0.06	0.38	0.08	11.87	88.8	
8/18	CLRO	118.7	0.24	0.08	0.08	0.08	12.18	1.8	
8/20	A2	484.2	78.93	9.95	14.18	0.08	0.08	179.5	
8/20	A3	340.0	74.52	9.92	14.88	0.08	0.08	138.7	
8/20	A4	466.4	87.01	10.00	15.80	0.08	0.08	296.6	
8/20	ABI	180.7	93.44	1.22	0.29	0.08	11.51	86.1	
8/20	ABM	333.7	83.75	4.93	4.31	0.121	7.05	294.6	
8/20	ABE	448.3	91.53	1.66	0.47	0.08	11.61	432.9	
8/20	CLRI	131.4	64.46	0.32	0.20	0.08	10.50	98.4	
8/20	CLRO	134.9	0.17	0.08	0.09	0.08	10.02	0.8	

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APPENDIX A - AWT LABORATORY DATA

DATE	Loc	ALK mg/L	TOT-P mg P/L	OR-P mg P/L	NH4 mg N/L	NO2 mg N/L	NO3NO2 mg N/L	TKN mg N/L	PH siu
8/23	A2	368.2	76.77	9.40	15.49	0.08	0.08	294.0	
8/23	A3	308.3	89.74	9.42	16.58	0.08	0.08	122.8	
8/23	A4	266.5	90.59	9.42	18.51	0.08	0.08	173.7	
8/23	ABI	180.4	93.14	1.76	0.25	0.08	11.25	307.1	
8/23	ABM	221.3	92.81	5.07	4.60	0.08	5.80	205.5	
8/23	ABE	348.1	87.54	1.77	0.15	0.08	10.92	178.3	
8/23	CLRI	134.5	55.97	0.31	0.08	0.08	9.82	104.2	
8/23	CLRO	116.4	0.21	0.14	0.13	0.08	10.43	0.7	
8/25	A2	469.4	75.84	7.25	20.22	0.08	0.08	174.6	
8/25	A3	387.5	76.70	7.45	18.52	0.08	0.08	428.1	
8/25	A4	423.0	76.55	7.66	17.60	0.08	0.08	168.4	
8/25	ABI	416.3	75.67	0.66	0.24	0.08	12.40	176.2	
8/25	ABM	394.5	72.11	2.13	5.35	0.08	8.25	326.9	
8/25	ABE	269.6	73.76	0.73	0.28	0.08	12.92	182.1	
8/25	CLRI	156.8	61.96	0.11	0.08	0.08	13.00	91.4	
8/25	CLRO	129.4	0.29	0.02	0.08	0.08	11.84	0.5	
8/27	A2	334.3	74.24	7.69	14.53	0.08	0.08	132.5	
8/27	A3	372.5	77.45	7.71	15.27	0.08	0.08	167.4	
8/27	A4	393.3	77.69	7.73	19.43	0.08	0.08	157.6	
8/27	ABI	289.3	74.81	0.72	0.32	0.08	11.96	164.0	
8/27	ABM	351.2	72.34	3.49	4.28	0.117	7.11	193.5	
8/27	ABE	282.8	73.71	0.63	0.15	0.08	12.09	146.4	
8/27	CLRI	154.3	56.10	0.17	0.08	0.08	12.07	90.3	
8/27	CLRO	133.1	0.28	0.05	0.08	0.08	12.02	0.8	

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APPENDIX B

HYDROLAB DATA, PHASE I, BIO-P REMOVAL STUDY

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APPENDIX B - HYDROLAB DATA

Region	DO	pH	ORP	Cond	Temp	Date	
A2	0.25	7.12	165	2040	22.60	23-Mar-99	7560
A3	0.22	7.12	88	2040	22.60	23-Mar-99	
A4	0.22	7.11	52	2040	22.65	23-Mar-99	
ABI	0.74	6.87	203	1930	22.80	23-Mar-99	2150
ABM	1.74	6.67	362	1780	22.90	23-Mar-99	
CLRO	0.32	6.75	338	1770	22.90	23-Mar-99	
CLRI	0.36	6.76	340	1770	22.90	23-Mar-99	1.90
A2	0.25	7.17	160	2130	22.80	25-Mar-99	7650
A3	0.22	7.17	68	2130	22.80	25-Mar-99	
A4	0.19	7.14	9	2120	22.80	25-Mar-99	
ABI	0.73	6.80	305	1890	23.00	25-Mar-99	2040
ABM	1.76	6.74	319	1900	23.00	25-Mar-99	
CLRO	0.39	6.78	332	1830	23.10	25-Mar-99	
CLRI	0.31	6.76	315	1840	23.10	25-Mar-99	1.30
A2	0.27	7.17	160	2020	23.40	27-Mar-99	7650
A3	0.19	7.15	70	2030	23.40	27-Mar-99	
A4	0.18	7.14	38	2050	23.40	27-Mar-99	
ABI	1.14	6.86	204	1960	23.50	27-Mar-99	2040
ABM	1.80	6.70	352	2000	23.40	27-Mar-99	
CLRO	0.37	6.75	355	1910	23.30	27-Mar-99	
CLRI	0.26	6.72	329	1910	23.30	27-Mar-99	1.65
A2	0.30	7.21	155	2110	22.50	06-Apr-99	7250
A3	0.23	7.20	105	2120	22.50	06-Apr-99	
A4	0.19	7.18	62	2110	22.50	06-Apr-99	
ABI	0.50	6.90	201	1910	22.50	06-Apr-99	2140
ABM	1.50	6.78	278	1870	22.60	06-Apr-99	
CLRO	0.43	6.90	345	1880	22.40	06-Apr-99	
CLRI	0.37	6.86	315	1880	22.50	06-Apr-99	2.00

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APPENDIX B - HYDROLAB DATA

A2	0.29	7.25	158	2110	22.50	08-Apr-99	7910
A3	0.23	7.27	109	2110	22.50	08-Apr-99	
A4	0.20	7.22	57	2120	22.50	08-Apr-99	
ABI	0.39	6.92	200	1910	22.55	08-Apr-99	2070
ABM	1.95	6.80	270	1890	22.73	08-Apr-99	
CLRO	0.48	6.86	361	1820	22.60	08-Apr-99	
CLRI	0.35	6.86	332	1850	22.65	08-Apr-99	2.20
A2	0.29	7.27	108	1980	23.20	11-Apr-99	8050
A3	0.26	7.27	69	1960	23.20	11-Apr-99	
A4	0.26	7.26	28	1970	23.20	11-Apr-99	
ABI	1.15	7.00	215	1870	23.20	11-Apr-99	2010
ABM	1.75	6.83	342	1910	23.18	11-Apr-99	
CLRO	0.51	6.86	325	1900	23.16	11-Apr-99	
CLRI	0.33	6.82	313	1930	23.16	11-Apr-99	2.30
A2	0.30	7.27	155	2150	22.70	15-Apr-99	7980
A3	0.22	7.27	127	2140	22.70	15-Apr-99	
A4	0.24	7.26	68	2140	22.70	15-Apr-99	
ABI	0.68	6.98	222	1920	23.10	15-Apr-99	2100
ABM	1.69	6.85	302	1810	23.14	15-Apr-99	
CLRO	0.49	6.90	222	1890	23.10	15-Apr-99	
CLRI	0.33	6.86	260	1890	23.10	15-Apr-99	2.20
A2	0.32	7.28	165	2010	23.75	18-Apr-99	8180
A3	0.26	7.29	132	2020	23.90	18-Apr-99	
A4	0.25	7.28	88	2030	23.90	18-Apr-99	
ABI	1.04	7.04	227	2010	24.00	18-Apr-99	2090
ABM	1.95	6.93	273	1910	24.00	18-Apr-99	
CLRO	0.5	6.95	343	1890	23.90	18-Apr-99	1.80
CLRI	0.52	6.90	325	1920	23.92	18-Apr-99	

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APPENDIX B - HYDROLAB DATA

A2	0.29	7.22	145	1970	24.00	20-Apr-99	6320
A3	0.26	7.21	111	1980	24.00	20-Apr-99	
A4	0.25	7.18	62	1920	24.40	20-Apr-99	
ABI	0.55	6.85	204	1950	24.50	20-Apr-99	1760
ABM	1.60	6.74	330	1950	23.80	20-Apr-99	
CLRO	0.43	6.75	330	1950	24.45	20-Apr-99	
CLRI	0.36	6.74	320	1940	24.45	20-Apr-99	1.70
A2	0.29	7.43	160	2010	23.65	24-Apr-99	5560
A3	0.27	7.44	141	2020	23.70	24-Apr-99	
A4	0.21	7.41	110	2020	23.70	24-Apr-99	
ABI	1.45	7.15	217	2010	23.65	24-Apr-99	1540
ABM	2.38	7.03	275	1920	23.60	24-Apr-99	
CLRO	0.70	7.03	308	1860	23.50	24-Apr-99	
CLRI	0.63	6.98	305	1920	23.60	24-Apr-99	1.90
A2	0.44	7.50	81	2180	25.00	24-May-99	7290
A3	0.34	7.48	56	2190	25.01	24-May-99	
A4	0.26	7.50	19	2190	24.97	24-May-99	
ABI	1.16	7.27	154	2000	25.25	24-May-99	1900
ABM	2.05	7.20	225	1910	25.34	24-May-99	
CLRO	0.37	7.23	244	1820	25.40	24-May-99	
CLRI	0.55	7.14	254	1840	25.40	24-May-99	2.30
A2	0.38	7.44	95	2200	25.10	26-May-99	**RAS**
A3	0.32	7.43	72	2190	25.15	26-May-99	5120
A4	0.29	7.42	42	2170	25.50	26-May-99	
ABI	0.60	7.17	185	1910	25.50	26-May-99	**MLSS**
ABM	2.40	7.15	206	1840	25.55	26-May-99	2020
ABE	2.60	7.15	240	1850	25.60	26-May-99	
CLRO	0.56	7.14	290	1840	25.60	26-May-99	**MDO**
CLRI	0.6	7.12	260	1850	25.60	26-May-99	2.00

