Analysis of temporal trends in southern Nevada wastewater pond parameters with an emphasis on ammonia removal

Bruce D Foster
University of Nevada, Las Vegas

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ANALYSIS OF TEMPORAL TRENDS IN SOUTHERN NEVADA
WASTEWATER POND PARAMETERS WITH AN
EMPHASIS ON AMMONIA REMOVAL

by

Bruce D. Foster

Bachelor of Science
University of Arizona, Tucson
1983

A thesis submitted in partial fulfillment
of the requirements for the degree of

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in

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Howard R. Hughes College of Engineering
University of Nevada, Las Vegas
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The Thesis prepared by

BRUCE D. FOSTER

Entitled

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Examination Committee Chair

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Examination Committee Member

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ABSTRACT

Analysis of Temporal Trends in Southern Nevada Wastewater Pond Parameters
With an Emphasis on Ammonia Removal

by

Bruce D. Foster

Dr. David E. James, Examination Committee Chair
Professor of Environmental Engineering
University of Nevada, Las Vegas

This paper examines physico-chemical and biological properties and processes in four Southern Nevada wastewater pond systems located in Alamo, Beatty, Blue Diamond, and Searchlight. Pond parameters examined include pond dimensions, hydraulic retention time (HRT), alkalinity, pH, chemical oxygen demand (COD), biochemical oxygen demand (BOD), dissolved oxygen (DO), phosphorus, nitrates, and ammonia. Data on each pond and pond system are presented including pond system comparisons.

A major focus of this paper is on ammonia-N removal. Individual pond ammonia-N removal performance is compared to published models. A model based solely on HRT in a given temperature regime is developed. Models describing Ammonia-N removal performance as a function of HRT, temperature, and pH are also developed. Ammonia-N removal mass transfer coefficients for well-mixed, plug flow, and plug flow with dispersion are also calculated.
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CHAPTER 1

INTRODUCTION

In recent years, much time and effort has gone into developing effective advanced wastewater treatment processes and technology. Most of this work has gone into high-volume, urban applications. In some small Southern Nevada communities, however, there exists a need to understand and efficiently operate cost-effective, low technology wastewater treatment solutions. Wastewater pond systems have historically been an effective solution for treating wastewater in small communities located in arid climates. The recent growth experienced by Southern Nevada communities has resulted in more expansion into rural areas serviced by wastewater pond systems. As the population using these facilities grows, greater pressure is placed on the ability of the pond system to provide effective treatment. This study was conceived in recognition of the need to better understand the behavior of wastewater pond systems located in the arid desert region of Southern Nevada. The intended result of this improved understanding is to identify options or approaches that small town operators may use to enhance the performance of their wastewater pond treatment facilities.
Scope

This study analyzes four domestic wastewater treatment pond systems located in Southern Nevada. These pond systems are located in the townships of Alamo, Beatty, Blue Diamond, and Searchlight, Nevada. Data was collected from these ponds during the time period from August 1996 through September 1997. The data collected from each pond included the following parameters:

- Physical pond dimensions
- Flow rates into the ponds
- Water temperature
- pH
- Alkalinity concentration as CaCO₃
- Dissolved oxygen concentration
- Ammonia-N concentration
- Nitrate concentration
- Phosphorus concentration
- Biochemical oxygen demand (BOD)
- Chemical oxygen demand (COD)
- Total suspended solids (TSS)
These data were obtained through field or laboratory analyses or through the pond operators. Supplementary data, obtained from other sources, is introduced where appropriate.

This information is organized into ten chapters and an appendix designed for ease of use by pond operators and wastewater treatment specialists. To this end, information and data are presented using a top-down approach with summary information presented in the earlier chapters and detailed information on each pond presented in subsequent chapters. Summary-level treatment of study topics is provided in the first five chapters. More detailed information is provided in the final five chapters. Chapter 2 addresses theoretical considerations associated with each pond property with an emphasis on application to the pond systems in the scope of this study. Chapter 3 provides an overall description of each of the pond systems. Pond dimensions and flow rates are described and hydraulic retention times (HRTs) are calculated. Chapter 4 presents influent characteristic data associated with each pond system. Chapter 5 presents summary-level data on each pond property comparing the results obtained from each pond system. Chapters 6 through 9 present detailed data from each individual pond. The intent is to include comprehensive data that pond operators can use in developing approaches for improving pond performance. Conclusions based on information in the data chapters are presented in Chapter 10. Recommendations associated with each pond system are provided. An appendix is presented at the end of this work discussing measurement and analytical error inherent in obtaining data associated with the above parameters.
Methodology

The data collected for this study was obtained by the author, through the pond operators, or through literature searches. Data obtained by the author was collected by collecting grab samples from each pond on an approximate monthly basis. These samples were collected primarily during the morning from the pond surface, though, some bottom samples were also collected. In addition, a diurnal sampling campaign was conducted at the Searchlight pond during September of 1997. Influent and pond samples were collected at the same sampling locations. These locations were at the pond headworks, in the primary ponds at the location where the inflow pipes from the primary to the secondary ponds are situated, and in the secondary pond opposite from the inflow location.

Samples were analyzed in the field and at the UNLV wastewater laboratory. Field collected data included recording, measuring, or analyzing pond dimensions, influent flow rates, pond depth, temperature, dissolved oxygen concentration, pH, alkalinity, ammonia-N concentration, nitrate concentration, and phosphorus concentration. Collection of phosphorus data did not commence until April 1997, however. Therefore, only limited phosphorus data are available. In addition, Beatty pond profile measurements of temperature, water depth, sludge depth, and dissolved oxygen concentration were taken at 16 sampling points across the entire pond.

Pond dimensions were measured using a Bushnell field laser range finder. Influent flow rates were recorded from flow meters located at the Beatty and Blue Diamond...
ponds. Pond depths were recorded by noting installed staff gage water levels as well as through use of a Sludge Judge™. Temperature and dissolved oxygen measurements were obtained through use of a Yellow Springs Instruments (YSI) Model 57 dissolved oxygen meter calibrated for the pond elevation and water temperature. Influent and pond pH were determined using an Omega Model PHB10 meter with an attached Omega pH probe calibrated for the high pH scale (pH 7 and 10). Alkalinity, ammonia-N, nitrate, and phosphorus data were obtained using Hach field kits. In addition, a Hach ammonia-N probe was used to determine ammonia-N concentrations greater than the range of the Hach field kit (25 mg/L). The ammonia-N probe was not available for use until January 1997, however.

Data obtained in the UNLV wastewater laboratory included pH, alkalinity titrations, dissolved oxygen concentration, COD concentration, and BOD concentration. BOD data was determined to be unreliable, however, and the resulting laboratory-derived concentrations are not reported in this study. Values for pH were obtained using a pH probe (model PHB-66) and meter calibrated for the low pH (pH 4 and 7) range to support alkalinity titrations (Omega Engineering, Inc., 1989). Alkalinity titrations were performed in accordance with Standard Method 2320B (Clesceri et. al., ed. 1989). Dissolved oxygen concentration data was obtained in the laboratory for those samples where field data were not available using a dissolved oxygen meter. COD values were obtained using a Hach COD reactor model 45600 and a Bausch and Lomb Spectronic 20D spectrophotometer using the reactor digestion method (Jirka and Carter, 1975).
Data obtained from the pond operators included BOD concentrations, flow rates, and pond dimensions. BOD data were obtained from each pond. Flow rate data were obtained from the Searchlight pond operator. Pond dimensions were obtained from the Alamo pond operator.

Data derived from literature searches included evaporation and population data. In addition, data describing theoretical principles were obtained from the literature as well as referenced theoretical and empirical models.
Strictly speaking, pH is defined as the negative log of the hydrogen ion activity. In typical wastewater applications, hydrogen ion concentration, $[H^+]$, can be substituted for activity with little error. This simplification typically holds true for ionic strengths of $10^{-3}$ moles/L or less. The pH scale ranges from 0 to 14, though some strong acids can have a pH less than 0 (Snoeyink and Jenkins, 1980). Since pH is a negative log scale, a unit increase in pH represents an order of magnitude decrease in $[H^+]$. Therefore, a wastewater with a pH of 8 will contain ten times the amount of hydrogen ions as will a wastewater with a pH of 9. The $[H^+]$ will double with an increase of 0.3 pH units. Waters with a pH of less than 7 are said to be acidic, and waters with a pH of greater than 7 are said to be basic. This representation can be understood by examining the following equilibrium reaction:

\[(1)\quad H_2O \leftrightarrow H^+ + OH^- \]

The corresponding equilibrium equation is:

\[(2)\quad K_w = [H^+][OH^-] \]
The value for $K_w$ can be determined through consideration of the standard free energy of
this reaction which is 19.09 kcal/mole at 25 C. Therefore:

\[ K_w = e^{-19.09/RT} \approx 1 \times 10^{-14} \] (Snoeyink and Jenkins, 1980)

where $R$ is the universal gas constant (cal/K-mol) and
$T$ is the Temperature (°K)

The negative log of $K_w$ ($pK_w$) is 14. Hence,

\[ 14 = pH + pOH \]

Therefore, the negative log of $[H^+]$ and $[OH^-]$ must add up to 14, and if the pH is known,
the pOH can be calculated. Thus, a wastewater with a pH of 10 has a pOH of 4 implying
that the $OH^-$ ion predominates resulting in a basic wastewater. If the pH were less than
7, the $H^+$ ion would predominate, resulting in an acidic wastewater.

This balance between $[H^+]$ and $[OH^-]$ has significant implications when considering
the optimum pH range for wastewater treatment. The pH affects the microbiology of the
organisms providing treatment in the wastewater pond, as well as equilibrium
relationships of chemical species. The pH of a wastewater is dependent on the source
water mineral content and the relative roles of algal photosynthesis, which tends to
increase pH, and respiration processes, which tend to decrease pH. In particular, pH
impacts ammonia, phosphorus, and BOD removal rates. This impact will become
apparent these topics are discussed in subsequent chapters.
Alkalinity

In water treatment proper chemical treatment requires pH control. Water treatment also frequently requires the addition of chemicals which can change the pH; therefore, measurement of pH alone is not sufficient for process control. The pH must be complemented with some measure of the capacity of the water to resist changes in pH. A measure of this capacity to resist changes in pH is the alkalinity (Mays, 1996) in wastewater pond applications. pH and alkalinity have been reported to fit the approximate empirical relationship:

\[
(5) \quad \text{pH} \approx 7.3 \exp[0.0005 \times \text{alk}] \quad \text{(Reed et al., 1995)}
\]

Rearranging equation (5) to solve for alkalinity yields the following:

\[
(6) \quad \text{alk (mg/L)} \approx 2000 \times [\ln(0.137 \times \text{pH})]
\]

Equation (6) can be used to estimate alkalinity values based on measured pH values. However, equation 6 does not address the total carbonate species that are a key parameter in determining alkalinity (see discussion below). Therefore, equation 6 should be used with caution.

Alkalinity is due principally to salts of weak acids and strong bases. These substances act as buffers to resist a drop in pH resulting from acid addition. Alkalinity is therefore, a measure of the buffer capacity and is used to a great extent in wastewater treatment practice (Sawyer et al., 1994).

Although many materials may contribute to the alkalinity of a water, the major portion of the alkalinity is caused by three major ions which may be ranked in order of
their association with high pH values as follows: (1) hydroxide, (2) carbonate, and (3) bicarbonate. For most practical purposes, alkalinity due to other materials is insignificant and may be ignored (Sawyer et. al.. 1994).

Carbonates and bicarbonates are responsible primarily for buffering, and for the buffering capacity of water. Alkalinity is the capacity of water to neutralize the acid added to it. Alkalinity is operational defined as the amount of acid required to titrate a water to a specific pH, i.e., pH = 4.3 to 4.8 (Mays. ed.. 1996).

Total alkalinity of natural waters can often be approximated by alkalinity associated with carbonate and bicarbonate:

\[ \text{alkalinity} = [\text{HCO}_3^-] + 2[\text{CO}_3^{2-}] - [\text{OH}^-] - [\text{H}^+] \]

Alkalinity includes the following components:

Hydroxide alkalinity = [OH⁻]

Bicarbonate alkalinity = [HCO₃⁻]

Carbonate alkalinity = [CO₃²⁻] (Mays. ed.. 1996)

Temperature

The temperature of a wastewater plays a significant role in the chemical and biological processes occurring in a wastewater pond. Warmer temperatures tend to increase reaction rates while cooler temperatures retard reaction rates. As a consequence, wastewater ponds typically provide more efficient treatment during the warmer summer months. Reaction rates are a function of reaction rate constants that are temperature-
dependent. In a well-mixed pond model, the influence of temperature on BOD removal reaction rate can be estimated from the following:

\[ k_w = k_{w,35} \times (1.085)^{T-35} \quad \text{(Reed et. al., 1995)} \]

where: 
- \( k_w \) = reaction rate at water temperature \( T \), \( \text{d}^{-1} \)
- \( k_{w,35} \) = reaction rate at \( 35 \text{ °C} \) = 1.2 \( \text{d}^{-1} \)
- \( T \) = wastewater temperature, \( \text{°C} \)

In a plug flow pond model, this influence can be estimated as follows:

\[ k_p = k_{p,20} \times (1.09)^{T-20} \quad \text{(Reed et. al., 1995)} \]

where: 
- \( k_p \) = plug flow reaction rate at temperature \( T \), \( \text{d}^{-1} \)
- \( k_{p,20} \) = reaction rate at \( 20 \text{ °C} \), \( \text{d}^{-1} \) (determined as a function of the organic loading rate)
- \( T \) = wastewater temperature, \( \text{°C} \)

The effect of well-mixed and plug-flow conditions is discussed further under the section on ammonia-N removal.

Temperature also influences dissolved oxygen (DO) concentrations, pH, and volatilization processes in a wastewater. The temperature dependence of DO is related to the saturated DO concentration value which fluctuates with the Henry’s law constant (see DO discussion). Saturated DO concentrations show an inverse relationship with temperature. The dependence of pH on temperature in wastewater ponds is an indirect relationship tied to algal respiratory and photosynthetic processes. Algal densities are highest during the warm, bright months. Higher algal densities increase photosynthesis, thus increasing pH. Lower algal densities during winter months result in depressed photosynthetic activity and hence, lower pH values. Temperature effects on the
volatilization process are primarily due to the temperature dependence of reaction rate equilibrium constants (see ammonia removal discussion).

**Dissolved Oxygen**

The dissolved oxygen (DO) concentration in a wastewater pond is often a limiting property in removal of organic material and nutrients from wastewater. The makeup of a wastewater microbial population is dependent, to some extent, on the dissolved oxygen conditions in the wastewater. These conditions can be aerobic or anaerobic. An aerobic process is a biological treatment process that occurs in the presence of oxygen, while oxygen is not present in anaerobic processes. Aerobic processes can be oxic or anoxic. In an oxic process, microbes use oxygen in aerobic pathways for cell respiration and synthesis. Removal of organics (BOD) and ammonia-N through nitrification are examples of bacteria using oxygen in combination with an energy source (either organic carbon or ammonia) during aerobic metabolism. In an anoxic process, aerobic metabolic pathways are used, but nitrite or nitrate ions are used in place of oxygen as electron acceptors for microorganism cell growth and synthesis. Denitrifying organisms, converting nitrite and nitrate to nitrogen gas, use anoxic processes. Anaerobic metabolic processes make use of a different pathway of cell respiration and synthesis. Sludge digestion is an example of anaerobic metabolism.

In a stratified wastewater treatment pond system, oxic, anoxic, and anaerobic conditions can co-exist. Oxic conditions suitable for BOD removal are typically present when the DO concentration is 2 mg/L or greater. This lower limit is present in a
wastewater pond to varying depths depending upon the degree of stratification and aeration present in the pond. Conditions suitable for nitrification are present when the DO concentration is closer to the saturation value. The saturation value, the maximum DO concentration achievable through gas exchange processes, is a function of temperature and pressure. Using Henry’s Law, the saturation concentration of oxygen in water can be calculated from the following relationship:

\[
Pg = Hx_g
\]

where \( Pg \) = partial pressure of oxygen in atmospheres (atm) 
\( H \) = Henry’s law constant in atm/mol fraction 
\( x_g \) = equilibrium mole fraction of dissolved gas = \( \frac{\text{mol(gas)}}{\text{mol(gas)} + \text{mol(water)}} \)

The approximate elevation of the pond systems analyzed in this study is 3500 feet. At this elevation, the air pressure is 0.875 atm. Air is made up of approximately 21 percent oxygen, therefore, the partial pressure of oxygen at 3500 feet of elevation is 0.875 x 0.21 = 0.184 atm. Using this value for \( Pg \), noting that one liter of water contains 55.6 moles which is much larger than the molar concentration of gas, and noting that a mole of oxygen weighs 32 g., solving equation 10 for the mole concentration of gas and converting it to mg/L yields the following relationship:

\[
C_s(O_2) = 55.6 \times 32 \times 0.184/H \times 1000 = 327.372.8/H
\]

In equation 11, the value of \( H \) is a function of temperature, resulting in DO saturation value also being a function of temperature. Application of equation 11 to determine DO saturation values for the pond systems in this study results in the saturation
concentrations at various temperatures shown in Table 1. Therefore, the DO concentration cannot exceed Table 1 values for mechanical reaeration processes.

![Table 1. Dissolved Oxygen Concentration at 3500 Feet Elevation as a Function of Temperature Using Equation 9](image)

In wastewater ponds, reaeration processes include gas exchange with the atmosphere or across the pond surface, or through technological means involving mechanical and diffused gas aeration. In mechanical aeration, the surface of the water is agitated creating a greater surface area of water in contact with the atmosphere, resulting in a greater volume of water involved with gas exchange. In diffused gas systems, air or oxygen is bubbled through the water using aspirators or diffusers. The smaller the bubbles, the greater the total bubble area in contact with the water and, hence, the greater oxygen transfer efficiency.
Reaeration is not the only means for increasing the dissolved oxygen concentration in a wastewater pond. Photoautotrophic processes utilize CO$_2$ and light with water as an electron acceptor to produce oxygen through photosynthesis. In wastewater ponds, the primary producers of oxygen through this mechanism are microscopic algae. In warm, bright conditions, with sufficient nutrients, algae can produce DO conditions that exceed the saturation value, resulting in a supersaturated wastewater. Observations made from the ponds in this study have shown that the DO in unaerated wastewater ponds varies directly with the level of photosynthetic activity, being low at night and early morning, and rising to a peak in the late afternoon. The photosynthetic responses of algae are controlled by the presence of light, the temperature of the water, and the availability of nutrients.

Many facultative ponds support extensive algal populations. Values of pH ranging as high as 10 have been observed where algae are growing rapidly, particularly in shallower ponds. Algae use carbon dioxide and bicarbonate in photosynthetic activity, and this removal is responsible for high pH conditions. Photosynthetic removal of carbon dioxide tends to increase the pH to between 8 and 9 in water with moderate alkalinity. Algae can reduce the aqueous carbon dioxide concentration below its equilibrium concentration with air and consequently can cause an even greater increase in pH. As the pH increases, the alkalinity forms change, resulting in extraction of carbon dioxide for algal growth from bicarbonates and carbonates according to the following equilibrium equations (Mays, ed. 1996):

(12) \[ 2\text{HCO}_3^- \Leftrightarrow CO_3^{2-} + H_2O + CO_2 \]
\[(13) \quad \text{CO}_3^{2-} + \text{H}_2\text{O} \leftrightarrow 2\text{OH}^- + \text{CO}_2\]

The removal of carbon dioxide by algae tends to cause a shift in the forms of alkalinity present from bicarbonate to carbonate, and from carbonate to hydroxide. During these changes the total alkalinity remains constant, however. \(\text{OH}^-\) is produced, thus raising the pH. Algae can continue to extract carbon dioxide from water until an inhibitory pH is reached, which is usually in the range of pH 10 to 11, at which point \(\text{CO}_2\) and \(\text{HCO}_3^-\) may not be present in sufficient amounts to support maximum growth rates.

During the dark hours of the day, algae produce rather than consume carbon dioxide. This is because algal respiratory processes continue in darkness when photosynthetic processes have shut down. This carbon dioxide production has an effect opposite to that of photosynthesis tending to reduce the pH. Diurnal variations in pH due to algal photosynthesis and respiration are common (Sawyer et. al., 1994).

The fundamental process controlling growth of algae is the balance between photosynthesis and respiration. Respiration is described as a function of biomass:

\[(14) \quad \frac{dR}{dt} = -RA\]

where:

\(R = \text{rate of respiration}\)
\(A = \text{algal concentration (James, ed. 1993)}\)
The rate of photosynthesis is also dependent on light intensity, which varies with time and depth. The relationship with light is generally expressed in terms of the maximum rate of photosynthesis, $P_{\text{max}}$:

\[ \frac{dP}{dt} = P_{\text{max}}(I/I_{\text{opt}}) \exp(1 - I/I_{\text{opt}}) \]

where:

$I = \text{light intensity}$
$I_{\text{opt}} = \text{light intensity corresponding to } P_{\text{max}}$ (James, ed., 1993)

Light intensity decreases with depth in an exponential manner at a rate which depends upon the turbidity:

\[ I(z + h) = I(z)\exp(-Kh) \]

where:

$I(z)$ and $I(z + h)$ are the light intensities at depth $z$ and $z + h$, respectively. $K$ is the extinction coefficient (James, ed., 1993)

The daily photosynthesis in a water column integrated over its depth yields the following relationship:

\[ GP = (NP_{\text{max}}K) \times 0.6 \times (1.33 \sin h^{-1} \times I/I_{\text{opt}} - I_{\text{opt}}/I \times (1 - (I/I_{\text{opt}})^2)^{0.5}) \]

where:

Gross daily production per unit area = day length $h = \text{depth}$ $N = \text{algal concentration}$ (James, ed. 1993)

The rate of photosynthesis increases with temperature up to an optimum and thereafter decreases. This may be expressed in a similar way to the light response equation:

\[ P_T = P_{\text{max}}(T/T_{\text{opt}}) \exp(1 - T/T_{\text{opt}}) \]
where:

\[ P_T = \text{rate of photosynthesis at temperature } T \]
\[ T_{\text{opt}} = \text{optimum temperature giving } P_{\text{max}} \text{ (James, ed., 1993)} \]

Removal of Organics From Wastewater Ponds

The primary function of domestic wastewater ponds is to reduce organic material in the pond below limits established in individual pond system treatment permits. The most widely used parameter for measuring this organic pollution is biochemical oxygen demand (BOD). BOD can be defined as a measurement of the amount of dissolved oxygen consumed by microorganisms to oxidize organic matter (Metcalf and Eddy, 1991). BOD data have broad application in wastewater treatment and are used for the following:

- determining the approximate quantity of oxygen required to biologically stabilize organic matter.
- sizing wastewater stabilization ponds.
- measuring the efficiency of treatment processes, and
- determining compliance with wastewater discharge permits (Metcalf and Eddy, 1991)

The rate of BOD exerted on a wastewater can be modeled through first order reaction kinetics as the following:

\[ y_t = L(1 - e^{-kt}) \]  

(Metcalf and Eddy, 1991)

where:  
\[ y_t = \text{BOD exerted at time } t \]
\[ L = \text{ultimate BOD (maximum BOD exerted at approximately 20 days)} \]
\[ k = \text{reaction rate constant (typically 0.23 } \text{d}^{-1} \text{ for domestic wastewater)} \]
$t = \text{time}$

BOD is typically determined through a 5-day test to measure a $\text{BOD}_5$ value. This value is then used in conjunction with equation 18 to determine an ultimate BOD concentration. A classical method for determining $\text{BOD}_5$ concentrations is to place known volumes of the wastewater sample into 300 mL BOD bottles (three or four samples). The samples are then diluted with organic free water of a known DO concentration level to the full 300-mL bottle volume. The bottles are allowed to incubate at a known temperature (usually 20 °C) for 5 days. At the end of the 5 days, the DO concentrations in each of the BOD bottles is measured. The DO concentration difference between the start of the test and at the end of the 5 days is calculated. This difference is then divided by the wastewater volume fraction in the BOD bottle to calculate a $\text{BOD}_5$ concentration. The concentrations for each sample are then averaged, ignoring outliers, to arrive at a final $\text{BOD}_5$ concentration. Typical $\text{BOD}_5$ values range from 110 to 400 mg/L for weak to strong domestic wastewaters, respectively.

A surrogate measurement for BOD is chemical oxygen demand (COD). COD is the oxygen equivalent of organic matter that can be chemically oxidized (Metcalf and Eddy, 1991). The COD value of a wastewater is generally higher than the BOD value of a wastewater since more organic compounds can be chemically oxidized than can be biologically oxidized. Typical values of COD range from 250 to 1000 mg/L for weak to strong domestic wastewaters, respectively (Metcalf and Eddy, 1991). As a general rule, COD values will be approximately 60 percent greater than $\text{BOD}_5$ values. The main
advantage of measuring COD is the relatively short time required to obtain a COD value (3 hours, as opposed to 5 days for BOD$_5$).

Wastewater treatment pond design is based on BOD loading. Several design approaches have been applied. Design approaches for facultative ponds are described below.

A common approach based on experience is the areal loading rate method. Most states have design criteria for organic loading and/or hydraulic detention time for facultative ponds. Based on experience, the following loading rates for various climatic conditions are recommended: for average winter air temperatures above 15 C (59 F), a BOD$_5$ loading rate range of 45-90 kg/ha-d (40 - 80 lb/ac-d) is recommended. When the average winter air temperature ranges between 0 and 15 C (32-59 F), the organic loading rate should be in the range 22-45 kg/ha-d (20-40 lb/ac-d). For average winter temperature below 0 C, the organic loading should be in the range 11-22 kg/ha-d (10-20 lb/ac-d).

In multiple cell ponds, the BOD loading rate in the first cell is usually limited to 40 kg/ha-d (35 lb/ac-d) or less, and the total hydraulic detention time in the system is 120-180 days in climates where the average air temperature is below 0 C. In mild climates where the air temperature is higher than 15 C, loadings on the primary cell can be 100 kg/ha-d (89 lb/ac-d) (Reed et al, 1995).

Another design approach is to use what is known as the Gloyna equation. The following empirical equation has been proposed for design of facultative wastewater stabilization ponds:

\[ \text{Gloyna equation} \]
\[ V = (3.5 \times 10^{-5}) (Q) (L_a) [q^{135.7}] (f)(f') \]

Where: 
- \( V \) = pond volume, \( m^3 \)  
- \( Q \) = influent flow rate, L/d  
- \( L_a \) = ultimate influent BOD or COD, mg/L  
- \( q \) = temperature correction coefficient = 1.085  
- \( T \) = pond temperature, C  
- \( f \) = algal toxicity factor  
- \( f' \) = sulfide oxygen demand (Reed et al. 1995)

A pond depth of 1.5 m (5 ft) is suggested for systems with significant seasonal variations in temperature and major fluctuations in daily flow. The surface area design should be based on a 1-m (3-ft) depth in situations with moderate temperature variations and flow fluctuations. The algal toxicity factor, \( f \) is assumed to be equal to 1.0 for domestic wastes. The sulfide oxygen demand, \( f' \), is equal to 1.0 for sulfate equivalent ion concentration of less than 500 mg/L. The design temperature is the average pond temperature in the coldest month. Sunlight is not considered to be critical, but can be incorporated by multiplying the pond volume by the ratio of sunlight at the design location to the average found in the southwestern United States.

Evaluation of the Gloyna method with actual data provides the following best fit equation in terms of \( V \), BOD\(_5\), light, \( Q \), and \( T \).

\[ V = 0.035Q(BOD)(1.099)^{light(35-T)250} \]

where  
- BOD = BOD\(_5\) in the system influent, mg/L  
- light = solar radiation, langley's  
- \( V \) = pond volume m\(^3\)  
- \( Q \) = influent flow rate, m\(^3\)/d  
- \( T \) = pond temperature, C (Reed et al., 1995)
The Marias and Shaw equation is based on a complete-mix model and first order kinetics. The basic relationship is as follows:

\[(22) \quad C_f/C_0 = (1/(1 + k_c t_n))^n\]

where:

- \(C_f\) = effluent BOD\(_5\) concentration, mg/L
- \(C_0\) = influent BOD\(_5\) concentration, mg/L
- \(k_c\) = complete-mix first-order reaction rate, \(d^{-1}\)
- \(t_n\) = hydraulic residence time in each cell, \(d\)
- \(n\) = number of equal-sized pond cells in series (Reed et. al., 1995)

The influence of the water temperature on the reaction rate can be estimated by applying equation 8.

For plug flow conditions, the basic model is as follows:

\[(23) \quad C_f/C_0 = exp(-k_p t)\]

where:

- \(C_f\) = effluent BOD\(_5\) concentration, mg/L
- \(C_0\) = influent BOD\(_5\) concentration, mg/L
- \(k_p\) = plug flow first order reaction rate constant, \(d^{-1}\)
- \(t\) = hydraulic retention time, \(d\) (Reed et. al., 1995)

The influence of water temperature on the reaction rate for this mode can be estimated by applying equation 9.

Experience has shown that flow conditions are typically somewhere between complete-mixed and plug flow. To address this situation, the Wehner-Wilhelm equation (Wehner and Wilhelm, 1956) may be applied. Application of this equation is demonstrated in the discussion on pond ammonia-N removal performance.
Phosphorus Removal

Phosphorus typically exists in wastewater as orthophosphate (PO$_4^{3-}$), polyphosphate (P$_2$O$_7$), and organically bound phosphorus. The last two components may account for up to 70 percent of the influent phosphorus concentration (Metcalf and Eddy, 1991). Microorganisms consume phosphorus during cell synthesis and energy transport. As a result, 10 to 30 percent of the influent phosphorus is removed during conventional secondary biological treatment. Additional uptake beyond that needed for normal cell maintenance and synthesis is required to achieve low effluent concentration levels. Under certain aerobic conditions more phosphorus than is needed may be taken up by the microorganisms. Phosphorus may be released from cells under anoxic conditions. Biological phosphorus removal is accomplished by alternating oxic and anoxic environmental conditions in the wastewater treatment cells (Metcalf and Eddy, 1991).

Removal of phosphorus can be achieved by chemical, biological, and physical means. Chemical precipitation through use of iron and aluminum salts or lime has commonly been employed for phosphorus removal. Biological phosphorus removal methods are based on stressing microorganisms, causing them to take up more phosphorus than is required for normal cell growth. Filtration techniques are used in combination with either chemical or biological methods where low levels of phosphorus in effluents are required. (Metcalf and Eddy, 1991)

For most wastewaters, approximately 10 percent of the phosphorus corresponding to the insoluble portion is settled out during conventional primary treatment. With the exception of the amount incorporated into cell tissue, additional removal achieved in
conventional biological treatment is minimal since most of the phosphorus present after primary sedimentation is soluble.

One of the primary organisms responsible for removal of phosphorus is *Acinetobacter*. These organisms react to volatile fatty acids (VFAs) in the influent wastewater under anaerobic conditions by releasing stored phosphorus. The VFAs are an important food for *Acinetobacter* bacteria during competition with heterotrophic microorganisms. When an anoxic zone is followed by an aerobic (oxic) zone, the microorganisms consume phosphorus above normal levels. Phosphorus is used for cell maintenance, synthesis, and energy transport in addition to being stored for subsequent use by the microorganisms. Sludge containing the excess phosphorus is either wasted or removed and treated in a separate reactor to release the excess phosphorus. Since release of phosphorus occurs under anaerobic conditions, biological phosphorus removal requires both anaerobic and aerobic reactors or zones within a reactor. (Metcalf and Eddy, 1991)

**Ammonia Removal**

The primary function of wastewater stabilization ponds and lagoons is to provide for biological treatment of organic wastes. An ancillary, though not primary, benefit of such treatment is to reduce the concentration of ammonia in the wastewater. Reduction of ammonia concentrations can be important when the treated wastewater is released into natural water bodies. In southern Nevada, wastewater stabilization ponds and lagoons are designed for discharge to groundwater whereby the pond is sized to hold the entire wastewater flow volume for a time period sufficient to allow evaporation and infiltration.
of that volume. However, the growing concerns with water usage in southern Nevada make reuse of wastewater a potential consideration. With this possibility in mind, ammonia removal performance becomes an important issue.

Ammonia-N can be removed in pond systems by plant or algal uptake, nitrification and denitrification, adsorption, sludge deposition, and loss of ammonia gas to the atmosphere (volatilization.) In facultative wastewater treatment ponds, the dominant mechanism is believed to be volatilization. The rate of ammonia removal depends primarily on pH, temperature, and detention time. The pH varies as a result of the algae-carbonate interactions in the pond, so wastewater alkalinity is also important. Under ideal conditions, ammonia-N removal in wastewater stabilization ponds can approach and exceed 95 percent. The amount of aqueous, neutrally charged ammonia (NH₃) present at or near neutral pH levels is relatively small, but when some of this gas is lost to the atmosphere, additional ammonium (NH₄⁺) ions shift to the ammonia form to maintain equilibrium. Although the rate of conversion and loss may be low, the long detention time in these ponds compensates for the low rate, resulting in effective removal over the long term. (Reed et. al., 1995)

Ammonia Removal Theoretical Models

Ammonia stripping in wastewater ponds may be expressed by assuming a well mixed pond and a first-order reaction. The mass balance becomes:

\[ \frac{dC}{dt} = \frac{VC}{Q} (C_i - C_{sat}) - k_{overall} (C_{sat} - C_{sat}) \]

(24) \[ V \frac{dC}{dt} = QC_{in} - QC_{sat} - k_{overall} (C_{sat} - C_{sat}) \]

(James, 1998)
where:
\( Q \) = steady state flow rate, \( \text{m}^3/\text{d} \);
\( C_{in} \) = influent concentration of \((\text{NH}_4^+ + \text{NH}_3)\), \( \text{mg/L as N} \);
\( C_{out} \) = effluent concentration of \((\text{NH}_4^+ + \text{NH}_3)\), \( \text{mg/L as N} \);
\( C_{sat} \) = concentration in water \((\text{NH}_4^+ + \text{NH}_3)\) in equilibrium with background concentration in air;
\( V \) = volume of the pond, \( \text{m}^3 \);
\( k_{overall} \) = overall mass transfer coefficient, reciprocal time;
\( t \) = time, days \ (James, 1998) \)

Assuming steady state conditions and neglecting \( C_{sat} \), equation 24 can be solved for \( k_{overall} \) as follows:

\[
(25) \quad k_{overall} = \frac{1}{C_{out}} \left( \frac{Q}{V} C_{in} - \frac{Q}{V} C_{out} \right) = \frac{Q}{V} \left( \frac{C_{in}}{C_{out}} - 1 \right)
\]

If \( k_{overall} \) is known, a theoretical removal efficiency for a well-mixed pond can be determined through rearrangement of equation 25 as follows:

\[
(26) \quad \text{Efficiency(\%)} = \left[ 1 - \frac{1}{k_{overall}} \left( \frac{V}{Q} + 1 \right) \right] 100
\]

Equations 24 through 26 are valid for well mixed ponds. This approach may not be valid for partial mixed or facultative ponds. Another approach is to assume plug flow conditions. The basic equation governing ventilation of volatile compounds such as ammonia from a plug flow system can be expressed as follows:

\[
(27) \quad u \frac{dC}{dx} = -k_{overall} (C - C_{sat}) \quad \text{(James 1998)}
\]

where:
\( u \) = average plug flow velocity
\( C \) = ammonia concentration at position \( x \) in pond of length \( L \)
\( x \) = instantaneous position of fluid packet
Noting that the average pond HRT is the pond length divided by the average plug flow velocity (=\(V/Q\)) and assuming that a small ammonia background partial pressure will be exerted in air allowing \(C_{\text{sat}}\) to be neglected, equation 27 can be solved to yield the following relationship:

\[
(28) \quad \frac{C_{\text{out}}}{C_{\text{in}}} = \exp\left(-k_{\text{overall}} \frac{V}{Q}\right)
\]

Solving for \(k_{\text{overall}}\), equation 33 becomes:

\[
(29) \quad k_{\text{overall}} = \frac{Q}{V} \ln\left(\frac{C_{\text{in}}}{C_{\text{out}}}\right)
\]

Equations 28 and 29 can be used to calculate the theoretical overall ammonia removal rate constant and removal efficiencies for ponds under plug flow conditions.