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APPENDIX B - HYDROLAB DATA

A2	0.30	7.44	155	2190	25.5	28-May-99	**RAS**
A3	0.27	7.44	106	2190	25.50	28-May-99	5570
A4	0.24	7.44	55	2190	25.52	28-May-99	
ABI	0.98	7.18	211	2190	25.80	28-May-99	**MLSS**
ABM	2.34	7.04	328	1880	25.94	28-May-99	1890
ABE	3.06	7.10	330	1880	25.98	28-May-99	
CLRO	0.5	7.25	347	1830	25.98	28-May-99	**MDO**
CLRI	0.52	7.14	338	1830	25.99	28-May-99	2.00
A2	0.29	7.49	158	2000	25.33	31-May-99	**RAS**
A3	0.28	7.47	112	1980	25.40	31-May-99	5620
A4	0.27	7.46	56	1950	25.42	31-May-99	
ABI	0.92	7.21	200	1780	25.70	31-May-99	**MLSS**
ABM	3.89	7.33	232	1750	25.70	31-May-99	1890
ABE	3.91	7.32	240	1770	25.80	31-May-99	
CLRO	0.9	7.33	250	1800	25.70	31-May-99	**MDO**
CLRI	1.02	7.25	260	1770	25.70	31-May-99	3.90
	Begin the "Before" Period, SRT = 4.85 Days						
A2	0.33	7.55	202	2260	25.08	02-Jun-99	**RAS**
A3	0.29	7.53	167	2250	25.08	02-Jun-99	5830
A4	0.25	7.30	105	2250	25.05	02-Jun-99	
ABI	0.60	7.32	200	2020	25.20	02-Jun-99	**MLSS**
ABM	2.32	7.30	225	1930	25.40	02-Jun-99	1710
ABE	2.8	7.27	252	1980	25.40	02-Jun-99	
CLRO	0.72	7.29	255	1830	25.40	02-Jun-99	**MDO**
CLRI	0.91	7.25	265	1830	25.40	02-Jun-99	2.20
A2	0.32	7.48	178	2010	25.4	07-Jun-99	**RAS**
A3	0.29	7.47	105	1980	25.45	07-Jun-99	4180
A4	0.24	7.47	82	1980	25.40	07-Jun-99	
ABI	0.96	7.35	198	1810	25.50	07-Jun-99	**MLSS**
ABM	2.20	7.32	215	1800	25.50	07-Jun-99	1850
ABE	2.9	7.3	225	1780	25.60	07-Jun-99	
CLRO	0.72	7.32	231	1770	25.60	07-Jun-99	**MDO**
CLRI	0.96	7.31	229	1790	25.60	07-Jun-99	2.40

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APPENDIX B - HYDROLAB DATA

A2	0.30	7.55	161	1990	25.33	09-Jun-99	**RAS**
A3	0.30	7.55	121	1960	25.32	09-Jun-99	3330
A4	0.28	7.55	91	1950	25.35	09-Jun-99	
ABI	0.95	7.35	195	1800	25.45	09-Jun-99	**MLSS**
ABM	3.50	7.37	230	1790	25.55	09-Jun-99	1510
ABE	3.00	7.46	238	1790	25.60	09-Jun-99	
CLRO	0.76	7.33	243	1820	25.40	09-Jun-99	**MDO**
CLRI	1.02	7.33	250	1810	25.50	09-Jun-99	3.20
A2	0.30	7.56	131	2030	25.60	11-Jun-99	**RAS**
A3	0.28	7.54	96	2040	25.60	11-Jun-99	3950
A4	0.25	7.54	65	2010	25.90	11-Jun-99	
ABI	1.06	7.39	195	1840	25.90	11-Jun-99	**MLSS**
ABM	3.11	7.33	225	1830	25.90	11-Jun-99	1450
ABE	3.17	7.38	236	1810	25.90	11-Jun-99	
CLRO	0.66	7.30	240	1830	25.90	11-Jun-99	**MDO**
CLRI	0.95	7.30	246	1850	25.90	11-Jun-99	3.10
A2	0.36	7.54	168	2180	26.07	14-Jun-99	**RAS**
A3	0.30	7.50	118	2160	26.10	14-Jun-99	4680
A4	0.28	7.50	77	2170	26.09	14-Jun-99	
ABI	1.60	7.28	205	2010	26.30	14-Jun-99	**MLSS**
ABM	2.25	7.22	231	1910	26.50	14-Jun-99	1270
ABE	2.34	7.25	273	1920	26.50	14-Jun-99	
CLRO	0.38	7.27	268	1810	26.60	14-Jun-99	**MDO**
CLRI	0.48	7.22	261	1860	26.55	14-Jun-99	2.20
A2	0.33	7.52	121	1980	26.40	16-Jun-99	**RAS**
A3	0.26	7.51	98	1960	26.15	16-Jun-99	3680
A4	0.25	7.51	65	1930	26.18	16-Jun-99	
ABI	1.26	7.29	190	1820	26.40	16-Jun-99	**MLSS**
ABM	3.35	7.41	221	1790	26.50	16-Jun-99	1410
ABE	3.38	7.36	230	1790	26.50	16-Jun-99	
CLRO	0.70	7.29	233	1800	26.6	16-Jun-99	**MDO**
CLRI	1.07	7.30	240	1810	26.6	16-Jun-99	3.40

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APPENDIX B - HYDROLAB DATA

A2	0.25	7.54	119	1940	26.20	18-Jun-99	**RAS**
A3	0.19	7.53	93	1910	26.25	18-Jun-99	3210
A4	0.29	7.52	68	1890	26.25	18-Jun-99	
ABI	1.25	7.33	180	1730	26.50	18-Jun-99	**MLSS**
ABM	3.65	7.37	230	1770	26.50	18-Jun-99	1410
ABE	3.9	7.47	238	1780	26.50	18-Jun-99	
CLRO	0.72	7.31	240	1840	26.40	18-Jun-99	**MDO**
CLRI	1.13	7.28	250	1820	26.50	18-Jun-99	3.60
A2	0.20	7.56	99	2030	26.35	21-Jun-99	**RAS**
A3	0.19	7.55	76	2040	26.30	21-Jun-99	5420
A4	0.26	7.54	40	2020	26.60	21-Jun-99	
ABI	0.49	7.33	158	1790	26.60	21-Jun-99	**MLSS**
ABM	2.64	7.50	239	1790	26.85	21-Jun-99	1410
ABE	2.65	7.43	225	1770	26.80	21-Jun-99	
CLRO	0.55	7.37	225	1770	26.80	21-Jun-99	**MDO**
CLRI	0.8	7.33	230	1770	26.80	21-Jun-99	2.20
A2	0.24	7.61	108	2020	26.36	23-Jun-99	**RAS**
A3	0.19	7.59	92	2010	26.38	23-Jun-99	4650
A4	0.16	7.57	60	2000	26.40	23-Jun-99	
ABI	0.49	7.41	175	1810	26.60	23-Jun-99	**MLSS**
ABM	2.05	7.40	215	1790	26.80	23-Jun-99	1510
ABE	2.52	7.41	240	1780	26.70	23-Jun-99	
CLRO	0.64	7.30	249	1800	26.00	23-Jun-99	**MDO**
CLRI	0.49	7.37	240	1790	26.70	23-Jun-99	1.90
A2	0.34	7.47	98	1990	26.46	25-Jun-99	**RAS**
A3	0.29	7.46	71	1980	26.49	25-Jun-99	4790
A4	0.28	7.45	46	1980	26.55	25-Jun-99	
ABI	0.65	7.25	172	1810	26.70	25-Jun-99	**MLSS**
ABM	2.35	7.26	260	1760	26.75	25-Jun-99	1620
ABE	2.60	7.26	272	1770	26.80	25-Jun-99	
CLRO	0.5	7.33	284	1810	26.90	25-Jun-99	**MDO**
CLRI	0.56	7.23	283	1810	26.80	25-Jun-99	2.10

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APPENDIX B - HYDROLAB DATA

A2	0.27	7.57	78	2050	26.55	28-Jun-99	**RAS**
A3	0.22	7.55	57	2030	26.55	28-Jun-99	5250
A4	0.21	7.52	42	2030	26.59	28-Jun-99	
ABI	0.58	7.33	165	1810	26.80	28-Jun-99	**MLSS**
ABM	2.90	7.47	220	1820	26.88	28-Jun-99	1946
ABE	3.15	7.43	237	1790	26.89	28-Jun-99	
CLRO	0.41	7.41	241	1750	26.90	28-Jun-99	**MDO**
CLRI	0.8	7.30	237	1760	27.00	28-Jun-99	2.20
A2	0.21	7.54	105	1980	26.85	30-Jun-99	**RAS**
A3	0.18	7.52	80	1980	26.90	30-Jun-99	4980
A4	0.18	7.50	47	1980	26.90	30-Jun-99	
ABI	0.57	7.33	177	1780	27.20	30-Jun-99	**MLSS**
ABM	2.41	7.48	220	1790	27.20	30-Jun-99	1980
ABE	2.61	7.41	239	1730	27.30	30-Jun-99	
CLRO	0.5	7.38	258	1790	27.20	30-Jun-99	**MDO**
CLRI	0.58	7.30	256	1800	27.20	30-Jun-99	2.00
A2	0.35	7.55	112	2040	26.85	02-Jul-99	**RAS**
A3	0.27	7.54	78	2020	26.90	02-Jul-99	7060
A4	0.24	7.50	50	2030	27.10	02-Jul-99	
ABI	0.55	7.35	169	1870	27.20	02-Jul-99	**MLSS**
ABM	2.51	7.43	230	1800	27.25	02-Jul-99	1840
ABE	2.95	7.49	268	1790	27.30	02-Jul-99	
CLRO	0.47	7.4	269	1800	27.30	02-Jul-99	**MDO**
CLRI	0.77	7.4	277	1800	27.30	02-Jul-99	2.20
A2	0.35	7.55	112	2040	26.85	02-Jul-99	7060
A3	0.27	7.54	78	2020	26.90	02-Jul-99	
A4	0.24	7.50	50	2030	27.10	02-Jul-99	
ABI	0.55	7.35	169	1870	27.20	02-Jul-99	1840
ABM	2.51	7.43	230	1800	27.25	02-Jul-99	
ABE	2.95	7.49	268	1790	27.30	02-Jul-99	
CLRO	0.47	7.4	269	1800	27.30	02-Jul-99	2.20
CLRI	0.77	7.4	277	1800	27.30	02-Jul-99	

End the "Before" Period, SRT = 4.85 Days

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APPENDIX B - HYDROLAB DATA

A2	0.33	7.55	90	2000	27.2	07-Jul-99	6860
A3	0.28	7.55	76	1990	27.25	07-Jul-99	
A4	0.25	7.54	58	1970	27.25	07-Jul-99	
ABI	0.42	7.37	193	1810	27.50	07-Jul-99	2020
ABM	2.10	7.43	226	1780	27.60	07-Jul-99	
ABE	2.90	7.42	242	1750	27.65	07-Jul-99	
CLRO	0.45	7.43	246	1780	27.60	07-Jul-99	1.90
CLRI	0.38	7.32	259	1780	27.60	07-Jul-99	
A2	0.34	7.60	150	2130	27.01	09-Jul-99	7570
A3	0.29	7.58	128	2130	27.05	09-Jul-99	
A4	0.25	7.57	98	2030	27.15	09-Jul-99	
ABI	0.65	7.36	205	1800	27.30	09-Jul-99	2020
ABM	2.12	7.30	254	1800	27.40	09-Jul-99	
ABE	2.31	7.31	260	1810	27.40	09-Jul-99	
CLRO	0.41	7.32	265	1790	27.40	09-Jul-99	1.90
CLRI	0.7	7.27	270	1780	27.40	09-Jul-99	
	Begin the "Transition" Period						
A2	0.31	7.61	142	1890	27.05	14-Jul-99	6060
A3	0.27	7.59	121	1890	27.05	14-Jul-99	
A4	0.25	7.57	92	1890	27.05	14-Jul-99	
ABI	0.51	7.40	177	1770	27.30	14-Jul-99	2270
ABM	2.32	7.40	244	1710	27.60	14-Jul-99	
ABE	2.65	7.45	259	1700	27.60	14-Jul-99	
CLRO	0.30	7.40	258	1730	27.70	14-Jul-99	2.10
CLRI	0.42	7.32	261	1740	27.70	14-Jul-99	
A2	0.27	7.60	104	2020	27.20	16-Jul-99	7170
A3	0.25	7.59	89	2000	27.20	16-Jul-99	
A4	0.24	7.56	69	2000	27.25	16-Jul-99	
ABI	0.55	7.36	191	1810	27.60	16-Jul-99	2310
ABM	2.65	7.40	235	1800	27.70	16-Jul-99	
ABE	2.75	7.47	260	1790	27.70	16-Jul-99	
CLRO	0.35	7.38	250	1820	27.68	16-Jul-99	2.30
CLRI	0.45	7.39	261	1810	27.70	16-Jul-99	

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APPENDIX B - HYDROLAB DATA

A2	0.32	7.59	96	2030	27.15	19-Jul-99	8110
A3	0.28	7.58	77	2040	27.15	19-Jul-99	
A4	0.25	7.56	58	1980	27.17	19-Jul-99	
ABI	0.55	7.45	158	1800	27.50	19-Jul-99	2610
ABM	1.95	7.43	230	1780	27.60	19-Jul-99	
ABE	2.6	7.43	251	1710	27.60	19-Jul-99	
CLRO	0.38	7.49	250	1790	27.58	19-Jul-99	1.40
CLRI	0.42	7.42	260	1780	27.60	19-Jul-99	
A2	0.31	7.65	89	2020	26.98	21-Jul-99	4470
A3	0.28	7.64	75	2020	27.00	21-Jul-99	
A4	0.24	7.64	75	2020	27.00	21-Jul-99	
ABI	0.55	7.57	55	1870	27.25	21-Jul-99	2730
ABM	1.99	7.47	204	1810	27.35	21-Jul-99	
ABE	2.7	7.52	230	1800	27.45	21-Jul-99	
CLRO	0.42	7.67	242	1790	27.40	21-Jul-99	1.70
CLRI	0.51	7.62	238	1810	27.40	21-Jul-99	
Begin the "After" Period, SRT = 6.0 Days							
A2	0.38	6.77	105	NR	27.10	23-Jul-99	8760
A3	0.32	6.76	101	NR	27.15	23-Jul-99	
A4	0.27	6.74	81	NR	27.45	23-Jul-99	
ABI	2.45	6.53	260	NR	27.50	23-Jul-99	2830
ABM	3.20	6.49	352	NR	27.60	23-Jul-99	
ABE	3.15	6.50	363	NR	27.60	23-Jul-99	
CLRO	0.35	6.53	345	NR	27.50	23-Jul-99	2.10
CLRI	0.43	6.51	349	NR	27.50	23-Jul-99	
A2	0.33	6.71	80	NR	27.42	26-Jul-99	9060
A3	0.30	6.70	76	NR	27.40	26-Jul-99	
A4	0.27	6.70	68	NR	27.43	26-Jul-99	
ABI	1.75	6.52	232	NR	27.76	26-Jul-99	2880
ABM	2.34	6.54	313	NR	27.85	26-Jul-99	
ABE	2.60	6.53	319	NR	27.89	26-Jul-99	
CLRO	0.37	6.56	311	NR	27.85	26-Jul-99	2.00
CLRI	0.39	6.53	313	NR	27.84	26-Jul-99	

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APPENDIX B - HYDROLAB DATA

A2	0.33	6.75	86	NR	27.45	28-Jul-99	8990
A3	0.28	6.73	82	NR	27.42	28-Jul-99	
A4	0.23	6.71	69	NR	27.40	28-Jul-99	
ABI	0.78	6.53	202	NR	27.75	28-Jul-99	2790
ABM	2.55	6.55	251	NR	27.90	28-Jul-99	
ABE	2.70	6.52	277	NR	27.95	28-Jul-99	
CLRO	0.36	6.52	281	NR	27.81	28-Jul-99	1.90
CLRI	0.35	6.52	278	NR	27.82	28-Jul-99	
A2	0.35	6.85	105	NR	27.4	30-Jul-99	9420
A3	0.29	6.79	92	NR	27.41	30-Jul-99	
A4	0.28	6.78	79	NR	27.45	30-Jul-99	
ABI	0.90	6.58	209	NR	27.70	30-Jul-99	2670
ABM	2.77	6.65	267	NR	27.85	30-Jul-99	
ABE	2.95	6.66	283	NR	27.80	30-Jul-99	
CLRO	0.34	6.6	281	NR	27.82	30-Jul-99	2.30
CLRI	0.42	6.61	279	NR	27.84	30-Jul-99	
A2	0.34	6.82	95	NR	27.38	02-Aug-99	8950
A3	0.28	6.78	65	NR	27.37	02-Aug-99	
A4	0.27	6.76	74	NR	27.42	02-Aug-99	
ABI	0.79	6.59	211	NR	27.69	02-Aug-99	2840
ABM	2.63	6.64	259	NR	27.82	02-Aug-99	
ABE	2.79	6.64	269	NR	27.79	02-Aug-99	
CLRO	0.35	6.60	275	NR	27.80	02-Aug-99	2.10
CLRI	0.40	6.60	281	NR	27.81	02-Aug-99	
A2	0.31	6.76	77	NR	27.35	06-Aug-99	8720
A3	0.27	6.77	71	NR	27.30	06-Aug-99	
A4	0.25	6.72	63	NR	27.35	06-Aug-99	
ABI	0.59	6.60	207	NR	27.66	06-Aug-99	2760
ABM	2.38	6.62	250	NR	27.76	06-Aug-99	
ABE	2.50	6.60	255	NR	27.76	06-Aug-99	
CLRO	0.36	6.60	270	NR	27.76	06-Aug-99	2.20
CLRI	0.35	6.58	285	NR	27.75	06-Aug-99	