The flow pattern in facultative ponds has been observed to be somewhere between complete mix and plug flow conditions. In such conditions, dispersion effects become significant. To address these conditions, the following equation developed by Wehner and Wilhelm for chemical reactor design is recommended for first order kinetics:

\[
(30) \quad \frac{C_{\text{out}}}{C_{\text{in}}} = \frac{4ae^{\frac{H}{2D}}}{(1 + a)(1 - a)(e^{\frac{H}{2D}} - e^{-\frac{H}{2D}})} \quad \text{(Reed et. al., 1995)}
\]

where:

- \(C_{\text{in}}\) = influent concentration
- \(C_{\text{out}}\) = effluent concentration
- \(a = (1 + 4k_{\text{overall}}tD)^{0.5}\)
- \(k_{\text{overall}} = \) overall first order rate constant, time\(^{-1}\)
- \(t = \) hydraulic residence time, d
- \(D = \) dimensionless dispersion number
- \(D = \frac{H}{vL} = \frac{H_1}{L^2}\)
\[ D = \frac{0.184f}{(Ld)^{0.489}} \frac{rv(W + 2d)^{0.899}(W)^{1.311}}{(Ld)^{0.489}} \]  

(31)  

where:

\[ D = \text{dimensionless dispersion number} \]
\[ t = \text{hydraulic residence time, } d \]
\[ v = \text{kinematic viscosity, } m^2/d \]
\[ d = \text{depth of pond, } m \]
\[ W = \text{width of pond, } m \]
\[ L = \text{length of pond, } m \]

In equation 31, the kinematic viscosity varies with temperature as follows:

<table>
<thead>
<tr>
<th>( T (^\circ C) )</th>
<th>( v \times 10^6 \text{ (m}^2/\text{s)} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.785</td>
</tr>
<tr>
<td>5</td>
<td>1.519</td>
</tr>
<tr>
<td>10</td>
<td>1.306</td>
</tr>
<tr>
<td>15</td>
<td>1.139</td>
</tr>
<tr>
<td>20</td>
<td>1.003</td>
</tr>
<tr>
<td>25</td>
<td>0.893</td>
</tr>
<tr>
<td>30</td>
<td>0.800</td>
</tr>
</tbody>
</table>

(Metcalf and Eddy, 1985)

Note that the kinematic viscosity must be converted to units of \( m^2/d \) before being used in equation 31. In the above equations, the overall mass transfer coefficient, \( k_{overall} \), is
composed of a liquid phase mass transfer coefficient, $k_L$, and an interfacial volumetric surface area, $a$ (Montgomery, 1985). Therefore:

$$(32) \quad k_{overall} = k_L a$$

**Ammonia-N Removal Empirical Models**

Pano and Middlebrooks developed an empirical model describing volatilization of ammonia-N from facultative wastewater ponds (Pano and Middlebrooks, 1982). This model describes ammonia-N removal as a function of pH, temperature, and hydraulic loading and can be depicted as follows:

For temperatures from 1 to $20 \, ^{\circ}C$:

$$(33) \quad \frac{C_e}{C_0} = [1 - \frac{A}{Q}(0.0038 + 0.000134T) \times \exp((1.041 - 0.044T)(pH - 6.6))]^{-1}$$

where: $C_e, C_0$ = ammonia-N concentrations, mg/L  
$Q =$ flow rate into the pond  
$A =$ pond surface area  
$T =$ temperature, °C

For temperatures between 21 and $25 \, ^{\circ}C$, they obtained:

$$(34) \quad \frac{C_e}{C_0} = [1 - 5.035 \times 10^{-3} \times \frac{A}{Q}\exp(1.540*(pH - 6.6))]^{-1}$$

A comparison of equations 33 and 34 with equations 25 and 28 result in the observation that $A/Q$ multiplied by the lengthy expressions in equations 33 and 34 is a surrogate for $k_La$ multiplied by the HRT (i.e., $V/Q$). Therefore, $k_La \times \frac{V}{Q} = k_L \times A/Q$ and the following relationship can be derived:

$$(35) \quad a = \frac{A}{V}$$

where: $A =$ interfacial area (i.e., the pond surface area)  
$V =$ unit volume (i.e., the pond volume)
A simplified model based solely on HRT has been proposed for diffused air aerated ponds. A minimum HRT of 45 days is indicated for such ponds. The model equation is as follows:

\[ C_{\text{out}}C_{\text{in}} = 0.0066 \times \text{HRT} \quad \text{(Middlebrooks and Pano, 1983)} \]

While equation 36 showed good correlation with actual data for diffused air aerated ponds, it was not shown to be applicable to surface aerated ponds. However, the applicability of a simple model based solely on HRT is worth exploring.

**Ammonia-N Volatilization**

Ammonia-N removal is influenced by the equilibrium expression:

\[ K_a = \frac{[\text{NH}_3][\text{H}^+]}{[\text{NH}_4^+]} \]

where \( K_a \) = ammonium dissociation constant. (Pano and Middlebrooks, 1982)

\( K_a \) in equation 37 is temperature-dependent. It has been shown to vary with temperature as follows:

<table>
<thead>
<tr>
<th>T (°C)</th>
<th>pK_a</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>9.90</td>
</tr>
<tr>
<td>10</td>
<td>9.73</td>
</tr>
<tr>
<td>15</td>
<td>9.57</td>
</tr>
<tr>
<td>20</td>
<td>9.40</td>
</tr>
<tr>
<td>25</td>
<td>9.26</td>
</tr>
</tbody>
</table>

(Stumm and Morgan, 1996)

where pK_a is the negative log of K_a.

The implication of equation 37 is that as pH approaches and exceeds the pK_a, more ammonia-N is converted to the un-ionized form, thus increasing the potential rate of volatilization as described by equations 24 or 27. Therefore, if mass transfer coefficients
are equal, volatilization of ammonia-N is increased at higher pH values, because the concentration of un-ionized ammonia will be higher.

\textit{Nitrification}

Ammonia-N removal can also be accomplished through nitrification. The opportunities for nitrification exist where conditions are aerobic, when there is sufficient alkalinity and a suitable temperature, and after most of the carbonaceous BOD has been removed so that the nitrifying organisms can compete with the heterotrophic organisms for the available oxygen. Theoretical relationships indicate that 4.6 grams of oxygen are required to oxidize 1 gram of ammonium nitrogen. (Reed et al., 1995)

Alkalinity is required to support biological nitrification reactions. The accepted theoretical design ratio is 7.1 grams alkalinity (as CaCO3) per gram NH4-N oxidized (Reed et al., 1995). Two bacterial genera are primarily responsible for nitrification: \textit{Nitrosomonas} and \textit{Nitrobacter}. \textit{Nitrosomonas} converts ammonia to nitrite. Nitrite is then converted to nitrate by \textit{Nitrobacter}. Approximate equations for these reactions are as follows (Metcalf and Eddy, 1991):

Ammonia to nitrite:

\begin{equation}
55NH_4^- + 76O_2 + 109HCO_3^- \rightarrow C_3H_7O_2N + 54NO_2^- + 57H_2O + 104H_2CO_3
\end{equation}

Nitrite to nitrate:

\begin{equation}
400NO_2^- + NH_4^+ + 4H_2CO_3 + HCO_3^- + 195O_2 \rightarrow C_3H_7O_2N + 3H_2O + 400NO_3^-
\end{equation}

A pond detention time of 18 to 20 days has been suggested as the minimum periods required to provide for complete respiration of ammonia (Metcalf and Eddy, 1991). With
the exception of the Beatty pond system, each of the pond systems addressed in this study was found to have a sufficient total HRT. in theory, to accomplished the desired ammonia removal through nitrification. The Beatty pond system, with a calculated HRT of approximately 15 days (see Chapter 3), may not have a sufficient residence time to accomplish desired removal. As will be shown in Chapter 5, the low concentrations of nitrates and nitrites in most Southern Nevada pond effluents indicate that nitrification generally does not account for a significant portion of ammonia-N removal (Pano and Middlebrooks, 1982).
CHAPTER 3

POND PHYSICAL CHARACTERISTICS

Pond Descriptions

The pond systems analyzed in this study are comprised of well-mixed, partial-mixed, and facultative ponds located in the small southern Nevada townships of Alamo, Beatty, Blue Diamond, and Searchlight. Each of these systems are in arid to semi-arid desert regions around Las Vegas, Nevada and are discharged to groundwater. A map showing pond locations is depicted in Figure 1. Pond locations are shaded. These ponds are at a similar elevation of approximately 3,500 feet, subject to similar seasonal weather patterns, and exhibit similar diurnal temperature variations. Slight differences in meteorological conditions do exist, however. These differences will be noted as individual pond systems are discussed.

Individual pond physical characteristics are summarized in Table 2 which lists pond physical dimensions, volumes, flow rates into each pond, and hydraulic retention times (HRT). Pond volumes for the Alamo, Blue Diamond, and Searchlight pond systems were calculated using the following equation:

\[ V = [(LW) + (L - 2\, sd)(W - 2sd) + 4(L - sd)(W - sd)]d/6 \]

where:  
V = Volume  
L = Length of pond at water surface
W = width of pond at water surface
s = horizontal to vertical slope factor
d = depth of pond  (Corbitt. 1990)

Figure 1. Sampling Site Location Map.

The Beatty pond system exhibits irregular depth characteristics necessitating the volume
summing approach described in the Beatty pond system discussion. Secondary pond
influent flow rates were estimated by subtracting out evaporation rates from the primary
ponds. Evaporation rate data was not available at any of the pond sites. However, monthly evaporation data for 1995 was available for Boulder City, Nevada which is located at a somewhat lower elevation (approximately 2500 feet) in the vicinity of the pond systems under consideration. Therefore, the average daily Boulder City evaporation value of 0.42 inches (NOAA. 1996) was used for the secondary ponds flow rate calculations. Infiltration rates through the primary pond bottoms were considered insignificant and were thus neglected for this calculation. HRT values were calculated by dividing pond volumes (V) by the corresponding average flow rate (Q).

<table>
<thead>
<tr>
<th>Pond</th>
<th>Width (ft)</th>
<th>Length (ft)</th>
<th>Depth (ft)</th>
<th>Slope Factor (H/V)</th>
<th>V (ft³)</th>
<th>Q (ft³/d)</th>
<th>HRT (d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alamo Primary</td>
<td>146</td>
<td>176</td>
<td>3</td>
<td>3</td>
<td>68718</td>
<td>3850</td>
<td>17.85</td>
</tr>
<tr>
<td>Alamo Secondary</td>
<td>138</td>
<td>438</td>
<td>1.0</td>
<td>3</td>
<td>58728</td>
<td>2951</td>
<td>19.90</td>
</tr>
<tr>
<td>Beatty Aerated</td>
<td>variable 129-165</td>
<td>~130</td>
<td>variable</td>
<td>1</td>
<td>115909.5</td>
<td>18480</td>
<td>6.27</td>
</tr>
<tr>
<td>Beatty Facultative</td>
<td>variable 165-219</td>
<td>~300</td>
<td>variable</td>
<td>1</td>
<td>158596.1</td>
<td>17811</td>
<td>8.90</td>
</tr>
<tr>
<td>Blue Diamond Primary</td>
<td>114</td>
<td>210</td>
<td>3.9</td>
<td>3</td>
<td>79293.71</td>
<td>4755</td>
<td>16.68</td>
</tr>
<tr>
<td>Blue Diamond Secondary</td>
<td>100</td>
<td>210</td>
<td>2.9</td>
<td>3</td>
<td>53371.37</td>
<td>3917</td>
<td>13.63</td>
</tr>
<tr>
<td>Searchlight Primary</td>
<td>210</td>
<td>210</td>
<td>3</td>
<td>3</td>
<td>121284</td>
<td>6550</td>
<td>18.52</td>
</tr>
<tr>
<td>Searchlight Secondary</td>
<td>220</td>
<td>340</td>
<td>2.4</td>
<td>3</td>
<td>170009.1</td>
<td>5007</td>
<td>33.95</td>
</tr>
</tbody>
</table>
Alamo Pond System

The Alamo pond is located approximately 100 miles north of Las Vegas, Nevada in Alamo, Nevada just off the Great Basin Highway (US 93). Alamo, with a population of about 1000, is located adjacent to the Pahranagat Lake Wildlife Refuge in a narrow greenbelt surrounded by desert. Water is supplied to this greenbelt region by runoff from the surrounding mountains and interflow from Pahranagat Lake.

The Alamo pond system consists of a partially aerated primary pond and a facultative secondary pond. A plan view of these ponds is shown in Figure 2.

![Figure 2. Plan View of Alamo Pond System.](image)

The primary pond is a partially mixed aerated pond approximately three feet deep with a flow rate estimated at 3850 ft$^3$/day (23.5 gal/min). No data were available for determining this flow rate. It was estimated based on population considerations (U.S. DOC. 1993).
and recorded flow rates for towns of similar size. A photograph of the primary pond is shown in Figure 3.

![Figure 3. Alamo Primary Pond.](image)

The secondary pond is very shallow (approximately 1 ft deep). Portions of the pond are choked with vegetation giving it the look of a wetlands rather than a facultative pond. The total pond system HRT was calculated to be slightly less than 38 days. A photograph of the secondary pond is shown in Figure 4.
Beatty Pond System

The Beatty pond is located approximately 110 miles northwest of Las Vegas, Nevada along US 95 in Beatty, Nevada. It consists of one large rectangular primary pond comprised of two distinct treatment regimes: a completely mixed aerated regime and a facultative regime. Once each week, flow from the primary is released to a rapid infiltration basin (RIB) located approximately one half mile from the primary pond. The aerated portion of the pond contains five aerators resulting in conditions approaching that of a completely mixed reactor. The aerated regime is variable in depth ranging from 7.5 to 4 ft., and the facultative regime varies in depth from 2.5 to 5 ft. with most of the depth in the 2.5- to 3-ft. range. A plan view indicating the depth variation is shown in Figure 5.
Figure 5. Plan View of the Beatty Pond System.

The flow rate into the Beatty pond, taken from a 24-hour average from an onsite flow meter, is estimated at 18,480 ft³/day (113 gpm). This flow rate is extremely variable ranging from around 20 gpm to 240 gpm. This variability is attributed to the large number of travelers along US 95 using Beatty as a rest stop or layover. As a result, the flow rate is much higher than would be expected for a town with a population of approximately 1630. The flow enters into the center of the aerated region through an eight-inch pipe where it is then mixed using five aerators consisting of three five horsepower (hp) aspirators, one 7.5 hp aspirator, and one 10 hp mechanical aerator. The aerators are positioned to force the wastewater to rotate in a circular motion. Once beyond the
aerated region, the wastewater moves into a quiescent region which constitutes the largest portion of the pond surface area and volume, finally exiting into a RIB through the far end of the facultative regime. The total pond system HRT was calculated to be 15 days which is less by a factor of 2 or 3 than the other pond systems. This short HRT could present special problems in meeting state mandated wastewater treatment criteria. A photograph of the Beatty pond is shown in Figure 6.

![Figure 6. Beatty Pond System.](image)

**Blue Diamond Pond System**

The Blue Diamond pond is located approximately 20 miles southwest of Las Vegas, Nevada just off of Blue Diamond Road at the south entrance of the Red Rock Recreation Area. Serving the small community of Blue Diamond, this pond system consists of a
partially aerated primary, a facultative secondary, and a facultative overflow or tertiary pond. A plan view of this system is provided as Figure 7.