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APPENDIX B - HYDROLAB DATA

A2	0.31	6.83	75	NR	27.25	09-Aug-99	9300
A3	0.28	6.81	70	NR	27.25	09-Aug-99	
A4	0.25	6.80	69	NR	27.30	09-Aug-99	
ABI	0.67	6.67	191	NR	27.55	09-Aug-99	2790
ABM	2.35	6.80	235	NR	27.67	09-Aug-99	
ABE	2.50	6.74	270	NR	27.70	09-Aug-99	
CLRO	0.35	6.70	272	NR	27.65	09-Aug-99	1.90
CLRI	0.32	6.71	204	NR	27.69	09-Aug-99	
A2	0.30	6.82	78	NR	27.36	11-Aug-99	9580
A3	0.26	6.81	67	NR	27.40	11-Aug-99	
A4	0.25	6.80	56	NR	27.39	11-Aug-99	
ABI	0.68	6.67	212	NR	27.66	11-Aug-99	2850
ABM	2.42	6.63	255	NR	27.76	11-Aug-99	
ABE	2.39	6.74	261	NR	27.75	11-Aug-99	
CLRO	0.33	6.70	267	NR	27.62	11-Aug-99	1.90
CLRI	0.31	6.72	263	NR	27.68	11-Aug-99	
A2	0.32	6.88	95	NR	27.25	13-Aug-99	8960
A3	0.26	6.86	83	NR	27.26	13-Aug-99	
A4	0.24	6.83	73	NR	27.29	13-Aug-99	
ABI	0.62	6.67	191	NR	27.62	13-Aug-99	2870
ABM	2.24	6.64	224	NR	27.75	13-Aug-99	
ABE	2.42	6.71	256	NR	27.77	13-Aug-99	
CLRO	0.33	6.68	325	NR	27.80	13-Aug-99	1.90
CLRI	0.38	6.67	321	NR	27.78	13-Aug-99	
	End the "After" Period, SRT = 6.0 Days						
A2	0.32	6.94	93	NR	27.32	16-Aug-99	8120
A3	0.29	6.92	81	NR	27.31	16-Aug-99	
A4	0.26	6.88	70	NR	27.32	16-Aug-99	
ABI	0.69	6.79	168	NR	27.60	16-Aug-99	2675
ABM	1.95	6.80	225	NR	27.72	16-Aug-99	
ABE	2.55	6.79	277	NR	27.71	16-Aug-99	
CLRO	0.31	6.76	268	NR	27.62	16-Aug-99	1.90
CLRI	0.33	6.79	261	NR	26.68	16-Aug-99	

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APPENDIX C

STATISTICAL METHODS, PHASE I, BIO-P REMOVAL STUDY

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APPENDIX C

STATISTICAL METHODS

Hypothesis testing was used to determine the statistical confidence in the degree of change experienced between the two effluent phosphorus averages of the "before" and "after" period, ($\overline{X_1}$ and $\overline{X_2}$) . This method uses a student's "t" as the test statistic, in a single tailed, modified small sample test. This test assumes that the variances of the two independent data sets are not equal, ($\sigma_1^2 \neq \sigma_2^2$). The method and the equations used are documented in Mendenhall, (1995), page 455.

The "t" test statistic is found using:

$$t = \frac{(\mu 1 - \mu 2) - Do}{\sqrt{\frac{s1^2}{n1} + \frac{s2^2}{n2}}} \qquad \text{Eq. A1}$$

The degrees of freedom, associated with the small sample test is calculated using:

$$v = \frac{\left(\frac{s1^2}{n1} + \frac{s2^2}{n2}\right)}{\sqrt{\frac{\left(\frac{s1^2}{n1}\right)^2}{n1-1} + \frac{\left(\frac{s2^2}{n2}\right)^2}{n2-1}}} \qquad \text{Eq. A2}$$

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APPENDIX C

STATISTICAL METHODS

Where: s1 ($=\sigma_1$) and s2 ($=\sigma_2$) are the sample standard deviations of the average effluent phosphorus concentrations during the "before" and "after" periods.

n1, n2 = sample counts, assumed to be unequal

ν = degrees of freedom

Do = the expected difference (set to zero in this instance)

The "t" and "ν" values are then used with a table of critical values for Student's "t" to find the level of significance, "p" in favor of the Hypothesis that $(\bar{X}_1 - \bar{X}_2)$ is equal to zero.

The values of S_i, n_i, and $(\bar{X}_1 - \bar{X}_2)$ for the samples AB4, CLRO and CE are given in that Table A1.

Table A.1 Significance Valued "p" for Hypothesis Testing of $(\bar{X}_1 - \bar{X}_2)$

	AB4		CLRO (grab)		Plant Ave @ CE	
	TP	OP	TP	OP	TP	OP
p value =	l.t. 0.001	l.t. 0.001	g.t. 0.10	l.t. 0.032	l.t. 0.032	l.t. 0.002
t =	4.84	5.49	1.46	2.31	4.14	3.86
Variables Used to compute t and v						
$(\bar{X}_1 - \bar{X}_2)$ =	0.361	0.390	0.153	0.164	0.115	0.06
S1, before	0.422	0.429	0.326	0.251	0.16	0.089
S2, after	0.132	0.041	0.114	0.041	0.043	0.023
n1	37	37	11	13	37	37
n2	23	23	10	10	23	23
ν =	7	6	4	4	7	7

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APPENDIX D

CCSD WASTEWATER PLANT DESIGN SPECIFICATIONS

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APPENDIX D

CCSD PLANT DESIGN SPECIFICATIONS

Clark County Sanitation District		
Central Plant Expansion (222)		B&V Project 15225.332
Civil Basis of Design		24-Aug-90
Memorandum, Phase 3	15	Revised July 1, 1991

Table 3
DESIGN INFLUENT WASTEWATER CHARACTERISTICS

Item	Average	Maximum Month	Peak Day
BOD5, mg/L	180	220	240
Suspended Solids, mg/L	170	190	255
Phosphorus, mg-P/L	7	8	10
Ammonia, mg-N/L			
Winter (Nov-May)	22	27	27
Summer (Jun-Oct)	18	22	22
Temperature, deg C			
Winter	20	-	18
Summer	27	-	30

Table 5
SUMMARY OF PROCESS AIR REQUIREMENTS

Air Flow Required	Flow 57 MGD	Flow 66 MGD	Flow 87.5 MGD
Loading Conditions			
Winter-Nitrification/Denitrification			
Minimum Air for Mixing	18750	22500	30000
Average	20400	25300	34400
Maximum Month	25100	33730	45700
Peak Day	25800	34700	47000
Winter - Carbonaceous			
Minimum Air for Mixing	15000	20000	30000
Average	13800	20300	26700
Maximum Month	17300	26100	34500
Peak Day	17900	27200	35900
Summer - Nitrification/Denitrification			
Minimum Air for Mixing	18750	22500	30000
Average	19100	23900	35500
Maximum Month	23600	32000	43800
Peak Day	24300	33000	45100

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APPENDIX D

CCSD PLANT DESIGN SPECIFICATIONS

Table 6
DESIGN FLOW RATES

Treatment Plant	Minimum Flow (MGD)	Average Flow (MGD)	Maximum Flow (MGD)
Advanced Secondary Plant, Primary Complex			
Design Year 2000	18.5	37.0	59.2
Design Year 2010	27.8	55.5	88.8
Advanced Secondary Plant, Secondary Complex			
Design Year 2000	34.5	69.0	110.4
Design Year 2010	43.8	87.5	140.0

Table 9
DESIGN CRITERIA FOR PRIMARY CLARIFIERS

	Existing	New
Number of Units	2	2
Drive Designation	-	PCD-3, PCD-
type	Center feed	Center feed
Diameter,	120	120
Side Water Depth, ft.	10	12
Bottom Slope	1 in 12	1 in 12
Design Surface Overflow Rates, gpd/sq.		
At 9.25 MGD average flow	-	818
At 14.8 MGD peak hourly	-	1309
Design Removal Rate, percent		
TSS	-	50
BOD	-	25
Drive Mechanism Horsepower	2-Jan	2
Scum Collection	Rotating weir	Rotating weir

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APPENDIX D

CCSD PLANT DESIGN SPECIFICATIONS

Table 11
DESIGN CRITERIA FOR AERATION BASINS

Number of Basins	8
Width of Basin, ft.	108.92
Length of Basin, ft.	163.5
Side Water depth, ft.	18
Volume Per Basin, mil gal	2.31
Freeboard, ft	3
Hydraulic Detention Time at 10.94 MGD	
Design flow, hrs	5.1
Anoxic Zone	
Width, ft.	30
Length, ft.	120
Number of cells	4
Cell dimensions, ft	30 by 30
Anoxic Zone Mechanical Mixing	
Number of units per basin	3
Designation	AM-1-1 through AM-8-3
Type	Submerged propeller
Motor horsepower per unit	10
Mixed Liquor Recycle Pumping Equipment	
Number of units per basin	2
Designation	MLR-1-1 through MLR-8-2
Type	Submerged propeller; variable-speed
Capacity range per unit, gpm	8851-17500; @ 12.75 to 25.22 MGD
Head, ft.	0.5
Motor horsepower per unit	14-15
Oxic Zone Aeration Equipment	
Diffuser type	9 inch ceramic disk, fine bubble
Number of diffusers per basin	2992
Diffuser submergence, ft.	17.25
Anoxic Zone Aeratin Equipment	
Diffuser type	Coarse-bubble
Number of diffusers per basin	240
Diffuser submergence, ft.	17.25

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APPENDIX D

CCSD PLANT DESIGN SPECIFICATIONS

Table 12
DESIGN CRITERIA FOR SECONDARY CLARIFIERS

Number of Units	8
Drive Designation	SCD-1 through
Type	Clarifier-flocculator, center
Diameter, ft.	140
Side Water Depth, ft.	14
Bottom slope	1 in 12
Flocculation Well diameter, ft.	70
Flocculation Baffle Depth, ft.	8
Drive Mechanism Horsepower	2
Flocculation Mixing Equipment	
Type	Axial flow, up-pumping, variable-speed
Number of units per	4
Motor horsepower per unit	1
Surface Overflow rate, gpd/sq ft.	
At 10.5 MGD ave flow	710
At 17.5 MGD ave flow	1140
Rotating Scum Weir Drive Horsepower	1

Table 13
DESIGN CRITERIA FOR SECONDARY SLUDGE PUMPING STATIONS

Number of Stations	4
Return Activated Sludge Pumps	
Number per station	4
Designation	RAS-1 through RAS-16
Type	Horizontal end-suction, centrifugal, constant-speed
Capacity per unit, gpm	4375 gpm/694=6.3 MGD ??
Head, ft.	24
Motor horsepower per unit	50
Waste Activated Sludge Pumps	
Number per station	3
Designation	WAS-1 through WAS-16
Type	Horizontal end-suction, centrifugal, constant-speed
Capacity per unit, gpm	180
Head, ft.	40
Motor horsepower per unit	5