![Figure 7. Plan View of Blue Diamond Pond System.](image)

The pond system is located in a canyon area protected on the south and north by hills. The prevailing wind direction is out of the west. It should be noted, however, that the secondary and overflow ponds were not in continuous operation during the full length of this study. At times, the secondary, the overflow, or both were not in commission.
Photographs of the primary and secondary ponds are provided in Figures 8 and 9, respectively.

![Figure 8. Blue Diamond Primary Pond.](image)

The flow rate into the primary pond is 4755 ft$^3$/day (25 gpm) based on a 12-hour average taken from an onsite flow meter over the study duration. This flow is exclusively from the Blue Diamond community with little or no contribution from outside sources. The primary pond contains two mechanical aerators on an alternating aeration schedule. The primary and secondary pond depths average just under 4 and 3 feet, respectively. The pond system HRT, neglecting the overflow pond, is calculated to be just over 30 days yielding a similar length of treatment as the Alamo pond. When all three ponds (primary, secondary, and overflow) are in operation, however, the HRT is significantly...
greater. The depth of the overflow pond, when in use, was seen to vary from approximately 2 to 5 feet. It should be noted, however, that a HRT for this pond was not calculated due to a lack of available data on the pond dimensions.

Figure 9. Blue Diamond Secondary Pond.

Searchlight Pond System

The Searchlight pond system is located approximately 60 miles south of Las Vegas, Nevada along US 93 in the township of Searchlight. This pond system consists of two parallel facultative primary and two parallel facultative secondary ponds. A plan view is shown in Figure 10. The ponds are located on a flat desert plain where summer temperatures can exceed 115 F, slightly hotter than the other ponds in this study. These
ponds also are exposed to higher wind conditions than the other three pond systems with prevailing winds out of the south that can exceed 40 mph.

![Plan View of Searchlight Pond System](image)

**Figure 10. Plan View of Searchlight Pond System.**

The flow rate into each primary pond averages 6550 ft$^3$/day (40 gpm) based on 1996 data provided by the Clark County Sanitation District (Sanitation District, 1996).

Searchlight, with a population of around 1000, is a regular rest stop for travelers, and as such, receives significant flow from sources other than residents. The depths of the primary and secondary ponds average 3 and 2.4 feet, respectively. The pond system
HRT is calculated to be approximately 52.5 days making it the system with the longest HRT of the pond systems in this study. In fact, the secondary pond HRT of just under 34 days is twice as long as the entire Beatty system HRT. This long residence time provides greater opportunity for more complete treatment than the other ponds.

Photographs of the primary and secondary ponds are shown in Figures 11 and 12, respectively.
Figure 12. Searchlight Secondary Pond.
CHAPTER 4

INFLUENT CHARACTERISTICS

Physical Properties

The physical properties of the wastewater flowing into a pond system will have a direct bearing on the physical wastewater properties maintained in the system. Table 3 summarizes the average recorded temperatures, pH, alkalinity, and dissolved oxygen (DO) concentration of the wastewater influent at each of the pond system locations. These data represent values averaged over one year. Note that the Alamo and Beatty influents have one fourth the \([H^+]\) of the Searchlight influent (0.6 pH units higher). Also of note is the higher alkalinity of the Alamo influent. This difference suggests that the water source used in Alamo is more alkaline than the other locations. Influent temperatures are similar for the ponds, with the exception of Searchlight which is significantly warmer. Average dissolved oxygen values are above 2.0 in all cases providing sufficient initial dissolved oxygen for aerobic processes. Based on these average values, it can be concluded that the Beatty and Blue Diamond ponds have similar wastewater inputs. The Alamo pond appears to have an influent that would be the easiest to treat as evidenced by the higher pH, alkalinity, and dissolved oxygen values.
while the Searchlight influent with its lowest average pH, alkalinity, and dissolved oxygen values would be the most problematic to treat effectively.

<table>
<thead>
<tr>
<th>Pond Location</th>
<th>pH</th>
<th>Alkalinity (mg/L)</th>
<th>Temperature (°C)</th>
<th>DO (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alamo</td>
<td>8.35</td>
<td>504</td>
<td>21.6</td>
<td>3.1</td>
</tr>
<tr>
<td>Beatty</td>
<td>8.34</td>
<td>329</td>
<td>22.2</td>
<td>2.7</td>
</tr>
<tr>
<td>Blue Diamond</td>
<td>8.13</td>
<td>347</td>
<td>22.7</td>
<td>2.6</td>
</tr>
<tr>
<td>Searchlight</td>
<td>7.74</td>
<td>294</td>
<td>25.9</td>
<td>2.3</td>
</tr>
</tbody>
</table>

Table 3 represents averaged values taken over the period of this study. In order to gain an understanding of how these properties varied over time, it is necessary to plot recorded values versus time. Figures 13 through 16 are plots showing influent properties as they varied over the period of this study for each respective pond system. Alkalinity is indicated on the left-hand axis, and temperature and pH are indicated on the right-hand axis.

Examination of Figure 13 shows that significant variations were recorded in alkalinity and temperature throughout the one-year study time period. Alkalinity varied from 420 to 560 mg/L, showing a range of 140 mg/L. Temperature ranged from 14 °C in the winter to 25 °C in the summer, an 11 degree variation. Hydrogen ion concentration varied from 8.1 to 8.7, a 0.6 pH unit difference. This difference represents a swing in $[H^+]$ of a factor of 4. DO concentrations ranged from 1.5 to 5.0 mg/L, averaging 3.1 mg/L.
Beatty alkalinity varied from 260 to 400 mg/L, representing a 140 mg/L change, with the highest values recorded during the summer months and the lowest recorded during the winter months (Figure 14). Values of pH ranged between 8.1 and 8.6. Influent
temperatures ranged between 18 °C during the winter months to 25 °C during the summer months. Note the general trend of increasing alkalinity with temperature. Dissolved oxygen concentrations ranged from 1.5 to 5.6 mg/L with most of the values around 2 mg/L.

Figure 15. Blue Diamond Influent Properties.

Figure 15 depicts Blue Diamond influent properties. With the exception of a 770 mg/L spike, alkalinity was seen to vary from 240 to 360 mg/L, a 120 mg/L range. Values of pH tracked the major alkalinity variation for the large change, the pH change corresponding to the alkalinity spike in August 1996. This mirroring effect does not appear to hold for small changes in alkalinity, however. Influent pH ranged from 7.6 to
9.2. a swing of 1.6 pH units. The influent temperature was seen to vary from 13.5 °C during the winter months to 29 °C in the summer, a change of 15.5 degrees.

Figure 16 shows Searchlight influent properties. Alkalinity was seen to vary from 255 to 340 mg/L, a range of 85 mg/L. This range was smaller than observed influents from the other three locations. The pH values mirrored alkalinity, ranging from 7.7 to 8.5. Temperatures were warmer than the other locations, varying from 18 °C in the winter to 32 °C in the summer, a 14 degree swing.

![Searchlight Influent Alkalinity vs pH and Temperature](image)

*Figure 16. Searchlight Influent Properties.*

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Influent Organic Concentrations

The average pond system influent organic loading in terms of BOD and COD is shown in Table 4. BOD values were obtained from the various pond operators, and COD values were obtained from sampling and analysis performed by the author. The reported BOD value for the Alamo system was based on limited data and may not be truly representative of an annual average. Comparison of the Alamo BOD value with the average Alamo COD value indicates the reported average BOD value may be low. Blue Diamond and Searchlight BOD values were based on quarterly sampling, and the Beatty system values were based on monthly sampling. COD values were based on monthly or bi-monthly sampling. Note that the organic concentrations were similar for each pond system with Blue Diamond recording the weakest wastewater.

<table>
<thead>
<tr>
<th>Pond</th>
<th>Average BOD (mg/L)</th>
<th>Average COD (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alamo Influent</td>
<td>204</td>
<td>390</td>
</tr>
<tr>
<td>Beatty Influent</td>
<td>249</td>
<td>338</td>
</tr>
<tr>
<td>Blue Diamond Influent</td>
<td>166</td>
<td>296</td>
</tr>
<tr>
<td>Searchlight Influent</td>
<td>252</td>
<td>363</td>
</tr>
</tbody>
</table>

Influent Chemical Characteristics

Table 5 presents average influent nitrogen and phosphorus concentrations measured for the pond locations addressed by this study. The ammonia-N values were obtained through ammonia probe measurements. The ammonia probe was not available for use
until January 1997. Prior measurements, using Hach Ammonia-N field kits, exceeded the maximum range of the test (25 mg/L). The average ammonia-N values shown in Table 5 were used as the influent concentration for determining pond ammonia-N removal efficiencies. Nitrate values provide information to determine whether nitrification is occurring in the ponds.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Alamo</td>
<td>14</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>25</td>
<td>0.04</td>
</tr>
<tr>
<td>Beatty</td>
<td>14</td>
<td>4</td>
<td>18</td>
<td>1</td>
<td>19</td>
<td>31</td>
<td>0.01</td>
</tr>
<tr>
<td>Blue Diamond</td>
<td>13</td>
<td>1</td>
<td>14</td>
<td>0.5</td>
<td>14.5</td>
<td>28.3</td>
<td>0.04</td>
</tr>
<tr>
<td>Searchlight</td>
<td>13</td>
<td>3</td>
<td>16</td>
<td>2.5</td>
<td>18.5</td>
<td>44</td>
<td>0.02</td>
</tr>
</tbody>
</table>

The highest influent ammonia-N concentrations were measured at Searchlight, recording consistently high values with a maximum of 70 mg/L. Similar influent ammonia-N concentrations were observed for Alamo, Beatty, and Blue diamond with the lowest values recorded at Alamo, consistently measured at 24-25 mg/L. Nitrates in the influent were practically nonexistent at all four pond locations. Nitrate values listed in Table 5 represent averages, with no detectable nitrates recorded for the majority of influent readings. These nitrate values were used as a baseline to determine if nitrification was occurring in any of the ponds.
Phosphorus measurements included both inorganic and organic phosphorus with total phosphorus representing the sum of both measurements. Inorganic phosphorus is comprised of ortho-phosphate and poly-phosphate. The primary phosphorus component in the wastewater flowing into all four pond systems was found to be ortho-phosphate, which represented 74 to 90 percent of the average influent phosphorus.
CHAPTER 5

POND COMPARISONS - SUMMARY DATA

This chapter provides summary-level data comparing the pond system performances in this study. Data are organized by pond properties, organic removal characteristics, and chemical characteristics with a primary focus on ammonia-N removal. The reader is referred to Chapters 6 through 9 for detailed data on each pond system.

Pond Properties

Wastewater properties in each pond will be a function of influent properties, meteorological conditions, and HRT. This section summarizes pH, alkalinity, temperature, and dissolved oxygen concentrations data. Relationships between these properties are examined and the potential impacts on treatment processes are discussed.

A comparison of average pond properties is shown in Table 6. The properties in this table are difficult to average since they vary seasonally and daily and can be influenced by the number of samples measured during a given season and/or time of day. Samples were typically taken at approximately same time of day to mitigate this impact. This concern notwithstanding, general conclusions regarding analyzed properties in each pond are indicated.
Of particular interest in this table are pH, alkalinity, and the pH/alkalinity relationship. The Alamo and Beatty ponds tend to reflect the influent pH and alkalinity values. The Blue Diamond ponds show a trend of increasing pH and decreasing alkalinity. The Searchlight ponds show increasing pH with increasing alkalinity. The Searchlight secondary pond exhibited by far the highest alkalinity. The difference between the primary and secondary pond alkalinity was 496 mg/L. This large a difference

<table>
<thead>
<tr>
<th>Pond</th>
<th>pH</th>
<th>Alkalinity (mg/L)</th>
<th>Temp (°C)</th>
<th>DO (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alamo Influent</td>
<td>8.35</td>
<td>504</td>
<td>21.6</td>
<td>3.1</td>
</tr>
<tr>
<td>Alamo Primary</td>
<td>8.32</td>
<td>497</td>
<td>17.2</td>
<td>7.3</td>
</tr>
<tr>
<td>Alamo Secondary</td>
<td>8.71</td>
<td>497</td>
<td>15.7</td>
<td>2.7</td>
</tr>
<tr>
<td>Beatty Influent</td>
<td>8.34</td>
<td>329</td>
<td>22.2</td>
<td>2.7</td>
</tr>
<tr>
<td>Beatty Aerated</td>
<td>8.23</td>
<td>332</td>
<td>15.1</td>
<td>6.2</td>
</tr>
<tr>
<td>Beatty Facultative</td>
<td>8.34</td>
<td>336</td>
<td>15.1</td>
<td>7</td>
</tr>
<tr>
<td>Blue Diamond Influent</td>
<td>8.13</td>
<td>347</td>
<td>22.7</td>
<td>2.6</td>
</tr>
<tr>
<td>Blue Diamond Primary</td>
<td>8.62</td>
<td>302</td>
<td>18.5</td>
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</tr>
<tr>
<td>Blue Diamond Secondary</td>
<td>9.19</td>
<td>299</td>
<td>16.6</td>
<td>10.2</td>
</tr>
<tr>
<td>Blue Diamond Overflow</td>
<td>9.14</td>
<td>274</td>
<td>11.3</td>
<td>7.7</td>
</tr>
<tr>
<td>Searchlight Influent</td>
<td>7.74</td>
<td>294</td>
<td>25.9</td>
<td>2.3</td>
</tr>
<tr>
<td>Searchlight Primary</td>
<td>8.85</td>
<td>316</td>
<td>19</td>
<td>11.1</td>
</tr>
<tr>
<td>Searchlight Secondary</td>
<td>9.64</td>
<td>812</td>
<td>19.1</td>
<td>11.2</td>
</tr>
</tbody>
</table>
is difficult to account for. The primary reason for this difference may be the exceptionally long HRT in this pond system. This longer time, coupled with favorable conditions for algal growth, will result in higher alkalinity values. Interactions with the carbonate system through soil-water exchanges, may also serve to raise the pH and alkalinity.

A graph of alkalinity versus pH for each of the ponds included in this study is provided as Figure 17. This graph serves to illustrate the variability of each pond. The
Alamo pond operates in the narrowest band while the Searchlight secondary pond shows the greatest variability.

Pond temperature data indicated that the Alamo and Beatty ponds experienced cooler wastewater temperatures than the Blue Diamond and Searchlight ponds during the study period. This result was consistent with meteorological conditions at the pond locations. The cooler temperatures, while raising the saturated DO concentration limit, produce an opposite effect on algae growth. In addition, cooler winter temperatures will slow microbial activity, reducing the loading the pond can effectively accommodate. Therefore, on average, lower surface DO concentrations will be observed in the Alamo and Beatty pond systems.

In conclusion, the properties manifested in each pond system were adequate to provide sufficient treatment. Observed values of alkalinity, pH, temperature, and DO concentration suggest adequate conditions for the ponds to perform as designed. However, the relatively short HRTs for the Alamo and Beatty pond systems may make achieving permit limits problematic. Another source of concern is the increasing alkalinity observed in the Searchlight secondary pond. The disparity between summer 1996 and 1997 recorded values (Figure 84) suggests a trend that the pond may be moving towards longer anoxic periods due to the extensive algal growth. It is suggested that steps be taken to lower the algal density in this pond.
Organic Removal Characteristics

Summary data on wastewater pond organic material concentrations are presented in Table 7. Calculated removal efficiencies are also shown. Instances where no data were available are indicated by a dash. The Beatty pond BOD data shown in Table 7 reflects total system performance (aerated and facultative regions). The Beatty system exhibited the highest removal performance, and the Blue Diamond and Searchlight systems exhibited the lowest removal performance.

<table>
<thead>
<tr>
<th>Pond</th>
<th>Average BOD (mg/L)</th>
<th>Average COD (mg/L)</th>
<th>Total Suspended Solids (mg/L)</th>
<th>BOD Removal Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alamo Primary</td>
<td>60</td>
<td>166</td>
<td>92</td>
<td>71</td>
</tr>
<tr>
<td>Alamo Secondary</td>
<td>-</td>
<td>234</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Beatty Aerated</td>
<td>-</td>
<td>280</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Beatty Facultative</td>
<td>50</td>
<td>297</td>
<td>137</td>
<td>75</td>
</tr>
<tr>
<td>Blue Diamond Primary</td>
<td>64</td>
<td>243</td>
<td>136</td>
<td>56</td>
</tr>
<tr>
<td>Blue Diamond Secondary</td>
<td>71</td>
<td>238</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Blue Diamond Overflow</td>
<td>72</td>
<td>331</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>Searchlight Primary</td>
<td>100</td>
<td>492</td>
<td>250</td>
<td>60</td>
</tr>
<tr>
<td>Searchlight Secondary</td>
<td>119</td>
<td>943</td>
<td>415</td>
<td>0</td>
</tr>
</tbody>
</table>

The most significant conclusion that can be derived from this information is that BOD treatment appears to be occurring in the primary ponds. BOD and COD concentrations, on average, tend to increase in the secondary ponds. This result is particularly evident in the Searchlight ponds. A potential explanation for this finding is that the higher BOD and COD concentrations can be attributed to increased algal growth.
Total Suspended Solids (TSS) data supports this hypothesis. TSS measurements at the Searchlight secondary pond have shown an increasing trend consistent with the increasing alkalinity trend observed earlier. More data collected at a greater frequency would be required before a definitive conclusion on this issue could be reached.

Chemical Characteristics

The chemical data obtained from the ponds in this study are related to nitrogen and phosphorus with a primary emphasis on ammonia-N removal. These data are summarized below.

*Phosphorus*

Average phosphorus concentrations are reported in Table 8. Compare this table with influent phosphorus concentrations (Table 5). With the exception of the Blue Diamond primary pond, total phosphorus concentrations increased slightly above influent concentrations. The primary contribution to this increase was organic phosphate. Inorganic phosphorus concentrations decreased from influent concentrations with the exception of the Beatty pond. This decrease was due to the reduction of ortho-phosphate. Also note the corresponding increase in poly-phosphates. Therefore, ortho-phosphates were consumed and poly- and organic phosphates were produced in these ponds. This process was particularly evident in the Searchlight pond system where the 13 mg/L ortho-phosphate concentration in the influent was reduced to 1 mg/L by the time the wastewater reached the secondary pond. Correspondingly, poly- and organic phosphates increased from 3 and 2.5 mg/L in the influent, respectively, to 13.5 and 7
mg/L, respectively, by the time the wastewater reached the secondary pond. Since algal
density was greatest in this pond system (based on qualitative observations), it is
reasonable to conclude that this change was due primarily to algal. However, collection of
additional data on this topic is suggested before a more definitive conclusion is reached.

<table>
<thead>
<tr>
<th>Source</th>
<th>Ortho Phosphate</th>
<th>Poly Phosphate</th>
<th>Total Inorganic Phosphate</th>
<th>Organic Phosphate</th>
<th>Total Phosphate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alamo Primary</td>
<td>12.5</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Alamo Secondary</td>
<td>3</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Beatty Aerated</td>
<td>14.24</td>
<td>2.76</td>
<td>17</td>
<td>4</td>
<td>21</td>
</tr>
<tr>
<td>Beatty Facultative</td>
<td>13.5</td>
<td>4.5</td>
<td>18</td>
<td>3</td>
<td>21</td>
</tr>
<tr>
<td>Blue Diamond Primary</td>
<td>3.7</td>
<td>3.8</td>
<td>7.5</td>
<td>5.5</td>
<td>13</td>
</tr>
<tr>
<td>Blue Diamond Secondary</td>
<td>12</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Blue Diamond Secondary Overflow</td>
<td>4</td>
<td>1</td>
<td>5</td>
<td>11</td>
<td>16</td>
</tr>
<tr>
<td>Searchlight Primary</td>
<td>9</td>
<td>2.5</td>
<td>11.5</td>
<td>5.5</td>
<td>17</td>
</tr>
<tr>
<td>Searchlight Secondary</td>
<td>1</td>
<td>13.5</td>
<td>14.5</td>
<td>7</td>
<td>21.5</td>
</tr>
</tbody>
</table>

Nitrogen

The primary ammonia-N removal mechanism experienced by the ponds evaluated in
this study is volatilization. This section focuses on ammonia-N removal via
volatilization. Nitrate concentrations are also reported to determine if a nitrification contribution to ammonia-N removal is present. Data are presented over the study time period, and removal efficiencies are calculated based on recorded values. An average removal efficiency is computed for each pond. This average efficiency is used as the basis for calculating overall ammonia-N mass transfer coefficients using well-mixed and plug flow models. Pond dispersion numbers are also calculated for use in the Wehner-Wilhelm equation. Calculated dispersion numbers and average pond efficiencies are used in conjunction with the Wehner-Wilhelm equation to determine the overall mass transfer coefficient assuming a plug flow with dispersion model. Published empirical models of ammonia-N removal are applied for each pond and compared with actual data. The validity of applying such models to each of the ponds under consideration is discussed.

Average ammonia-N and nitrate-N concentrations are summarized in Table 9. The values indicated in Table 9 are averages; measured concentrations varied significantly from these average values as a function of wastewater temperature and pH. Recorded nitrate concentrations, for the most part, were negligible. However, elevated nitrate concentrations were recorded for the Searchlight secondary pond during the winter. This result is an indication that some nitrification may be occurring in this pond.

Ammonia-N removal performance summaries for the pond systems within the scope of this study are shown in Figure 18. The Searchlight pond system exhibited the highest consistent performance during warm weather months while the Blue Diamond system performed best during the winter months. The Beatty pond system experienced the
lowest performance overall. The Alamo pond system, while performing well overall, displayed the most inconsistent performance.

Table 9. Average Ammonia-N and Nitrate Concentrations

<table>
<thead>
<tr>
<th>Pond</th>
<th>Ammonia-N (mg/L)</th>
<th>Nitrates (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alamo Primary</td>
<td>10.6</td>
<td>0.7</td>
</tr>
<tr>
<td>Alamo Secondary</td>
<td>5.8</td>
<td>0.6</td>
</tr>
<tr>
<td>Beatty Aerated</td>
<td>19.0</td>
<td>0.1</td>
</tr>
<tr>
<td>Beatty Facultative</td>
<td>18.6</td>
<td>0.1</td>
</tr>
<tr>
<td>Blue Diamond Primary</td>
<td>10.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Blue Diamond Secondary</td>
<td>4.2</td>
<td>0.0</td>
</tr>
<tr>
<td>Blue Diamond Overflow</td>
<td>1.4</td>
<td>-</td>
</tr>
<tr>
<td>Searchlight Primary</td>
<td>7.2</td>
<td>0.1</td>
</tr>
<tr>
<td>Searchlight Secondary</td>
<td>2.9</td>
<td>2.6</td>
</tr>
</tbody>
</table>

Average ammonia-N removal efficiencies by pond and pond system are summarized in Figure 19. These data are broken down further by temperature regime in Table 10. In general, the best ammonia-N performance occurs at elevated wastewater temperatures and pH. Warmer temperatures increase the rate of ammonia volatilization by lowering the ammonium dissociation constant (equation 37), and by reducing ammonia solubility. A possible exception appears to be the Beatty facultative region where removal efficiencies

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decreased with increasing wastewater temperatures. From these data, it can be concluded that the Alamo, Blue Diamond, and Searchlight pond systems provide acceptable ammonia-N removal performance. The Beatty pond system, as currently configured, does not achieve acceptable levels of ammonia-N removal if such removal were a major concern. The HRT is very short in the Beatty system, calling into question whether reliable ammonia-N removal can be achieved in this pond.

Figure 18. Comparison of Pond System Ammonia-N Removal Efficiencies

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Comparison of Average Pond Ammonia Removal Performance

Figure 19. Average Ammonia-N Removal Efficiencies.

**Ammonia-N Removal Models**

Ammonia-N removal efficiencies were shown to be a function of HRT. The relationships between removal efficiency and HRT for various temperature ranges is depicted in Figure 20. Line fits based on linear regression are also shown for each of the temperature ranges. The equations of each line fit and their associated correlation coefficients are as follows:

\[(41) \text{Average Removal Efficiency (1-10 °C)} = 0.75 \times \text{HRT} + 15.7 \quad (r^2 = 0.39)\]
\[(42) \text{Average Removal Efficiency (10-20 °C)} = 1.41 \times \text{HRT} + 30.6 \quad (r^2 = 0.77)\]

\[(43) \text{Average Removal Efficiency (20-30 °C)} = 1.29 \times \text{HRT} + 45.5 \quad (r^2 = 0.62)\]

\[(44) \text{Average Removal Efficiency (Overall)} = 1.34 \times \text{HRT} - 32.5 \quad (r^2 = 0.73)\]

<table>
<thead>
<tr>
<th>Pond</th>
<th>Average Percent Removal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T = 1 - 10</td>
</tr>
<tr>
<td>Alamo Primary</td>
<td>0</td>
</tr>
<tr>
<td>Alamo Secondary</td>
<td>0</td>
</tr>
<tr>
<td>Alamo System</td>
<td>0</td>
</tr>
<tr>
<td>Beatty Aerated</td>
<td>19</td>
</tr>
<tr>
<td>Beatty Facultative</td>
<td>24</td>
</tr>
<tr>
<td>Beatty System</td>
<td>39</td>
</tr>
<tr>
<td>Blue Diamond Primary</td>
<td>26</td>
</tr>
<tr>
<td>Blue Diamond Primary</td>
<td></td>
</tr>
<tr>
<td>Blue Diamond Secondary</td>
<td>45</td>
</tr>
<tr>
<td>Blue Diamond Overflow</td>
<td>78</td>
</tr>
<tr>
<td>Blue Diamond System</td>
<td>92</td>
</tr>
<tr>
<td>Searchlight Primary</td>
<td>54</td>
</tr>
<tr>
<td>Searchlight Secondary</td>
<td>43</td>
</tr>
<tr>
<td>Searchlight System</td>
<td>73</td>
</tr>
</tbody>
</table>

The correlation coefficients for equations 41 through 44 (shown in parentheses) indicate a significant scatter in the data, particularly for the 1 to 10 °C temperature range. This result suggests that these equations should only be used as a rough estimate.
Predictive models which factor in the effects of temperature and pH, in addition to HRT, have been postulated to provide the best agreement with actual measurements. Equations 33 and 34 (page 30) are examples of such models. Detailed results from applying these models are presented in the ammonia-N removal discussions applicable to each pond. These results were derived from two predictions. Prediction 1 applies equation 33 for temperature ranges 1 to 20 °C and equation 34 for temperature ranges greater than 20 °C. Prediction 2 applies equation 33 for all temperature ranges. Table 11 lists the average accuracy recorded as average relative percent difference (RPD) for the
three temperature ranges and overall. RPD was calculated from the following equation (DOE/CAO, 1991):

\[ RPD = \frac{\text{measured} - \text{predicted}}{\left(\frac{\text{measured} + \text{predicted}}{2}\right)} \times 100 \]

An RPD value of 200 indicates 0 removal performance was recorded for that pond in the given temperature range. Prediction 2 (equation 33 only) provided consistently more accurate results than Prediction 1 (equations 33 and 34). However, if a minimum average accuracy indicated by an RPD of less than or equal to 20 were selected as the acceptable criterion, the predictive models provide adequate results only for the Searchlight pond over all temperatures. Model results with RPD values less than or equal to 20 are shaded in Table 11. Note that the temperature range from 20 to 30 °C showed results closest to measured values, and results below 20 average RPD were recorded only for the Blue Diamond and Searchlight ponds in this temperature range. Model predictions diverged significantly from measured values for the Alamo and Beatty pond systems. Therefore, application of predictions 1 and 2 are not recommended for these ponds.

The predictive models applied in this study were developed for facultative ponds with depths between 4 and 5 feet (Middlebrooks and Pano, 1982). None of the ponds in this study meet these criteria. The Blue Diamond pond system comes closest, but the results achieved are not consistently within the desired accuracy (RPD arbitrarily set at 20 percent or less). Therefore, some other model may be more applicable to these ponds.

Three predictive modeling approaches, in addition to the published models, were developed. These models are designated Prediction 3 through Prediction 5. Prediction 3 used the HRT-removal efficiency models for the various temperature ranges (equations 41
Table 11. Predictive Model Accuracy Summary
(shaded boxes indicate model agreement with predictions within 20%)

<table>
<thead>
<tr>
<th>Pond</th>
<th>T=0-10 C</th>
<th>T=10-20 C</th>
<th>T=20-30 C</th>
<th>Overall</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pred. 1</td>
<td>Pred. 2</td>
<td>Pred. 1</td>
<td>Pred. 2</td>
</tr>
<tr>
<td>Alamo Primary</td>
<td>200</td>
<td>200</td>
<td>37</td>
<td>37</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>75</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>76</td>
<td>69</td>
</tr>
<tr>
<td>Alamo Secondary</td>
<td>200</td>
<td>200</td>
<td>37</td>
<td>37</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>43</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>63</td>
<td>58</td>
</tr>
<tr>
<td>Alamo Pond System</td>
<td>200</td>
<td>200</td>
<td>37</td>
<td>37</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>61</td>
<td>48</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>70</td>
<td>64</td>
</tr>
<tr>
<td>Beatty Aerated</td>
<td>151</td>
<td>151</td>
<td>96</td>
<td>96</td>
</tr>
<tr>
<td></td>
<td>85</td>
<td>85</td>
<td>123</td>
<td>123</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>162</td>
<td>162</td>
</tr>
<tr>
<td>Beatty Facultative</td>
<td>118</td>
<td>118</td>
<td>118</td>
<td>118</td>
</tr>
<tr>
<td></td>
<td>118</td>
<td>118</td>
<td>181</td>
<td>158</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>141</td>
<td>132</td>
</tr>
<tr>
<td>Beatty Pond System</td>
<td>40</td>
<td>40</td>
<td>48</td>
<td>48</td>
</tr>
<tr>
<td></td>
<td>46</td>
<td>46</td>
<td>7</td>
<td>46</td>
</tr>
<tr>
<td></td>
<td>28</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blue Diamond Primary</td>
<td>45</td>
<td>45</td>
<td>27</td>
<td>27</td>
</tr>
<tr>
<td></td>
<td>34</td>
<td>14</td>
<td>35</td>
<td>25</td>
</tr>
<tr>
<td>Blue Diamond Secondary</td>
<td>43</td>
<td>43</td>
<td>41</td>
<td>41</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>11</td>
<td>46</td>
<td>28</td>
</tr>
<tr>
<td>Blue Diamond Pond System</td>
<td>34</td>
<td>34</td>
<td>42</td>
<td>42</td>
</tr>
<tr>
<td></td>
<td>51</td>
<td>16</td>
<td>46</td>
<td>25</td>
</tr>
<tr>
<td>Searchlight Primary</td>
<td>32</td>
<td>32</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>9</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Searchlight Secondary</td>
<td>33</td>
<td>33</td>
<td>36</td>
<td>36</td>
</tr>
<tr>
<td></td>
<td>33</td>
<td>13</td>
<td>34</td>
<td>23</td>
</tr>
</tbody>
</table>

through 43). Estimates using equations 41 through 43 were calculated along with correlation coefficients and RPD values for each. These results are compared with Predictions 1 and 2 in Table 12. Calculated correlation coefficients greater or equal to 0.85 and RPD values less than or equal to 20 are shaded.
Prediction 3 compared favorably with predictions 1 and 2, particularly with the Blue Diamond primary pond. Prediction 3, like predictions 1 and 2, should not be used to model ammonia-N removal performance of the Alamo or Beatty ponds, though Prediction 2 provides a reasonable rough estimate of ammonia-N removal in the Alamo secondary pond. Additional data on these two pond systems should be gathered before an adequate model is developed. Predictions 2 and 3 provide an adequate estimate of ammonia-N removal performance in both the Blue Diamond and Searchlight ponds. Prediction 3 requires less data and provides similar results.

<table>
<thead>
<tr>
<th>Pond</th>
<th>Prediction 1</th>
<th>Prediction 2</th>
<th>Prediction 3</th>
<th>Prediction 4</th>
<th>Prediction 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alamo Primary</td>
<td>0.45 76</td>
<td>0.38 69</td>
<td>0.49 64</td>
<td>0.44 60</td>
<td>0.50 60</td>
</tr>
<tr>
<td>Alamo Secondary</td>
<td>0.69 63</td>
<td>0.79 58</td>
<td>0.65 68</td>
<td>0.81 58</td>
<td>0.80 59</td>
</tr>
<tr>
<td>Beatty Aerated</td>
<td>0.25 120</td>
<td>0.68 103</td>
<td>0.55 36</td>
<td>0.59 66</td>
<td>0.62 51</td>
</tr>
<tr>
<td>Beatty Facultative</td>
<td>0.36 162</td>
<td>-0.12 162</td>
<td>-0.68 150</td>
<td>-0.39 170</td>
<td>-0.43 164</td>
</tr>
<tr>
<td>Blue Diamond Primary</td>
<td>0.83 46</td>
<td>0.85 28</td>
<td>0.93 17</td>
<td>0.92 11.5</td>
<td>0.93 11</td>
</tr>
<tr>
<td>Blue Diamond Secondary</td>
<td>0.36 35</td>
<td>0.68 25</td>
<td>0.84 34</td>
<td>0.68 41</td>
<td>0.75 21</td>
</tr>
<tr>
<td>Searchlight Primary</td>
<td>0.59 46</td>
<td>0.79 25</td>
<td>0.85 34</td>
<td>0.79 15</td>
<td>0.84 11</td>
</tr>
<tr>
<td>Searchlight Secondary</td>
<td>0.81 20</td>
<td>0.81 20</td>
<td>0.75 23</td>
<td>0.62 25</td>
<td>0.82 23</td>
</tr>
</tbody>
</table>
Prediction 3 models ammonia removal as a function of HRT and temperature. Predictions 1 and 2 determine ammonia removal as a function of HRT, temperature, and pH. A simplified multiple regression model based on this approach using data obtained from the Blue Diamond and Searchlight ponds is as follows:

\[
(46) \text{Removal Efficiency} \% = 44.27pH - 2.12T \cdot pH - 20.70T - 0.33HRT - 345.55
\]

This model had a calculated correlation coefficient of 0.80 and the results of applying it to the various ponds are shown as Prediction 4 in Table 12. Prediction 4 is comparable to prediction 3. The scatter of Prediction 4 data is illustrated in Figure 21. Prediction 4 estimates lower removal efficiencies, on average, on the high-end of the spectrum. This result may be due to not fully accounting for the effect that high pH values have on overall removal efficiency. Prediction 4 is recommended for use with both the Blue Diamond and Searchlight ponds as well as the Alamo secondary pond. Though it did not meet the established accuracy criteria, this model provided the closest results to measured values for the Alamo secondary pond.