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APPENDIX E

FREE (DISSOLVED) IRON MEASUREMENTS

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APPENDIX E - IRON MEASUREMENTS

Date	8/4/99	Wed	Date Sampled	7/28/99	Wed
Sort Order	Run #1	Run #2	Sort Order	Run #1	Run #2
Point	DATA	DATA	Point	DATA	DATA
AE	0.0	0.0	AE	0.1	0.1
AH	0.1	0.1	CE	0.1	0.1
CABI	0.2	0.2	CPEI	0.8	0.8
CE	0.0	0.0	PI	0.1	0.1
CPEI	0.5	0.5	AH	0.1	0.1
CPEPE1	0.1	0.1	CPWI	0.5	0.5
CPEPE2	0.1	0.1	CPWPE	0.3	0.3
CPWI	0.5	0.5	CABI	0.4	0.4
CPWPE	0.2	0.2	CPEPE2	0.4	0.4
PI	0.1	0.1	CPEPE1	0.3	0.3

Date	8/2/99	Mon	Date Sampled	7/26/99	Mon
Sort Order	Run #1	Run #2	Sort Order	Run #1	Run #2
Point	DATA	DATA	Point	DATA	DATA
AE	0.1	0.1	CPEI	0.4	0.4
AH	0.1	0.1	AE	0.1	0.1
CABI	0.4	0.4	ACPEPE1	0.9	0.9
CE	0.1	0.1	AH	0.0	0.0
CPEI	0.3	0.3	CPWI	0.5	0.5
CPEPE1	0.3	0.3	CE	0.0	0.0
CPEPE2	0.3	0.3	CPEPE2	0.3	0.3
CPWI	0.4	0.4	PI	0.1	0.1
CPWPE	0.3	0.3	CPWPE	0.2	0.2
PI	0.1	0.1	CABI	0.3	0.3

Date Sampled	7/30/99	Flame #1	Date Sampled	7/23/99	Fri
Sort Order	Run #1	Run #2	Sort Order	Run #1	Run #2
Point	DATA	DATA	Point	DATA	DATA
AE	0.0	0.0	AE	0.0	0.1
AH	0.0	0.0	AH	0.0	0.1
CABI	0.3	0.3	CABI	0.3	0.3
CE	0.0	0.0	CE	0.0	0.1
CPEI	0.4	0.4	CPCPE2	0.2	0.3
CPEPE1	0.3	0.3	CPEI	0.4	0.5
CPEPE2	0.3	0.3	CPEPEI	0.3	0.3
CPWI	0.4	0.4	CPWI	0.3	0.4
CPWPE	0.2	0.2	CPWPE	0.2	0.3
PI	0.1	0.1	PI	0.1	0.2

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APPENDIX E - IRON MEASUREMENTS

Date Sampled	7/21/99	Wed
Sort Order	Run #1	Run #2
Point	DATA	DATA
AE	0.0	0.1
AH	0.0	0.1
CABI	0.3	0.3
CE	0.0	0.1
CPEI	2.1	1.9
CPEPE1	0.2	0.3
CPEPE2	0.2	0.3
CPWI	0.3	0.4
CPWPE	0.1	0.2
PI	0.1	0.1

Date Sampled	7/14/99	Wed
Sort Order	Run #1	Run #2
Point	DATA	DATA
AE	NRS	NRS
AH	0.0	0.1
CABI	0.4	0.4
CE	0.0	0.1
CPEI	1.9	1.9
CPEPE1	0.3	0.3
CPEPE2	0.3	0.3
CPWI	0.6	0.6
CPWPE	0.1	0.2
PI	0.1	0.1

Date Sampled	7/19/99	Mon
Sort Order	Run #1	Run #2
Point	DATA	DATA
AE	0.0	0.0
AH	0.0	0.1
CABI	0.3	0.4
CE	0.0	0.1
CPEI	0.9	0.6
CPEPE1	0.2	0.3
CPEPE2	0.3	0.3
CPWI	0.8	0.9
CPWPE	0.3	0.3
PI	0.0	0.1

Date Sampled	7/12/99	Mon
Sort Order	Run #1	Run #2
Point	DATA	DATA
AE	0.0	0.0
AH	0.0	0.1
CABI	0.1	0.1
CE	0.1	0.0
CPEI	0.4	0.4
CPEPE1	0.1	0.1
CPEPE2	0.1	0.1
CPWI	0.3	0.3
CPWPE	0.1	0.1
PI	0.1	0.1

Date Sampled	7/16/99	Fri
Sort Order	Run #1	Run #2
Point	DATA	DATA
AE	0.0	0.1
AH	0.0	0.1
CABI	0.9	1.0
CE	0.1	0.1
CPEI	4.1	4.1
CPEPE1	0.3	0.4
CPEPE2	0.3	0.4
CPWI	0.6	0.8
CPWPE	0.2	0.3
PI	0.1	0.1

Date Sampled	7/9/99	Fri
Sort Order	Run #1	Run #2
Point	DATA	DATA
AE	NRS	NRS
AH	0.0	0.1
CABI	0.1	0.1
CE	0.0	0.1
CPEI	0.6	0.6
CPEPE1	0.1	0.1
CPEPE2	0.4	0.1
CPWI	0.0	0.1
CPWPE	0.1	0.1
PI	0.0	0.1

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APPENDIX E - IRON MEASUREMENTS

Date Sampled	7/7/99	Wed
Sort Order	Run #1	Run #2
Point	DATA	DATA
AE	0.0	0.1
AH	0.0	0.1
CABI	0.1	0.2
CE	0.0	0.1
CPEI	1.0	1.1
CPEPE1	0.1	0.2
CPEPE2	0.2	0.2
CPWI	0.2	0.2
CPWPE	0.1	0.2
PI	0.0	0.1

Date Sampled	6/28/99	Friday
Sort Order	Run #1	Run #2
Point	DATA	DATA
CPEI	0.5	0.5
AE	0.1	0.1
AH	0.1	0.1
CPEPE2	0.3	0.3
CPWPE	0.2	0.2
CABI	0.3	0.3
PI	0.1	0.1
CE	0.1	0.1
CPWI	0.4	0.4
CPEPE1	0.3	0.3

Date Sampled	7/2/99	Fri
Sort Order	Run #1	Run #2
Point	DATA	DATA
AE	0.0	0.0
AH	0.0	0.0
CABI	0.2	0.2
CE	0.0	0.1
CPEI	NRS	NRS
CPEPE1	0.1	0.1
CPEPE2	0.1	0.2
CPWI	0.2	0.2
CPWPE	0.1	0.1
PI	0.0	0.1

Date Sampled	6/25/99	Friday
Sort Order	Run #1	Run #2
Point	DATA	DATA
CE	0.1	0.1
CPWPE	0.2	0.2
CPEI	0.4	0.3
CABI	0.3	0.2
AH	0.1	0.1
PI	0.1	0.1
AE	0.1	0.1
CPEPE2	0.2	0.2
CPWI	0.4	0.4
CPEPE1	0.3	0.2

Date Sampled	6/30/99	Wed
Sort Order	Run #1	Run #2
Point	DATA	DATA
AE	0.1	0.1
AH	0.1	0.1
CABI	0.2	0.2
CE	0.1	0.1
CPEI	1.4	1.4
CPEPE1	0.2	0.2
CPEPE2	0.2	0.2
CPWI	0.3	0.3
CPWPE	0.1	0.1
PI	0.1	0.1

Date Sampled	6/23/99	Wed
Sort Order	Run #1	Run #2
Point	DATA	DATA
AE	0.1	0.1
AH	0.1	0.1
CABI	0.2	0.2
CE	0.1	0.1
CPEI	0.4	0.4
CPEPE1	0.2	0.2
CPEPE2	0.2	0.2
CPWI	0.3	0.3
CPWPE	0.2	0.2
PI	0.1	0.1

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APPENDIX E - IRON MEASUREMENTS

Date Sampled	6/21/99	Mon
Sort Order	Run #1	Run #2
Point	DATA	DATA
AE	0.0	0.0
AH	0.0	0.0
CABI	0.1	0.1
CE	0.1	0.1
CPEI	0.5	0.5
CPEPE1	0.2	0.2
CPEPE2	0.2	0.2
CPWI	0.3	0.3
CPWPE	0.1	0.1
PI	0.1	0.1

Date Sampled	6/14/99	Mon
Sort Order	Run #1	Run #2
Point	DATA	DATA
AE	0.1	0.1
AH	0.1	0.1
CABI	0.2	0.2
CE	0.1	0.1
CPEI	0.2	0.2
CPEPE1	0.2	0.2
CPEPE2	0.2	0.2
CPWI	0.2	0.2
CPWPE	0.2	0.2
PI	0.1	0.1

Date Sampled	6/18/99	Fri
Sort Order	Run #1	Run #2
Point	DATA	DATA
AE	0.1	0.1
AH	0.1	0.1
CABI	0.2	0.2
CE	0.1	0.1
CPEI	0.2	0.2
CPEPE1	0.2	0.2
CPEPE2	0.2	0.2
CPWI	0.3	0.3
CPWPE	0.2	0.2
PI	0.1	0.1

Date Sampled	6/9/99	Wed
Sort Order	Run #1	Run #2
Point	DATA	DATA
AE	0.1	0.1
AH	0.1	0.1
CABI	0.2	0.2
CE	0.1	0.1
CPEI	0.2	0.2
CPEPE1	0.2	0.2
CPEPE2	0.2	0.2
CPWI	0.2	0.2
CPWPE	0.2	0.2
PI	0.2	0.2