Predictions 3 and 4 are based on simple linear regression. A third approach is to couple linear regression of measured data with theoretical considerations. Predictions 1 and 2 were developed in this manner. Prediction 2 (equation 33) is a hybrid model with well-mixed pond (equation 26) and plug flow (equation 28) characteristics. The Prediction 2 model is repeated here for convenience:

\[
(33) \frac{C_f}{C_o} = \left[1 + \frac{A}{Q(0.0038 + 0.000134T)} \cdot \exp((1.041 + 0.044T)(pH - 6.6)) \right]^{-1}
\]
Equations 26 and 28 can be rearranged in a manner similar to equation 33 as follows:

\[ C_{\text{out}/C_{\text{in}} \text{ (well mixed)}} = (1 - k_L a \times \text{HRT})^{-1} \]  

\[ C_{\text{out}/C_{\text{in}} \text{ (plug flow)}} = \exp(-k_L a \times \text{HRT}) \]

where: \( k_L a = k_{\text{overall}} \) and \( a = \text{A(pond area)}/\text{V(pond volume)} \)

Since \( Q \) (flow rate) = \( V/\text{HRT} \), \( a \times \text{HRT} = V/\text{V x HRT} = A/V \times V/Q = A/Q \). Therefore, \( A/Q \) can be substituted into equations 47 and 48 to yield:

\[ C_{\text{out}/C_{\text{in}} \text{ (well mixed)}} = (1 - A/Q \times k_L)^{-1} \]  

\[ C_{\text{out}/C_{\text{in}} \text{ (plug flow)}} = \exp(A/Q \times k_L) \]

Equation 49 has a similar form as equation 33 with the term that is multiplied by \( A/Q \) in equation 33 acting as a surrogate for \( k_L \). Isolating the \( k_L \) surrogate term from equation 33 results in the following relationship:
Designating the left-hand term of equation 51 as \( y \) and the right hand terms as variables \( x_1 \) through \( x_4 \). A multiple regression using data obtained from the Blue Diamond and Searchlight ponds results in the following relationship with a correlation coefficient of 0.75:

\[
\ln \left[ \frac{Q}{A} \left( \frac{C_{in}}{C_{out}} - 1 \right) \right] = k_L = f(\ln T, pH, TpH, T)
\]

Application of equation 52 is shown in Table 12 as Prediction 5. Results are similar as to those achieved for Predictions 3 and 4, though RPD is shown to be slightly improved.

This model is suggested for both the Blue Diamond and Searchlight ponds, and it can be used to provide a rough estimate of ammonia-N removal from the Alamo ponds. In addition, since the derivation of this model has a theoretical basis, equation 52 is recommended for other pond systems similar to the Blue Diamond and Searchlight systems.

**Determination of Ammonia-N Removal Mass Transfer Coefficients**

The primary mechanism for ammonia-N removal from the wastewater ponds in this study is volatilization. The rate of volatilization will be affected by the flow conditions in the pond. Three general types of flow conditions can exist in these ponds: well-mixed, plug-flow, or plug-flow with dispersion. These three conditions are described by equations 25, 29, and 30, respectively (pp 27-28). A key constant is each of these equations is the overall mass transfer coefficient, which determines the rate that ammonia...
gas volatilizes from the pond surface. Average overall removal coefficients and dispersion numbers were calculated for each pond using equations 25 and 29 through 31, respectively. These values are summarized in Table 13. A more detailed analysis of these parameters is provided in the individual chapters on each pond system.

| Table 13. Average Overall Ammonia-N Removal Coefficients and Dispersion Numbers |
|----------------------------------|---------|---------|---------|-----|
| Pond                | k_M (d^-1) | k_P (d^-1) | k_D (d^-1) | D   |
| Alamo Primary       | 0.076    | 0.048    | 0.067    | 1.43 |
| Alamo Secondary     | 0.084    | 0.049    | 0.075    | 1.79 |
| Beatty Aerated      | 0.100    | -        | -        | -    |
| Beatty Facultative  | 0.008    | 0.008    | 0.008    | 0.81 |
| Blue Diamond Primary| 0.110    | 0.062    | 0.081    | 0.45 |
| Blue Diamond Secondary| 0.175  | 0.090    | 0.123    | 0.50 |
| Searchlight Primary | 0.282    | 0.099    | 0.219    | 2.30 |
| Searchlight Secondary| 0.072  | 0.036    | 0.063    | 2.29 |

Table 13 values were calculated by determining pond average ammonia-N removal efficiencies and applying the pertinent equation (equation 25 for k_M, equation 29 for k_P, and equation 30 for k_D) assuming flow conditions were well-mixed, plug flow, or somewhere between well-mixed and plug flow, respectively. For the facultative ponds (Alamo secondary, Beatty facultative, Blue Diamond secondary, Searchlight primary, and Searchlight secondary), the actual k value is assumed to be closest to k_D, for the partially
aerated ponds (Alamo primary and Blue Diamond primary) the actual value is assumed to be between \( k_D \) and \( k_M \), and for the well mixed pond (Beatty aerated) the actual value is assumed to be close to \( k_M \).

Examination of Table 13 shows that flow conditions vary significantly among the various ponds. Dispersion numbers range from 0.45 to 2.3, with the Searchlight ponds exhibiting the greatest dispersion. Overall \( k \) values are similar for the Alamo primary, Alamo secondary, Blue Diamond primary, Blue Diamond secondary, and Searchlight secondary. This topic is treated in much greater depth in the chapters discussing the individual pond systems.
CHAPTER 6

ALAMO POND SYSTEM DATA

Alamo Primary Pond

Pond Properties

Measured properties of the Alamo primary pond are shown in Figure 22. Alkalinity ranged between 420 and 540 mg/L. This concentration and variation was consistent with the corresponding influent values. Values of surface water pH mirrored alkalinity for the first four months and exhibited an opposite relationship during subsequent months with
alkalinity increasing with decreasing pH. Swings in pH were between 8.2 and 8.6, indicating a $[H^+]$ variation by a factor of 3. Pond surface temperatures ranged from just under 7 °C in the winter to 26 °C in the summer. Dissolved oxygen concentrations at the pond surface ranged from 5.0 to 9.5 mg/L. This concentration provided sufficient DO for aerobic treatment processes. Values above the saturated concentration (see Table 2) were due to contributions from algae. This contribution was minimal in this pond. However, most samples were taken during the early morning, a time of day when photosynthetic processes have not had much time to affect DO concentration due to short sunlight exposure.

The relationship between alkalinity and pH can be determined through examination of Figure 23. In this figure, pH is shown at a greater resolution (right-hand axis) to provide the basis for analyzing alkalinity/pH relationships. This relationship is reported in the literature to follow the empirical equation 6. Application of this equation yields the predicted alkalinity values shown in Figure 23. These predicted values, ranging from 212 to 321 mg/L, are significantly less than the actual recorded values. Equation 6 does not consider total carbonic acid species or algae photosynthetic or respiratory processes which also impact alkalinity. Therefore, use of this equation is not recommended.

As mentioned previously, DO concentrations in ponds may vary by time of day due to algae photosynthetic action, pond location due to degree of mixing and microbial action, and depth due to stratification effects. DO measurements of the Alamo primary pond were taken from the same pond location during the morning hours at approximately 9:00 am. At this time, a small DO concentration contribution from algae is expected, resulting
in reaeration as the primary DO source. By holding sampling location and time reasonably constant, a DO profile with depth can be taken.

![Graph showing Alamo Primary Alkalinity vs pH.](image)

*Figure 23. Alamo Primary Alkalinity and pH.*

Figure 24 shows a rough DO concentration profile of the Alamo primary pond averaged from measurements taken during each of the four seasons. Significant stratification occurred in summer and spring, with the surface DO concentration much greater than the concentration at a 6-inch depth. This stratification was primarily due to increased algal activity during this time period. The increased algal concentration limited sunlight penetration, thus effectively cutting off oxygenation due to algal photosynthesis below the 6-inch depth. Note that even though the samples were taken in the morning when DO concentration increase due to algae was expected to be less, surface DO concentration increase was significant in the spring and summer months. The greater DO
concentration with depth during the winter months was due to the lower pond temperature resulting in a higher saturated DO value. During all seasons, the DO concentration throughout the pond depth was approximately 2 mg/L or higher, providing sufficient DO concentration for aerobic microbial processes.

![Alamo Primary DO Profile](image)

**Figure 24. Alamo Primary Pond Seasonal DO Concentration Profile.**

**Organic Removal Characteristics**

COD values measured from the Alamo primary pond are shown in Figure 25. Influent values are also shown. The average COD concentration in this pond was 166 mg/L, and the average COD removal was 52 percent. The BOD concentration, taken from one data point, was 60 mg/L, corresponding to a BOD removal performance of 71
percent. The TSS concentration was 92 mg/L, the lowest value obtained from the ponds in this study. The BOD and TSS data was taken from one data point provided by the pond operator. Additional BOD and TSS data should be obtained before conclusions regarding the organic removal capabilities of this pond are formalized.

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**Average Alamo Primary Pond COD Values**

![Graph showing COD values from 8/25/96 to 8/20/97](image)

**Figure 25. Alamo Primary Pond COD Concentrations.**

**Chemical Characteristics**

Data on phosphorus and nitrogen in the form of ammonia-N and nitrates is presented below. Inferences derived from studies on Ammonia-N removal from pond systems...
indicate a total system HRT of 40 to 75 days should be sufficient to provide adequate removal of ammonia, given the temperature and pH conditions in the ponds addressed by this study (Middlebrooks and Pano, 1983; Pano and Middlebrooks, 1982). The total HRT for the Alamo pond system was approximately 37.7 days. This HRT may not be adequate for achieving desired removal efficiencies of 80 percent or more. The data presented below explore this hypothesis.

*Phosphorus*

Data on ortho-phosphate concentrations were collected for this pond. An average concentration of 12.5 mg/L was recorded, indicating that 1.5 mg/L was consumed by pond processes (when compared to influent concentrations). Data on poly- and organic phosphorus concentrations was not collected for this pond.

*Nitrogen*

*Ammonia-N*

*Measurement Data*

Temporal ammonia-N concentrations recorded at the Alamo primary pond are shown in Figure 26. Values for pH are found on the right-hand axis. Recorded values followed the general pattern of low concentrations (and therefore, high removal performance) at high pH and wastewater temperatures, and conversely, high ammonia-N concentrations at lower pH values and wastewater temperatures. Two data points recorded in the late summers of 1996 and 1997 appear to refute this general trend, however. This
discrepancy may be due to higher than average influent ammonia-N concentrations during this timeframe.

**Figure 26. Measured Alamo Primary Ammonia-N Concentrations.**

**Alamo Primary Pond Removal Performance**

Primary pond removal performance is examined in Figure 27. Actual performance is compared with predicted performance using equations 33 and 34. Equation 33 is specified for wastewater temperature ranges of between 1 and 20 °C, while equation 34 is indicated as being applicable to wastewater temperature ranges between 20 and 25 °C. Equation 33 predicts higher removal efficiencies than equation 34, however, and it was recognized that the ponds examined in this study exhibited very high removal efficiencies.
at high wastewater temperatures. Therefore, Prediction 1 uses equations 33 and 34, as indicated in the literature, for lower and higher wastewater temperature ranges, respectively. Prediction 2 uses only equation 33 since this equation predicts higher ammonia-N removal performance at elevated wastewater temperatures.

![Figure 27](image)

*Figure 27. Comparison of Actual VS Predicted Ammonia-N Removal Performance of the Alamo Primary Pond (Predictions 1 and 2).*

Figure 27 shows that a maximum removal efficiency of 68 percent was predicted, while actual removal ranged up to 100 percent. Reasonable agreement with predicted removal was shown for lower wastewater temperatures, and poor agreement with these predictions was evident for higher wastewater temperatures. Predictions 1 and 2 did not provide consistently close agreement with measured values, however, and are not recommended for use with this pond.
Figure 28 shows predicted versus actual ammonia-N removal results using the three models developed by the author. Prediction 3 makes use of equations 41 through 43 in a given temperature range. Prediction 4 applies equation 46, and Prediction 5 illustrates use of equation 52. All three predictions provide similar results, though Prediction 5 provided the closest results to measured values. Predictions 5 was within 10 percent of measured values for 4 of 8 data points and is the only model that is recommended for providing a rough estimate of ammonia-N removal in this pond.

![Alamo Primary Pond Performance](image)

**Figure 28. Comparison of Actual VS Predicted Ammonia-N Removal Performance of the Alamo Primary Pond (Predictions 3 through 5).**

**Calculation of Alamo Primary Ammonia-N Removal Mass Transfer Coefficients**

Ammonia-N mass transfer coefficients were calculated using equation 25 for the well-mixed pond assumption, $k_M$, and equation 29 for the plug flow assumption, $k_P$, based
on the removal performance achieved on each sampling date. The literature states that conditions in wastewater ponds are typically somewhere between well-mixed (complete dispersion) and plug flow (no dispersion). To determine where in this range the Alamo primary pond lies, a dispersion number, $D$, was calculated using equation 31. The $D$ value and pond removal efficiency were inserted into equation 30 to calculate an overall mass transfer coefficient with dispersion, $k_D$. Estimated $k_D$ values were inserted into equation 30 until the removal efficiency recorded on the given sampling date was achieved. The results of these calculations are depicted in Figure 29.

In Figure 29, calculated overall mass transfer coefficients are shown on the left-hand axis and calculated dispersion numbers are shown on the right-hand axis. The left-hand axis scale has been magnified to provide better resolution showing distribution of $k$ values on a given date. This magnification resulted in some data points falling off-scale. The maximum calculated $k$ value was $1.4 \text{ d}^{-1}$ recorded for $k_M$ from data collected on May 16, 1997. Mass transfer coefficients were not calculated for days where removal efficiency was 100 percent since the equations did not yield a useful result at this value. Significant variation in calculated $k$ values was noted for two data points. These two data points, recorded on May 16 and September 19, 1997, respectively, correspond to days when greater than 90 percent removal efficiency was recorded. Since removal efficiencies were calculated using an average influent value, it is conceivable that the influent concentration may have been significantly less than the average value during the time periods when these samples were taken. The range of the calculated $k$ values on a given date provide a general indication as to the closeness of the influent ammonia-N concentration on the
sampling date with the average value that was used. Calculated dispersion numbers, as determined through equation 31, are a function of pond dimensions and kinematic viscosity and are thus seen to vary with temperature since viscosity is a function of temperature.

![Alamo Primary Ammonia-N Removal Coefficients](image)

**Figure 29. Calculated Alamo Primary Pond Overall Mass Transfer Coefficients and Dispersion Numbers for Various Assumed Flow Conditions**

An average mass transfer coefficient and dispersion number was calculated for the Alamo primary pond based on the average removal efficiency of 57 percent. These values were calculated as follows:

Alamo primary well-mixed pond overall mass transfer coefficient, \( k_M = 0.076 \, \text{d}^{-1} \)
Alamo primary plug flow pond overall mass transfer coefficient, $k_p = 0.048 \, \text{d}^{-1}$

Alamo primary dispersion number, $D$ (dimensionless) = 1.43

Alamo primary mass transfer coefficient, $k_D$ (57.4 percent removal) = 0.067 $\, \text{d}^{-1}$.

A comparison of the $k_D$ value of 0.0672 $\, \text{d}^{-1}$ with the respective $k$ values for the well-mixed and plug flow assumptions, $k_M$ and $k_p$, indicate that the Alamo primary pond experiences flow conditions approaching a well-mixed pond. This result is reasonable given that mechanical surface aeration is employed at this pond. The affect of surface aeration (not accounted for above in considering dispersion) will drive the overall mass transfer coefficient closer towards the well-mixed model. Therefore, an average $k$ value of 0.071 $\, \text{d}^{-1}$ is suggested as the overall mass transfer coefficient for this pond.

**Nitrate Data**

Nitrate data show an average concentration of 0.71 mg/L with a maximum of 2.6 mg/L and a minimum of 0.05 mg/L. Most values were recorded in the lower range, however, the 2.6 mg/L nitrate concentration recorded on 4/18/97 indicates some nitrification may have occurred in this pond during that timeframe. Stoichiometric reaction relationships indicate approximately 1 mg/L nitrates corresponds to consumption of 1 mg/L ammonia-N. Therefore, ammonia-N removal performance through volatilization was 12.4 mg/L on that date, rather than 15 mg/L as suggested by the data with no nitrification component.
Alamo Secondary Pond

Pond Properties

Measured Alamo secondary pond properties are shown in Figure 30. This pond ranged in depth from 6 inches at the start of this study to just over 1 foot at the end of this study. Samples were collected from just underneath the pond surface. Alkalinity varied from 420 to 535 mg/L, reflecting values from the primary pond. Values for pH, however, exhibited a much greater variation than the primary pond ranging from 8.0 to 9.4, a variation in \([H^+]\) by a factor of greater than 12. This variation may be attributed, in part, to the high plant population observed in this pond. This pond has the appearance of a free-water surface wetland, and the interactions with plant and migratory bird populations may have an influence on pond pH. Temperatures were seen to vary from 7 °C in the winter to just over 23 °C in the summer months, a 16°C temperature swing.

The higher alkalinity values occur during the summer months when water temperatures

Figure 30. Alamo Secondary Pond Properties.
are higher. DO concentration varied from saturated conditions (9 mg/L) in the summer to close to anoxic conditions (minimum of 0.4 mg/L) during the fall and winter months. No significant algae population was observed in this pond, nor are any types of engineered aeration systems employed. Therefore, the DO concentration can be considered a function of plant photosynthesis, microbial action, and reaeration rate. The low levels of DO during the winter months imply anaerobic or anoxic processes may predominate during this time period.

The alkalinity/pH relationship for this pond is examined in Figure 31. This figure shows an indeterminate relationship between alkalinity and pH. In some instances alkalinity goes up with increasing pH while in other cases alkalinity can be seen to go down.

![Alamo Secondary Alkalinity vs pH.](image)

*Figure 31. Alamo Secondary Alkalinity and pH.*
This observation provides an indication that the pH/alkalinity relationship is dependent upon other factors. This concern notwithstanding, predicted alkalinity values based on equation 6 are shown in Figure 20. These predicted values, ranging from 191 to 501 mg/L, vary significantly from measured values. Therefore, equation 6 should not be used as a rough estimate of alkalinity for this pond. Carbonate system interactions (equation 7) and plant photosynthesis/respiratory processes result in alkalinities significantly different than that obtained using equation 6.

**Organic Removal Characteristics**

COD concentrations measured in the Alamo secondary pond are depicted in Figure 32. Influent and primary pond COD values are also included for comparison purposes. Note that measured secondary pond COD concentrations are higher than that recorded for the primary pond. A maximum difference of approximately 200 mg/L between primary and secondary pond COD concentrations was recorded. This result suggests that organic material is being introduced into the secondary pond. This material is likely generated through plant and migratory bird interactions. No data were obtained on secondary pond BOD concentrations.
Chemical Characteristics

Phosphorus

Data on ortho-phosphate concentrations were collected for this pond. An average concentration of 3 mg/L was recorded, indicating that 12.5 mg/L was consumed by pond processes when compared to the corresponding influent concentration. Data on poly- and organic phosphorus concentrations was not collected.
Nitrogen

Ammonia-N

Measurement Data

Ammonia-N concentrations versus pH and wastewater temperature are displayed in Figure 33. High ammonia-N concentrations were recorded in the winter (lower pH values and wastewater temperatures), and low concentrations were recorded in the spring and summer (higher pH values and wastewater temperatures). This result is consistent with theory. The impact of higher pH values is readily apparent from the data collected for this pond. Note that when the pH is equal to or greater than 9.3, the approximate
ammonium dissociation constant value. recorded ammonia-N concentrations were very low.

The low concentration is due, in part, to the NH$_4^+$ ion being converted to ammonia gas at the higher pH level. The effect of temperature on ammonia-N removal is also apparent from these data, the optimum condition being high wastewater temperatures coupled with high pH.

**Alamo Secondary Pond Ammonia-N Removal Performance**

Actual versus predicted ammonia-N removal performance (using equations 33 and 34 for Prediction 1 and equation 33 for Prediction 2) is examined in Figure 34. The overall shape of the actual ammonia-N removal curve mirrors the predicted curves. This observation lends credence to the assumption that pH, temperature, and HRT are the driving influences on ammonia-N removal performance. Lower than predicted performance was achieved during the first half of this study while performance approached predictions during the second half of the study. Prediction 2, using only equation 33, provides results closest to recorded values. However neither prediction could be said to consistently reflect measured values. Therefore, these predictive methods are not recommended for this pond.

Figure 34 shows predicted versus actual ammonia-N removal results using the three models developed by the author. Prediction 3 makes use of equations 41 through 43 in a given temperature range, Prediction 4 applies equation 46, and Prediction 5 illustrates use
of equation 52. Prediction 5 provides results closest to measured values, with 4 of 7 data points within 10 percent of the measured value. It should also be noted that during the early months of this study (through January 1997) the pond depth was less than 1 foot. As a consequence, the pond volume and flow rate varied during this period from the average value of 1 foot used in Prediction 1, 2, and 5 calculations. These predictions would have provided results closer to measured values if the shallower pond depth were used in the performance calculation during the first 5 months of the study time period.

The correlation coefficients for Predictions 1 through 5 are 0.69, 0.79, 0.65, 0.81, and 0.80, respectively. Prediction 5 is recommended as the best model for this pond.

Figure 33. Comparison of Actual VS Predicted Ammonia-N Removal Performance for the Alamo Secondary Pond (Predictions 1 and 2).
Figure 34. Comparison of Actual VS Predicted Ammonia-N Removal Performance for the Alamo Secondary Pond (Predictions 3 through 5).

Calculation of Alamo Secondary Ammonia-N Removal Mass Transfer Coefficients

The Alamo secondary pond is a relatively narrow, shallow pond of rectangular dimensions. The initial impression of this pond is that it will exhibit plug flow conditions. However, the shallow depth (1 foot) of this pond should result in significant dispersion to accommodate the calculated flow rate. Calculated overall ammonia-N mass transfer coefficients, based on recorded ammonia-N removal values using equations 25, 29, 30, and 31 are depicted in Figure 35. The calculated $k_D$ values tend to be close to the midpoint between the $k_M$ and $k_P$ values. Less variability between these values is exhibited for this pond than the primary pond, though $k$ values ranging from 0.7 to 0.1 were calculated for data obtained on August 8, 1997. Removal efficiency was 93 percent on that date, indicating that greater variability in calculated overall $k$ values result at higher
ammonia-N removal efficiencies. This conclusion is consistent with results obtained from the primary pond. Calculated dispersion numbers varied inversely with wastewater temperature from 1.66 to 2.02, a result higher than that calculated for the primary pond.

The average ammonia-N removal efficiency obtained from the secondary pond was 62 percent. This average value is typical of the removal efficiency that is achieved in the spring and fall months. Using this efficiency, values for $k_M$, $k_P$, $k_D$, and $D$ were calculated. The $k_M$ and $k_P$ coefficient values bound the range within which volatilization of ammonia can occur. The results of these calculations are as follows:

Figure 35. Calculated Alamo Secondary Pond Overall Mass Transfer Coefficients and Dispersion Numbers for Various Assumed Flow Conditions
Alamo secondary well-mixed pond overall mass transfer coefficient, \( k_M = 0.084 \, \text{d}^{-1} \)

Alamo secondary plug flow pond overall mass transfer coefficient, \( k_P = 0.049 \, \text{d}^{-1} \)

Alamo secondary dispersion number, \( D \), (dimensionless) = 1.79

Alamo secondary dispersive overall mass transfer coefficient, \( k_D = 0.075 \, \text{d}^{-1} \)

Use of Thirumurthi curves reproduced in Reed et al., 1995 validate this value of \( k_P \) for a dispersion number of approximately 2 and removal efficiency of 60 percent. This curve produces a \( k_t \) value of 1.5, where \( t \) is the HRT. Division of the \( k_t \) value by the HRT (19.90 days) yields a \( k_D \) of 0.075 \( \text{d}^{-1} \).

These results indicate that the flow conditions in this pond are close to well-mixed. If the pond depth were increased, \( k_D \) would decrease, and conditions approaching plug flow would be observed. For example, if the pond depth were increased to 1 meter, a dispersion number of 0.56 and a \( k_D \) of 0.019 \( \text{d}^{-1} \) is calculated. This \( k_D \) value is close to the \( k_P \) value which is calculated as 0.015 \( \text{d}^{-1} \) for the 1-meter pond depth.

**Ammonia-N Removal Performance Comparison**

Total Alamo pond system ammonia-N removal performance showing primary and secondary pond contributions is depicted in Figure 36. Individually, both ponds averaged close to 60 percent ammonia-N removal efficiency representing the removal typically achieved during spring and fall months. The overall pond system average performance was 77 percent, with cool weather removal performance averaging 53 percent, and warm weather removal performance averaging 86 percent.
The predictive models suggested by the literature, equations 33 and 34, do not, in general, give adequate results for predicting ammonia-N removal through volatilization in this pond system. A possible explanation for this result is that equations 35 and 36 were developed for ponds with depths between 4 and 5 feet. The Alamo ponds are shallower than this range. The empirical model based on HRT, equations 41 through 43, is also inadequate for predicting ammonia-N removal. However, less information is required for this model, and it provides results close to the models obtained from the literature.


*Nitrates*

Nitrate concentrations were seen to range from 0 to 1.8 mg/L, averaging 0.63 mg/L. These results indicate that some nitrification may have occurred in this pond around April 1997, the timeframe when the 1.8 mg/L value was recorded. Typical values are much lower than this average, however, and nitrification can be ruled out as a significant contributory mechanism of ammonia-N removal in this pond.
Beatty Aerated Region

Pond Properties

The Beatty primary pond has aerated and facultative regions. Aerated region pond properties are shown in Figure 38. Alkalinity ranged from 240 to 400 mg/L with the

Figure 38. Beatty Primary Aerated Region Properties.
lowest values recorded in the winter and the highest values recorded in the summer. Values of pH ranged from 7.9 to 8.8, a $[\text{H}^+]$ variation of a factor of 7.9.

Water temperature ranged from 6 °C in the winter to just over 22 °C in the summer, a 16 °C temperature difference. Surface DO concentration values varied from 3.0 to 9.9 mg/L, a surprising variation given the well-mixed and aerated conditions of the aerated pond region. This DO variability may be an artifact of surface conditions. As will be evidenced by the DO profile discussions later in this section, DO in this region of the pond tends to be constant at concentrations approaching saturated values throughout the pond depth. Such conditions are similar to that of an activated sludge reactor with no recycle. The lack of recycle results in a lower microbial density, thus resulting in a lower BOD removal efficiency than would be obtained through an activated sludge system.

The relationship between alkalinity and pH can be explored through examination of Figure 39. In general, alkalinity mirrors pH with an increase or decrease in pH corresponding to an increase or decrease in alkalinity with the exception of values recorded during the late summer months. Predicted alkalinity values using equation 6 correspond closely to measured values during fall and winter months, diverging significantly from measured values during spring and summer months. This divergence is an indication that other factors than pH impact alkalinity. These factors include total carbonic species in the wastewater and algal photosynthetic and respiratory processes.
Therefore, use of equation 6 to predict alkalinity is not recommended for this pond region.

The depth of the Beatty aerated region ranges approximately from 4 to 7.5 feet. For completely mixed reactor conditions such as those prevalent in the Beatty aerated region.

![Beatty Aerated Region Alkalinity vs pH.](image)

Figure 39. Beatty Aerated Region Alkalinity and pH.

it is expected that the DO profile will be constant showing little change with depth. This hypothesis is explored in Figure 40 which shows DO profiles in the Beatty aerated region by season. The DO measurements used to derive this graph were taken from the same location which has an approximate depth of 5 feet. The essentially constant linear profile evidenced in Figure 40 validates the constant DO profile hypothesis.

A review of influent BOD loadings shows that elevated loadings occurred during November, February, April, and May, with the largest loading of 620 mg/L occurring in
February. This difference in BOD loadings may explain the lower constant DO values in the winter and spring. The greater BOD loading results in a corresponding increase in microbial density, thus resulting in a decrease in DO concentration. The fall DO profile is based on data obtained in early December, a month where the average BOD loading was recorded at 174 mg/L, a relatively low value.

![Beatty Aerated Region DO Profile](image-url)

*Figure 40. Beatty Aerated Region Seasonal DO Concentration Profile.*

As mentioned previously, the Beatty aerated region depth is variable. In order to determine how the DO profiles vary at different locations within the Beatty aerated region, these parameters were measured at different locations. Figure 5 depicts the sampling locations within the Beatty aerated region. These locations are shown as
sampling points 12 through 16. DO profiles for these sampling points are illustrated in Figure 41. The endpoints of each data series represent the depth at that sampling point location.

![Beatty Aerated DO Profile By Location.](image)

**Figure 41. Beatty Aerated Region DO Concentration Profile By Sampling Location.**

Figure 41 shows that DO concentration is constant with depth at near the saturated value with the exception of the pond bottom at sampling point 13. These measurements were taken during July 1997, thus exhibiting consistency with the summer DO profile reported in Figure 40.
Organic Removal Characteristics

BOD and TSS data are recorded over the total pond system rather than within a specific region. BOD data are illustrated in Figure 42. Concentrations are indicated on the left-hand axis, and removal performance is indicated on the right-hand axis. BOD concentrations ranged from 37 to 62 mg/L, averaging 50 mg/L. The Beatty pond system provides acceptable BOD removal performance, averaging 75 percent. Recorded TSS concentrations ranged from 66 to 243 mg/L, averaging 137 mg/L. COD concentrations ranged from 231 to 337 mg/L, averaging 289 mg/L.

Figure 42. Beatty Pond System BOD Removal Performance.

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Chemical Characteristics

Phosphorus

Data on inorganic and organic phosphate was collected from the Beatty aerated region. Inorganic phosphate averaged 17 mg/L consisting of 14.2 mg/L ortho-phosphate and 2.8 mg/L poly-phosphates. These concentrations are essentially unchanged from the influent concentrations with a slight decrease in poly-phosphates (1 mg/L). Organic phosphates averaged 4 mg/L which is an increase of 3 mg/L over the average influent concentration. Therefore, minor production of organic phosphates in occurring in this pond region.

Nitrogen

Ammonia-N

The Beatty pond consists of an aerated region and a facultative region. The aerated region is designed to be well-mixed, using both surface aerators and subsurface bubble diffusers, while the facultative region is expected to provide closer to plug flow conditions. However, the high influent flow rate experienced by this pond (approximately 95 gpm) results in a very short total HRT of approximately 15 days, with the aerated region HRT estimated at 6 days and the facultative region estimated at 9 days. It is expected that the higher flow rate will force the pond to exhibit well-mixed conditions in both regions. Effective treatment in well-mixed conditions typically requires larger volumes than plug flow conditions, and the minimum HRT reported for
ammonia-N removal from aerated ponds is 45 days (Middlebrooks and Pano, 1983). These two facts make it unlikely that significant ammonia-N removal can be achieved in the current pond configuration. The viability of this hypothesis is explored below.

*Measurement Data*

Average ammonia-N concentrations recorded for the Beatty aerated region are displayed in Figure 43. Ammonia-N concentrations were recorded at greater than 10 mg/L for all but one data point with most of the data points over 15 mg/L, averaging 19 mg/L over the study period. Lower values were recorded during the spring and summer, however, the difference between winter and summer values is not as diverse as for the

![Beatty Primary - Aerated Region Ammonia V5 Temperature and pH](image)

*Figure 43. Measured Beatty Aerated Region Ammonia-N Concentrations.*
other pond locations. An inverse relationship between ammonia-N concentration and temperature is displayed as predicted by theory. The expected inverse relationship with pH is also apparent as a general trend. The pH values are in the higher range, but none of these values are over the equilibrium threshold value for converting NH$_4^+$ ions to NH$_3$, and thus, enhancing ammonia volatilization.

**Beatty Aerated Region Ammonia-N Removal Performance**

Actual versus predicted ammonia-N removal performance for the Beatty aerated region using the published models is shown in Figure 44. The overall average ammonia-N removal was calculated at 39 percent for this region. Cold weather removal efficiencies averaged 22 percent, and hot weather removal efficiencies averaged 52 percent. Though

![Beatty Aerated Removal Performance](image)

*Figure 44. Comparison of Actual VS Predicted Performance of the Beatty Aerated Region (Predictions 1 and 2).*

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ammonia-N removal performance was low for this pond. It was higher than the predicted values. Prediction 2, using equation 33, provided results closest to the recorded values. Note that the shape of the prediction 2 curve mirrors the recorded values for all but one data point, with the prediction 2 curve consistently lower by an approximate factor of 2. Neither prediction yielded acceptable results, however.

Figure 45 shows predicted versus actual ammonia-N removal results using the three models developed by the author. Prediction 3 makes use of equations 41 through 43 in a given temperature range. Prediction 4 applies equation 46, and Prediction 5 illustrates use of equation 52. Predictions 3 and 5 closest resemble recorded data, predicting removal
within 10 percent on 4 of 8 data points. Prediction 5 is therefore recommended as the most appropriate model to apply to this pond region for obtaining a rough estimate of ammonia-N removal. However, prediction 5 using equation 52 is modeled for a hybrid of well mixed and plug flow conditions. The Beatty aerated region is a well-mixed pond. Therefore, equation 52 should be used with caution. Collection of additional data and modeling this pond region as a completely-mixed reactor is suggested.