Date Sampled	6/16/99	Wed
Sort Order	Run #1	Run #2
Point	DATA	DATA
AH	0.1	0.1
AE	0.0	0.0
PI	0.1	0.1
CABI	0.2	0.2
CPEI	0.7	0.7
CE	0.1	0.1
CPWI	0.2	0.2
CPEPE2	0.2	0.2
CPWPE	0.2	0.2
CPEPE1	0.2	0.2

Date Sampled	6/7/99	Monday
Sort Order	Run #1	Run #2
Point	DATA	DATA
CPWPE	0.2	0.2
PI	0.1	0.1
CPEPE2	0.2	0.2
CPEPE1	0.1	0.1
AH	0.1	0.1
CE	0.2	0.2
CABI	0.2	0.2
AE	0.1	0.1
CPEI	0.2	0.2
CPWI	NRS	NRS

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APPENDIX E - IRON MEASUREMENTS

Date Sampled	5/28/99	Friday
Sort Order	Run #1	Run #2
Point	DATA	DATA
AE	0.0	0.0
AH	0.0	0.0
CABI	0.2	0.2
CE	0.1	0.1
CPEI	0.3	0.3
CPEPE1	0.2	0.2
CPEPE2	0.3	0.3
CPWI	0.2	0.2
CPWPE	0.1	0.1
PI	0.1	0.1

Date Sampled	5/21/99	Friday
Sort Order	Run #1	Run #2
Point	DATA	DATA
AE	0.1	0.1
AH	0.1	0.1
CABI	0.2	0.2
CE	0.1	0.1
CPEI	0.2	0.2
CPEPE1	0.3	0.3
CPEPE2	0.2	0.2
CPWI	0.3	0.3
CPWPE	0.2	0.2
PI	0.1	0.1

Date Sampled	5/26/99	Wed
Sort Order	Run #1	Run #2
Point	DATA	DATA
AE	0.1	0.1
AH	0.1	0.1
CABI	0.5	0.5
CE	0.1	0.1
CPEI	0.3	0.3
CPEPE1	0.2	0.2
CPEPE2	0.3	0.3
CPWI	0.3	0.3
CPWPE	0.3	0.3
PI	0.1	0.1

Date Sampled	5/19/99	Wed
Sort Order	Run #1	Run #2
Point	DATA	DATA
AE	0.1	0.1
AH	0.1	0.1
CABI	0.2	0.2
CE	0.1	0.1
CPEI	0.2	0.2
CPEPE1	0.2	0.2
CPEPE2	0.2	0.2
CPWI	0.4	0.4
CPWPE	0.2	0.2
PI	0.2	0.2

Date Sampled	5/24/99	Monday
Sort Order	Run #1	Run #2
Point	DATA	DATA
AE	0.1	0.1
AH	0.1	0.1
CABI	0.3	0.3
CE	0.1	0.1
CPEI	0.3	0.3
CPEPE1	0.3	0.3
CPEPE2	0.3	0.3
CPWI	0.3	0.3
CPWPE	0.3	0.3
PI	0.1	0.1

Date Sampled	5/17/99	Mon
Sort Order	Run #1	Run #2
Point	DATA	DATA
AE	0.1	0.1
AH	0.0	0.0
CABI	0.2	0.2
CE	0.0	0.0
CPEI	0.2	0.2
CPEPE1	0.2	0.2
CPEPE2	0.2	0.2
CPWI	0.2	0.2
CPWPE	0.1	0.1
PI	0.1	0.1

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APPENDIX E - IRON MEASUREMENTS

Date Sampled	5/12/99	Wed
Sort Order	Run #1	Run #2
Point	DATA	DATA
AE	0.1	0.1
AH	0.1	0.1
CABI	0.4	0.4
CE	0.1	0.1
CPEI	0.4	0.4
CPEPE1	0.5	0.5
CPEPE2	0.2	0.2
CPWI	0.5	0.5
CPWPE	0.2	0.2
PI	0.2	0.2

Date Sampled	5/5/99	Wed
Sort Order	Run #1	Run #2
Point	DATA	DATA
AE	0.1	0.1
AH	0.1	0.1
CABI	0.3	0.3
CE	0.1	0.1
CPEI	0.8	0.8
CPEPE1	0.4	0.4
CPEPE2	0.4	0.4
CPWI	0.5	0.5
CPWPE	0.3	0.3
PI	0.2	0.2

Date Sampled	5/10/99	Monday
Sort Order	Run #1	Run #2
Point	DATA	DATA
AE	0.1	0.1
AH	0.1	0.1
CABI	2.1	2.1
CE	0.1	0.1
CPEI	2.8	2.8
CPEPE1	1.4	1.4
CPEPE2	0.9	0.9
CPWI	1.4	1.4
CPWPE	1.4	1.4
PI	0.2	0.2

Date Sampled	5/3/99	Monday
Sort Order	Run #1	Run #2
Point	DATA	DATA
AE	0.1	0.1
AH	0.1	0.1
CABI	1.1	1.1
CE	0.1	0.1
CPEI	1.3	1.3
CPEPE1	0.7	0.7
CPEPE2	0.7	0.7
CPWI	1.0	1.0
CPWPE	0.7	0.7
PI	0.2	0.2

Date Sampled	5/7/99	Friday
Sort Order	Run #1	Run #2
Point	DATA	DATA
AE	0.1	0.1
AH	0.1	0.1
CABI	0.5	0.5
CE	0.1	0.1
CPEI	0.6	0.6
CPEPE1	0.5	0.5
CPEPE2	0.4	0.4
CPWI	0.6	0.6
CPWPE	0.3	0.3
PI	0.2	0.2

Date Sampled	4/30/99	Friday
Sort Order	Run #1	Run #2
Point	DATA	DATA
AE	0.1	0.1
AH	0.1	0.1
CABI	0.4	0.4
CE	0.1	0.1
CPEI	1.3	1.3
CPEPE1	0.3	0.3
CPEPE2	0.3	0.3
CPWI	0.5	0.5
CPWPE	0.3	0.3
PI	0.1	0.1

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APPENDIX E - IRON MEASUREMENTS

Date Sampled	4/28/99	Wed
Sort Order	Run #1	Run #2
Point	DATA	DATA
AE	0.1	0.1
AH	0.1	0.1
CABI	0.3	0.3
CE	0.1	0.1
CPEI	0.2	0.2
CPEPE1	0.3	NRS
CPEPE2	NRS	0.3
CPWI	0.4	0.4
CPWPE	0.3	0.3
PI	0.2	0.2

Date Sampled	4/21/99	Wed
Sort Order	Run #1	Run #2
Point	DATA	DATA
AE	0.1	0.1
AH	0.2	0.2
CABI	2.0	2.0
CE	0.2	0.2
CPEI	0.9	0.9
CPEPE1	0.9	0.9
CPEPE2	0.9	0.9
CPWI	1.8	1.8
CPWPE	1.6	1.6
PI	0.3	0.3

Date Sampled	4/26/99	Monday
Sort Order	Run #1	Run #2
Point	DATA	DATA
AE	0.1	0.1
AH	0.1	0.1
CABI	0.3	0.3
CE	0.1	0.1
CPEI	0.5	0.5
CPEPE1	0.2	0.2
CPEPE2	0.3	0.3
CPWI	0.3	0.3
CPWPE	0.2	0.2
PI	0.1	0.1

Date Sampled	4/19/99	Monday
Sort Order	Run #1	Run #2
Point	DATA	DATA
AE	0.1	0.1
AH	0.1	0.1
CABI	0.2	0.2
CE	0.1	0.1
CPEI	0.2	0.2
CPEPE1	0.2	0.2
CPEPE2	0.2	0.2
CPWI	0.3	0.3
CPWPE	0.3	0.3
PI	0.1	0.1

Date Sampled	4/23/99	Friday
Sort Order	Run #1	Run #2
Point	DATA	DATA
AE	NRS	NRS
AH	0.1	0.1
CABI	0.2	0.2
CE	0.1	0.1
CPEI	0.1	0.1
CPEPE1	0.2	0.2
CPEPE2	0.2	0.2
CPWI	0.3	0.3
CPWPE	0.2	0.2
PI	0.1	0.1

Date Sampled	4/16/99	Friday
Sort Order	Run #1	Run #2
Point	DATA	DATA
AE	0.1	0.1
AH	0.2	0.2
CABI	2.1	2.1
CE	0.2	0.2
CPEI	1.1	1.1
CPEPE1	1.1	1.1
CPEPE2	1.2	1.2
CPWI	3.0	3.0
CPWPE	1.4	1.4
PI	0.3	0.3

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APPENDIX E - IRON MEASUREMENTS

Date Sampled	4/14/99	Wed
Sort Order	Run #1	Run #2
Point	DATA	DATA
AE	0.1	0.1
AH	0.1	0.1
CABI	0.2	0.2
CE	0.1	0.1
CPEI	0.1	0.1
CPEPE1	0.2	0.2
CPEPE2	0.2	0.2
CPWI	0.3	0.3
CPWPE	0.2	0.2
PI	0.1	0.1

Date Sampled	4/7/99	Wed
Sort Order	Run #1	Run #2
Point	DATA	DATA
AE	0.1	0.1
AH	0.1	0.1
CABI	0.2	0.2
CE	0.1	0.1
CPEI	0.2	0.2
CPEPE1	0.2	0.2
CPEPE2	0.2	0.2
CPWI	0.3	0.3
CPWPE	0.2	0.2
PI	0.1	0.1

Date Sampled	4/12/99	Monday
Sort Order	Run #1	Run #2
Point	DATA	DATA
AE	0.1	0.1
AH	0.2	0.2
CABI	2.1	2.1
CE	0.2	0.2
CPEI	0.7	0.7
CPEPE1	1.7	1.7
CPEPE2	0.8	0.8
CPWI	3.3	3.3
CPWPE	1.4	1.4
PI	0.2	0.2

Date Sampled	4/5/99	Mon
Sort Order	Run #1	Run #2
Point	DATA	DATA
AE	0.1	0.1
AH	0.1	0.1
CABI	0.2	0.2
CE	0.1	0.1
CPEI	0.5	0.5
CPEPE1	0.2	0.2
CPEPE2	0.2	0.2
CPWI	0.4	0.4
CPWPE	0.2	0.2
PI	NRS	NRS

Date Sampled	4/9/99	Friday
Sort Order	Run #1	Run #2
Point	DATA	DATA
AE	0.3	0.3
AH	0.4	0.4
CABI	2.4	2.4
CE	0.2	0.2
CPEI	2.9	2.9
CPEPE1	1.4	1.4
CPEPE2	1.1	1.1
CPWI	2.2	2.2
CPWPE	1.4	1.4
PI	0.3	0.3

Date Sampled	4/2/99	Friday
Sort Order	Run #1	Run #2
Point	DATA	DATA
AE	0.0	0.0
AH	0.1	0.1
CABI	0.2	0.2
CE	0.1	0.1
CPEI	0.1	0.1
CPEPE1	0.2	0.2
CPEPE2	0.2	0.2
CPWI	0.4	0.4
CPWPE	0.2	0.2
PI	0.1	0.1

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APPENDIX E - IRON MEASUREMENTS

Date Sampled	3/31/99	Wed
Sort Order	Run #1	Run #2
Point	DATA	DATA
AE	0.1	0.1
AH	0.2	0.2
CABI	0.3	0.3
CE	0.1	0.1
CPEI	0.2	0.2
CPEPE1	0.3	0.3
CPEPE2	0.3	0.3
CPWI	0.5	0.5
CPWPE	0.2	0.2
PI	0.2	0.2

Date Sampled	2/17/99	Wed
Sort Order	Run #1	Run #2
Point	DATA	DATA
AE	0.1	0.1
AH	0.1	0.1
CABI	0.3	0.3
CE	0.1	0.1
CPEI	0.2	0.2
CPEPE1	0.2	0.2
CPEPE2	0.2	0.2
CPWI	0.1	0.1
CPWPE	0.2	0.2
PI	0.1	0.1

Date Sampled	3/29/99	Monday
Sort Order	Run #1	Run #2
Point	DATA	DATA
AE	0.0	0.0
AH	0.0	0.0
CABI	0.2	0.2
CE	0.1	0.1
CPEI	0.3	0.3
CPEPE1	0.2	0.2
CPEPE2	0.2	0.2
CPWI	0.1	0.1
CPWPE	0.2	0.2
PI	0.1	0.1

Date Sampled	2/12/99	Friday
Sort Order	Run #1	Run #2
Point	DATA	DATA
AE	0.1	0.1
AH	0.1	0.1
CABI	0.3	0.3
CE	0.1	0.1
CPEI	0.3	0.3
CPEPE1	0.3	0.3
CPEPE2	0.3	0.3
CPWI	NRS	NRS
CPWPE	0.3	0.3
PI	0.2	0.2

Date Sampled	2/19/99	Friday
Sort Order	Run #1	Run #2
Point	DATA	DATA
AE	0.0	0.0
AH	0.0	0.0
CABI	0.4	0.4
CE	0.0	0.0
CPEI	0.3	0.3
CPEPE1	0.2	0.2
CPEPE2	0.2	0.2
CPWI	0.2	0.2
CPWPE	0.2	0.2
PI	0.1	0.1

Date Sampled	2/10/99	Wed
Sort Order	Run #1	Run #2
Point	DATA	DATA
AE	0.1	0.1
AH	0.1	0.1
CABI	0.3	0.3
CE	0.1	0.1
CPEI	0.3	0.3
CPEPE1	0.3	0.3
CPEPE2	0.3	0.3
CPWI	0.3	0.3
CPWPE	0.3	0.3
PI	0.2	0.2

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REFERENCES

Alberts, B., Bray, D., Johnson, A., Lewis, J., Raff, M., Roberts, K., Walter, P.,; 1998; Essential Cell Biology; Garland Publishing, Inc., New York, New York.

Barker, P.S., Dold, P.L.; 1996; Denitrification Behavior in Biological Excess Phosphorus Removal Activated Sludge Systems; Elsevier Science Ltd., Pergamon Press, Great Britain.

Benjes, H. Jr., 1980; Handbook of Biological Wastewater Treatment; Garland STPM Press, New York, New York.

Birk, J.; Arizona State University; 1994; Chemistry; Houghton Mifflin Co., Boston

Bolin, B., Cook, R., Eds., 1983; The Major biogeochemical cycles and their Interactions, SCOPE Report 21, Wiley, Chichester, Chap. 2. *[SCOPE: Scientific Committee on Problems of the Environment]*.

Bowker, R., Stensel, D; (1990); Phosphorus Removal from Wastewater; Noyes Data Corporation, Park Ridge, New Jersey.

Butcher, S., Charlson, R., Orians, G., Wolfe, G.; 1992; Global Biogeochemical Cycles; Academic Press, , New York, New York.

Cech, J.S., Hartman, P.; 1990; Glucose induced Breakdown of Enhanced Biological Phosphate Removal; Environmental Technology, Vol. 11, pp. 651-656.

Ciba Foundation; 1978; Phosphorus in the Environment: its Chemistry and Biochemistry; Elsevier, New York.

Clark County, Nevada, Certified Laboratory Results; Years 1997, and 1998.

Collingwood, R.W.; 1978; The Dissipation of Phosphorus in Sewage and Sewage Effluents; Ciba Foundation Symposium 57, Elsevier Science, New York.

Drdjanovic, D.; Jooijmans, C.; Loosdrecht, M.; Alaerts, G.; Heijnen, J.; 1996; The Dynamic Effects of Potassium Limitation on Biological Phosphorus Removal; Elsevier Science ltd., Pergamon Press, Great Britain.

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Dudzinska, M.R., Montusiewicz, A.; Environmental Implications of Substitution of Polyphosphate in Detergents by Chelating Ligands; in Chemistry for the Protection of the Environment; Pawlowski, L., Lacy, W., Uchrin, C., Dudzinska, M. (eds.); 1996; Environmental Science Research, Vol 51; Plenum Press, New York.

Fukase, T. Shibata, M., Miyaji, Y.; 1984; The Role of an Anaerobic Stage on biological Phosphorus Removal; Water Science Technology, Vol 17, Amsterdam, pp. 69-80; IAWPRC; Great Britain.

Gerber, A., Mostert, E.S., Winter, C.T. de Villiers, R.H.; 1986; The Effect of Acetate and Other Short-Chain Carbon Compounds on the Kinetics of Biological Nutrient Removal; Water SA, Vol. 12, No. 1.

Gerber, A., Winter, C.; 1984; The influence of Extended Anaerobic Retention Time on the Performance of Phoredox Nutrient Removal Plants; IAWPRC, Water Science Technology, Vol 17, Amsterdam, pp.81-92; Pergamon Press, Great Britain.

Griffith, E., Beeton, A., Spencer, J., Mitchell, Dee.; 1973; Environmental Phosphorus Handbook; John Wiley & Sons, , New York, New York.

Halling-Sorensen, B., Jorgensen, S.E.; 1993; The Removal of Nitrogen Compounds from Wastewater; Elsevier Science Publishers, New York.

Hang-Bae Jun; Hang-Sik Shin; Chung-buk National University, Korea; 1997; Substrates Transformation in a Biological Excess Phosphorus Removal System; Elsevier Science ltd.; Pergamon Press, Great Britain.

Harder, W., Kuenen, J.G., Matin, A.; (1977); Microbial Selection in Continuous Culture: Journal of Applied Bacteriology, vol. 43: 1-24.

Harrington, J.; 1998; Relational Database Design Clearly Explained; AP Professional, div. Of Academic Press, New York.

Horan, N., Lowe, P., Stentiford, E.; 1994; Nutrient Removal from Wastewaters; Technomic Publications, Lancaster, PA.

Janssen, P.M.J., Rensink, J.H.; 1987; High Biological P- and N-Removal on a Full Scale Activated Sludge Plant with Alternating Aeration, in Advances in Water Pollution Control, by the IAWPRC, in Biological Phosphate Removal from Wastewaters (R. Ramadori, ed.); Pergamon Press, Oxford.

Kiessling, D.: 1997; in Detergents in the Environment; Schwuger, M.J. (ed.), Marcel Dekker, Inc. New York, New York.

Kolarik, L., Priestley, A.; 1995; Modern Techniques in Water and Wastewater Treatment; CSIRO Publishing, East Melbourne, Australia

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Koneman, E.; Allen, S.; Janda, W.; Schreckenerger, P.; Winn, W. Jr.; 1997; The Color Atlas and Textbook of Diagnostic Microbiology; 5th ed.; Lippincott, Philadelphia.

Kuba, T., Van Loosdrecht, M.C.M., Heijnen, J. J., 1996; Phosphorus and Nitrogen Removal with Minimal COD Requirement by Integration of Denitrifying Dephosphatation and Nitrification in a Two-Sludge System; Wat. Res. 30:7, pp. 1702-1720, Elsevier Science LTD, Pergamon Press, Great Britain.

Kuba, T., Wachtmeister, A., Van Loosdrecht, M.C.M,; 1994; Effect of Nitrate on Phosphorus Release in Biological Phosphorus Removal Systems; International Association for Water Quality; Pergamon Press, Great Britain.

Lim, D., University of South Florida; 1998; Microbiology, 2nd Edition; McGraw-Hill, New York, New York.

Liu, Wen-Tso; Mino, T.; Nakamura, K., Matsuo, T.; 1997; Internal Energy-Based Competition Between Polyphosphate and Glycogen-Accumulating Bacteria in Biological Phosphorus Removal Reactors-Effect of P/C Feeding Ratio; Water Research, Vol. 31, No. 6, pp. 1430-1438; by Elsevier Science Ltd.; Pergamon Press, Great Britain.

Liu, Wen-Tso; Mino, T.; Nakamura, K.; and Matsuo, T.; 1994; Role of Glycogen in Acetate uptake and Polyhydroxyalkanoate Synthesis in Anaerobic-Aerobic Activated Sludge with a minimized Polyphosphate Content; J. of Fermentation and Bioengineering, 77:5.

Lo, C.K., Yu, C.W., Tam, N.F.Y., Traynor, S.; 1994; Enhanced Nutrient Removal by Oxidation-Reduction Potential (ORP) Controlled Aeration in a Laboratory Scale Extended Aeration Treatment System; Water Research, Vol. 28, No. 10; Elsevier Science Ltd., Pergamon Press, Great Britain.

Loosdrecht, M.C.M, Smolders, G.J., Kuba, T., Heijnen; 1997; Metabolism of Micro-Organisms Responsible for Enhanced Biological Phosphorus Removal from Wastewater – Use of Dynamic Enrichment Cultures; Antonie van Leeuwehoek 71:109-116; Kluwer Academic Publishers, Netherlands.

Malakoff, D.; 1998; Death by Suffocation in the Gulf of Mexico; 1998; Science, July, Vol. 281, No. 5374, pp. 190-192; American Association for the Advancement of Science, Washington D.C.

Marais, G.v.R., Loewenthal, R.E., Siebritz, I.P.; 1983; Observations Supporting Phosphate Removal by Biological Excess Uptake-A Review; Wat. Sci. Tech., Vol. 15; Capetown, S.A., pp. 15-41.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Matsuo, Y.; 1994; Effect of the Anaerobic Solids Retention Time on Enhanced Biological Phosphorus Removal; Water Science Technology, Vol. 30, No. 6, pp. 193-202; IAWQ; Pergamon Press, Great Britain.

McGucken, W.; 1991; Biodegradable – Detergents and the Environment; Texas A&M University Press, College Station, Texas.

Menardiere, M. de la, Charpentier, J., Vachon, A., Martin, G.; 1991; ORP as a Control Parameter in a Single Sludge Biological Nitrogen and Phosphorus Removal Activated Sludge System; Water SA, Vol 17, No. 2.

Mendenhall, W., Sincich, T.; 1995; Statistics for Engineering and the Sciences; Prentice-Hall, New Jersey.

Tchobanoglous, G., Burton, F. (Principal Authors); 1991; Wastewater Engineering; Metcalf & Eddy, Inc.; McGraw-Hill; New York, New York.

Mino, T., Kawakami, T., Matsuo, T; 1984; Location of Phosphorus in Activated Sludge and Function of Intracellular Polyphosphates in Biological Phosphorus Removal Process; Wat. Sci. Tech., Vol 17, Amsterdam, pp. 93-106.

Mino, T., Satoh, H. Matsuo, T.; 1994; Metabolisms of Different Bacterial Populations in Enhanced Biological Phosphate Removal Processes; Water Science Technology, Vol. 29, No. 7, pp.67-70; IAWQ; Pergamon Press, Great Britain.
Metabolic section

Morel, F., Hering, J.; 1993; Principles and Applications of Aquatic Chemistry; John Wiley & Sons, New York, New York.

Nicholls, H.A., Osborn, D.W, Pitman, A.R.; 1986; Biological Phosphorus Removal at the Johannesburg Northern and Goudkoppies Wastewater Purification Plants; Water SA, 12:1.

Nicholls, H.A., Pitman, A.R, Osborn, D.W; 1985; The Readily Biodegradable Fraction of Sewage: Its Influence on Phosphorus Removal and Measurement; Wat. Sci. Tech., Vol. 17; Paris, pp. 73-87.

Noack, D.; 1986; Directed Selection of Differentiation Mutants of *Streptomyces noursei* Using Chemostat Cultivation; Journal of Basic Microbiology, vol. 26.

Paik, Y.H., Simon, E.S., Swift, G.; A Review of Synthetic Approaches to Biodegradable Polymeric Carboxylic Acids for Detergent Applications; in Hydrophilic Polymers – Performance with environmental Acceptability; 1996; Glass, J.E. (ed.); Advances in Chemistry Series 248; The American Chemical Society, Washington D.C.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Petersen, W., Skinner, J., and Strong, F.; 1949; Elements of Food Biochemistry, Prentice-Hall, Englewood Cliffs, New Jersey.

Pitman, A.R., Venter, S.L.V., Nicholls, H.A.; 1983; Practical Experience with Biological Phosphorus Removal Plants in Johannesburg; Wat. Sci. Tech., Vol. 15, Capetown, pp. 233-259.

Qasim, S.; Chiang, W. Zhu, G. Miller, R.; 1996; Effect of Biodegradable Carbon on Biological Phosphorus Removal; Journal of Environmental Engineering, Sept. 1996.

Qasim, S.; University of Texas at Arlington; 1999; Wastewater Treatment Plants; Technomic Publishing Co. Inc., Lancaster, PA.

Randall, A.A., Benefield, L.D., Hill, W.E.; 1994; The Effects of Fermentation Products on Enhanced Biological Phosphorus Removal, Polyphosphate Storage, and Microbial Population Dynamics; Water Science Technology, Vol. 30, No. 6, Pergamon Press, Great Britain.

Satoh, H.; Mino, T.; and Matsuo, T., Dept of Urban Engineering, University of Tokyo; 1992; Uptake of Organic Substrates and Accumulation of Polyhydroxyalkanoates Linked with Glycolysis of Intracellular Carbohydrates Under Anaerobic Conditions in the Biological Excess Phosphate Removal Processes: Wat. Sci. Tech., 26:5 –6, pp. 933-942; IAWPRC, Great Britain.

Schon, G. Geywitz, S., Mertens, F.; 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, Vol. 27, No. 3; Pergamon Press, Great Britain.

Sedlak, R.; 1991; Phosphorus and Nitrogen Removal from Municipal Wastewaters, 2nd ed.; Lewis Publishers, New York.

Shapiro, J.A., Trubatch, D.; 1991; Sequential Events in Bacterial Colony Morphogenesis; Physica D. vol. 49.

Shapiro, J.A.; 1984; The Use of Mudlac Transposons as Tools for Vital Staining to Visualize Clonal and non-Clonal Patterns of Organizations in Bacterial Growth on Agar Surfaces; Journal of General Microbiology, vol. 130, pp. 1169-1181.
Metabolic section

Sittig, M.; 1979; Detergent Manufacture Including Zeolite Builders and Other New Materials; Noyes Data Corporation, Park Ridge, New Jersey.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Skalsky, D.S., Daigger, G.T.; 1995; Wastewater Solids Fermentation for Volatile Acid Production and Enhanced Biological Phosphorus Removal; Water Environment Research, Vol. 67, #2.

Smolders, G.J.F., Van Loosdrecht, M.C.M., Hiejnen, J.J.; 1996; Steady-State Analysis to Evaluate the Phosphate Removal Capacity and Acetate Requirement of Biological Phosphorus Removing Mainstream and Sidestream Process Configurations; Elsevier Science Ltd., Pergamon Press, Great Britain.

Sorm, R., Bortone, G., Saltarelli, R., Jenicek, P., Wanner, J., Tilche, A.; 1996; Phosphate Uptake Under Anoxic Conditions and Fixed-Film Nitrification in Nutrient Removal Activated Sludge Systems; Water Research, Vol. 30, No. 7. Elsevier Science LTD, Pergamon Press, Great Britain.

Stryer, L.; 1995; Biochemistry, 4th ed.; W.H. Freeman and Co., New York.

Tiessen, H. Ed.; 1995; Phosphorus in the Global Environment, Transfers, Cycles and Management, SCOPE Report 54; John Wiley & Sons, Chichester, Chap. 2.

Unz, R.: 1999; Professor of Environmental Microbiology, The Pennsylvania State University; email to Dr. Jaci R. Batista concerning phosphorus in proteins, and proteins in wastewater.

van Loosdrecht, M.C.M., Smolders, G.J., Kuba, T., Heijnen, J.J.; 1997; Metabolism of Micro-Organisms Responsible for Enhanced Biological Phosphorus Removal from Wastewater; Kluwer Academic Publishers, Netherlands.

Venter, S.L., Halliday, J., Pitman, A.R.; 1978; Optimisation of the Johannesburg Olifantsvlei Extended Aeration Plant for Phosphorus Removal; Prog. Wat. Tech., Vol. 10, Nos. 1 / 2, pp. 279-292.

Wareham, D.G., Hall, K.J., Mavinic, D.S.; 1995; An ORP Screening Protocol for Biological Phosphorus Removal in Sequencing Batch Reactors; Canada, Jour. of Civil Engineering, Vol 22.

Webster's II, New Riverside University Dictionary; 1994; The Riverside Publishing Company and the Houghton Mifflin Company.

Wentzel, M.C., Lotter, L.H., Ekama, G.A., Loewenthal, R.E., Marais, G.v.R.; 1991; Evaluation of Biochemical Models for Biological Excess Phosphorus Removal; Wat. Sci. Tech., Vol. 23, Kyoto, pp. 567-576.

Yapijakis, C.; 1992; Treatment of Soap and Detergent Industry Wastes; in Handbook of Industrial Waste Treatment; Vol. 1; Wang, L.K., Wang, M.H.S, (Eds.); Marcel Dekker, Inc., New York, New York.

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