**Calculation of Beatty Aerated Region Ammonia-N Removal Mass Transfer Coefficients**

The Beatty aerated region can be described as completely mixed. This assumption is based on the amount of aeration applied and the essentially constant DO values recorded throughout the extent and depth of this region. Therefore, it is expected that the overall ammonia-N removal mass transfer coefficient will most closely resemble $k_M$ (well mixed). Figure 46 shows calculated dispersion numbers and $k_M$, $k_P$, $k_D$ values corresponding to recorded ammonia-N removal performance for this region. The $k_P$, $k_D$, and dispersion numbers are included for comparison purposes only. The calculated $k_P$ and $k_D$ parameters are not valid since the degree of mixing through aeration is not factored into the equations used to calculate the removal coefficients. Dispersion numbers are indicated by the right-hand axis. Calculated $k_M$ values range from 0.03 $d^{-1}$ to 0.46 $d^{-1}$ with the majority of calculated values in the lower range. The average removal performance for this pond region was 39 percent. The calculated $k_M$ value for this ammonia-N removal performance is as follows:
Beatty aerated region well-mixed pond overall mass transfer coefficient. $k_M = 0.10 \, d^{-1}$

![Beatty Aerated Region Ammonia-N Removal Coefficients](image)

**Figure 46. Calculated Beatty Aerated Region Overall Mass Transfer Coefficients and Dispersion Numbers for Various Assumed Flow Conditions**

**Nitrates**

Measured nitrate values ranged from 0.0 to 0.6 mg/L, with an average concentration of 0.14 mg/L. These low values indicate that nitrification is not occurring in this region and is therefore, not a significant contributor to ammonia-N removal.
Beatty Facultative Region

Pond Properties

The Beatty facultative region, though contained within the Beatty primary pond, performs secondary treatment. This treatment regime is located down channel from the aerated region. Pond properties, obtained from samples taken at the effluent inlet, are illustrated in Figure 47. Alkalinity in this region is seen to vary from 260 to 387 mg/L, a narrower range than the Beatty aerated region. Alkalinity values are at a minimum during the winter and at a maximum during the summer which is consistent with aerated region behavior. Values of pH range from 7.9 to 8.7, representing a difference in [H\(^+\)] of a factor of 6.3. Wastewater temperature varies from 6 °C in the winter to 24.5 °C in the summer.

Figure 47. Beatty Primary Facultative Region Properties.
a variation of 14.5 degrees. Note that higher alkalinity and pH values were recorded at elevated wastewater temperatures. Surface DO concentrations ranged from 3.7 to 12.8 mg/L, indicating sufficient DO at the surface to support aerobic treatment processes. The 12.8 mg/L value was recorded in the early afternoon when prolonged sunlight exposure results in extensive algal photosynthetic activity, thus increasing the DO concentration. DO values for the other sampling dates were recorded at approximately 9:00 am, a time when the DO contribution due to algal photosynthesis is limited by shorter sunlight exposure.

The relationship between alkalinity and pH is investigated with the aid of Figure 48. Alkalinity is shown on the left-hand axis, and pH is shown on the right-hand axis.
Application of equation 6 yields reasonable results for 5 of 7 data points. The two outlier data points are supported by both field and laboratory alkalinity and pH data that are in close agreement. Therefore, other factor influence alkalinity. These factors include both carbonate system interactions and algae photosynthetic and respiratory processes. The Beatty pond is unlined, therefore significant soil-water interactions are expected. These interactions enhance carbonate system alkalinity contributions. The reader is, therefore, cautioned to use equation 6 to predict alkalinity only in cases where alkalinity measurement data are not available.

The DO concentration profile by season as measured at the effluent outlet location of the Beatty facultative region is shown in Figure 49. DO contributions in this region are due to natural reaeration and algal photosynthesis. This profile exhibits stratified summer behavior and nearly constant winter behavior at close to saturated values. Fall and spring profiles exhibit intermediate DO concentrations with minor stratification. Low DO concentrations occur near the bottom in the summer months, thus creating the potential for anoxic processes to occur in the bottom of the pond.

The Beatty facultative region is of variable depths, and this region comprises the largest portion of the Beatty primary pond. In order to determine what the DO concentration profile looks like throughout the facultative region, it is necessary to take measurements at different locations across the pond. These measurements were taken in July 1997 with the sampling locations identified in Figure 5. Points 1 through 11, as
indicated on Figure 5. constitute the sampling locations within the Beatty facultative region. DO

![Beatty Facultative Region DO Profile](image)

*Figure 49. Beatty Facultative Region Seasonal DO Concentration Profile.*

measurements, starting with sampling point 1. commenced at 8:40 am. and measurements from sampling point 11 were completed at 10:00 am. Therefore, a small, but increasing, contribution to DO concentration is expected from algal photosynthesis as measurement activities progress throughout the day. Points 10 and 11 are located in a transition zone between the aerated and facultative portions of the pond. The DO profiles of these two points are shown in Figure 50.

In Figure 50, the deepest sampling point for each data series is the depth at that sampling location. Stratified DO concentrations are exhibited at point 10. The DO value
at the surface is greater than the saturated value, thus indicating that algal photosynthesis plays a significant role at this location. The stratified profile at point 10 implies that limited mixing occurred at that location, a characteristic of a facultative pond. Therefore, though sampling point 10 was located adjacent to the aerated region, the mixing influence from that region was minimal. This conclusion provides an indication that flow in the aerated region is circular, exiting at a location north of point 10.

Figure 50. Beatty Facultative DO Profile in the Transition Zone

This result is supported by data obtained from point 11. DO measurements at this location, ranging from 7.5 mg/L at the surface to 4.2 mg/L at the bottom, indicate that
some vertical mixing is occurring. Therefore, it can be postulated that the flow from the aerated region is exiting through or adjacent to the point 11 location.

DO profile data for the main body of the Beatty facultative region were obtained from sampling locations comprising points 1 through 9, as indicated in Figure 5. These data are illustrated in Figure 51. Examination of this graphic shows the overall stratified behavior of the Beatty facultative region. Surface DO concentrations above saturated levels were obtained from points 8 and 9 which were recorded later in the morning, indicating a DO contribution from algae. With the exceptions of points 1 and 4, stratification becomes significant at the 1-foot depth. Point 1 exhibited stratification just below the surface, and

![Beatty Facultative DO Profile By Location](image)

Figure 51. Beatty Facultative DO Profile
point 4 did not manifest appreciable stratification. Taken collectively, no specific pattern emerges from these data. The lower DO values recorded at points 2, 3, and 5, may be an indication of a greater BOD concentration in that location. This observation may be indicative of a stagnant zone. The DO levels at these locations are not alarmingly low, however. The only definitive conclusion that can be reached is that this region exhibits classical DO profile behavior.

**Organic Removal Characteristics**

BOD and TSS data for the Beatty pond system are summarized in the Beatty aerated region discussion. Recorded COD values in the Beatty facultative region varied from 242 to 328 mg/L, averaging 197 mg/L. This result represents a net increase in average COD as compared to the aerated region (average COD concentration of 280 mg/L).

**Chemical Characteristics**

**Phosphorus**

Data on inorganic and organic phosphorus were collected for this region. Inorganic phosphorus averaged 13.5 mg/L ortho-phosphate and 4.5 mg/L poly-phosphates. These concentrations reflect the influent concentrations (14 mg/L ortho-phosphate and 4 mg/L poly-phosphates. Organic phosphorus averaged 3 mg/L organic phosphate. This concentration represents a slight increase over the average recorded influent concentration
(1 mg/L). Therefore, limited production of organic phosphate is occurring in this pond region.

**Nitrogen**

**Ammonia-N**

**Measurement Data**

Ammonia-N concentrations recorded for the Beatty facultative region are depicted in Figure 52. Temperature and ammonia-N concentrations are read from the right-hand axis, and pH is read from the left-hand axis. Consistently high ammonia-N concentrations

![Beatty Primary-Facultative Region Ammonia VS Temperature and pH](image)

*Figure 52. Measured Beatty Facultative Region Ammonia-N Concentrations.*

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were recorded, averaging 17 mg/L during the summer and 24 mg/L during the winter, with an overall average of 18.6 mg/L. In general, the inverse relationship between concentration and temperature/pH holds, though the effect is not as dramatic as evidenced for other ponds. Recorded pH values are less than the equilibrium value required for the $\text{NH}_4^+ - \text{NH}_3$ reaction to proceed to the right, resulting in predominance of the $\text{NH}_4^+$ component. This observation, coupled with the short region HRT, results in conditions that are not conducive to ammonia-N removal.

**Beatty Facultative Region Ammonia-N Removal Performance**

Actual versus predicted ammonia-N removal performance using the published models (Predictions 1 and 2) is shown in Figure 53. In contrast to the aerated region, the

![Beatty Facultative Pond Performance](image)

*Figure 53. Comparison of Actual Versus Predicted Ammonia-N Removal Performance for the Beatty Facultative Region (Predictions 1 and 2).*
predicted values are consistently higher than the measured values. The data show that practically no ammonia-N removal is occurring in this region. Five of the 7 data points displayed in Figure 53 showed no removal, and the maximum removal recorded was 28 percent, with an average removal of 6 percent. This poor removal can be attributed to the short HRT and flow conditions in this region. Prediction 1 provides results closest to actual values in this region, though neither model can be said to provide accurate predictions.

Figure 54 shows predicted versus actual ammonia-N removal results using the three
models developed by the author. Prediction 3 makes use of equations 41 through 43 in a given temperature range, Prediction 4 applies equation 46, and Prediction 5 illustrates use of equation 52. Prediction 3 provides results closest to measured values, however, none of the predicted models are recommended for this pond region. Additional data collection and ammonia-N removal modeling of this region is recommended.

Calculation of Beatty Facultative Region Ammonia-N Removal Mass Transfer Coefficients

The Beatty facultative region has physical dimensions that suggest plug flow conditions. However, the high flow rate in this pond results in a short HRT (8.9 days), indicating a potential for greater dispersion and thus, conditions approaching that of a well-mixed pond. This potential is explored in Figure 55. The short HRT in this region did not provide sufficient time for meaningful ammonia-N removal with only 2 of 9 data points recording any ammonia-N reduction in the facultative region. The two data points with calculated k values show kp values tending towards well-mixed. The calculated dispersion numbers range from 0.75 to 0.94, relatively low values indicating that less dispersion is occurring in this region.

The overall ammonia-N removal efficiency for the Beatty facultative regions averaged 6 percent. Using this value, average ammonia-N mass transfer coefficients were calculated. The results are as follows:

Beatty facultative region well-mixed overall mass transfer coefficient, \( k_M = 0.008 \, \text{d}^{-1} \)

Beatty facultative region plug flow overall mass transfer coefficient, \( k_P = 0.008 \, \text{d}^{-1} \)
Beatty facultative region dispersion number, \( D \) (dimensionless) = 0.81

Beatty facultative region dispersive overall mass transfer coefficient, \( k_D = 0.008 \text{ d}^{-1} \)

Calculated overall \( k \) values converge to a single value at low ammonia-N removal performance levels.

![Beatty Facultative Region Ammonia-N Removal Coefficients](image)

Figure 55. Calculated Beatty Facultative Region Overall Mass Transfer Coefficients and Dispersion Numbers for Various Assumed Flow Conditions

Ammonia-N Removal Performance Comparison

The Beatty pond exhibited relatively poor ammonia-N removal performance. This fact is illustrated in Figure 56. A maximum system performance of 74 percent was
achieved on May 30, 1997. However, the average overall pond system performance was considerably less than this value, calculated at 43 percent.

Figure 36. Beatty Pond System Ammonia-N Removal Summary.

The facultative region provided little, if any, contribution to ammonia-N removal. The critical factor responsible for the poor ammonia-N removal performance is the short HRT. The aerated region is able to provide some ammonia-N removal, despite the short HRT, due to the extensive aeration occurring in this region. The aeration process increases the pond surface area exposed to the ambient air, thus enhancing volatilization. Application of the predictive models provided poor agreement with recorded data.
**Nitrates**

Measured nitrate values ranged from 0.0 to 0.3 mg/L, with an average concentration of 0.08 mg/L. These low values indicate that nitrification is not occurring in this region, and is, therefore, not a significant contributor to ammonia-N removal.
CHAPTER 8

BLUE DIAMOND POND SYSTEM DATA

Blue Diamond Primary Pond

_Pond Properties_

The Blue Diamond primary pond is a partially mixed aerated pond containing two mechanical aerators operating in an alternating sequence. Measured pond properties.

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**Figure 57. Blue Diamond Primary Pond Properties.**

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obtained from a sampling location diagonally opposite from the pond inlet, are depicted graphically in Figure 57. Temperature, pH, and DO values are read from the right-hand axis.

Pond alkalinity was seen to vary from 260 to 387 mg/L. This variation is within a narrow range (127 mg/L) with no apparent seasonal trends. Recorded values of pH ranged from 8.1 to 8.7, a $[\text{H}^+]$ difference of a factor of 4. Wastewater temperature varied from 4 °C in the winter to 27 °C in the summer, a temperature swing of 23 degrees. Surface DO values varied dramatically from 2.0 to 19.5 mg/L. This difference is a function, in part, of season of the year and sampling time of day. Values recorded in September 1996, March 1997, and August 1997 were recorded at 1:45 pm, 11:00 am, and

![Graph of Blue Diamond Primary Alkalinity vs pH](image)

**Figure 58. Blue Diamond Primary Alkalinity and pH.**

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8:10 PM, respectively. A significant algal contribution to DO concentration was expected at those times.

The relationship between alkalinity and pH is explored in Figure 58. Alkalinity is read from the left-hand axis, and pH is read from the right-hand axis. Alkalinity changes mirror pH changes with the exception of late spring and summer months. Alkalinity predictions using equation 6 yield good agreement for 6 of 10 data points recorded during late summer, spring, and fall. However, equation 6 should be applied with caution since it does not consider alkalinity contributions due to total carbonate species and algal photosynthesis and respiration.

![Figure 59. Blue Diamond Primary Pond Seasonal DO Concentration Profile.](image-url)
The DO profile of the Blue Diamond primary pond by season is shown in Figure 59. The very high supersaturated DO readings at the pond surface during the spring and summer months are due to extensive algae growth. The algae, though responsible for high surface DO concentrations, is also the primary reason for the stratified DO profile during these months. The high density of algae limits light penetration to the deeper depths, thus effectively suppressing photosynthetic activity. It is interesting to note that this stratified profile is apparent even though DO enhancement is being supplied through mechanical aeration in this pond. The degree of mixing provided by natural wind and mechanical aeration processes is not generally sufficient to provide saturated conditions throughout the pond depth. This conclusion does not appear to hold during the winter, however, which shows a near constant DO concentration at near saturated values for the entire depth of the pond. This result implies greater vertical mixing during the winter months, and the lower algae density during the winter allows greater, though less intense, sunlight penetration for a minor DO contribution from photosynthesis. A final conclusion that can be reached through examination of Figure 59 is that, although this pond is stratified over most of the year, the DO concentration does not fall below 2 mg/L until below the 3-foot depth. Therefore, DO conditions are adequate to support aerobic treatment processes over most of the pond depth throughout the year.
Organic Removal Characteristics

Recorded BOD and COD data obtained from the Blue Diamond primary pond are depicted in Figure 60. BOD data varied from 55 to 76 mg/L, with an average of 64 mg/L. The average BOD removal efficiency was 56 percent. COD data varied from 161 to 318 mg/L, averaging 243 mg/L. The average COD removal efficiency was 19 percent. A COD increase, as compared to influent concentration, was noted in this pond on one occasion. TSS data varied from 116 to 172 mg/L, average 137 mg/L.

![Figure 60. Blue Diamond Primary Pond BOD and COD Data.](image-url)
Chemical Characteristics

Phosphorus

Inorganic and organic phosphorus data were obtained from the Blue Diamond primary pond. Inorganic data measurements, associated with ortho- and poly-phosphates, were 3.7 and 3.8 mg/L, respectively. These values, when compared to the corresponding influent values, suggests that approximately 9 mg/L ortho-phosphates were consumed, and 3 mg/L poly-phosphates were produced in this pond. Organic phosphorus measurements, recorded as organic phosphate, averaged 5.5 mg/L. This concentration, when compared to the corresponding influent value, suggest that an average of 5 mg/L organic phosphate is produced in this pond. This consumption and production may be due to algal processes. Additional data on this topic is required before a definitive explanation of phosphorus activity in this pond is formalized.

Nitrogen

Ammonia-N Removal

The Blue Diamond pond system consists of a partially aerated primary pond and facultative secondary and secondary overflow ponds. The HRTs for the primary and secondary ponds are similar to the Alamo pond system, though physical pond dimensions are different. The Blue Diamond primary pond has more of a rectangular shape and a greater depth than the Alamo primary pond, and therefore, less dispersion is expected. The lower dispersion would result in closer to plug-flow conditions allowing volatilization of ammonia at lower overall mass transfer coefficient values. This condition
would tend to enhance ammonia-N removal performance. In addition, two surface aerators, operating in an alternating sequence, provide localized mixing. The local mixing increases interfacial surface area and thus, further enhances volatilization. These two complementary features, plug-flow geometry with localized sequential mixing, should result in efficient ammonia-N removal. This result is expected despite the relatively short HRT in this pond (16.7 days).

Measurement Data

Measured ammonia-N concentrations, wastewater temperature, and pH for the study period are displayed in Figure 61. The pH values are indicated on the right-hand axis. An inverse relationship between temperature and ammonia-N concentration is evident.

Figure 61. Measured Blue Diamond Primary Pond Ammonia-N Concentrations

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evident. Highest ammonia-N concentrations were recorded during the winter when wastewater temperatures were low. Recorded pH values also exhibit an inverse relationship with ammonia-N concentrations. This observation is explained by noting that effective volatilization of ammonia occurs at the higher pH values (i.e., values above the ammonium dissociation constant - equation 37) forcing the $\text{NH}_4^+ - \text{NH}_3$ reaction to proceed to the right (i.e., to the ammonia gas phase).

**Blue Diamond Primary Pond Ammonia-N Removal Performance**

Ammonia-N removal performance for the Blue Diamond primary pond is shown in Figure 62. Predictions using equation 38 and 39 are also shown with prediction 1 comprised of equation 38 and 39, and prediction 2 representing equation 39 results only. Warm weather performance averaged 77 percent, and cool weather performance averaged
46 percent. Overall pond performance averaged 65 percent.

Prediction 2 provided results closest to measured values, providing reasonable agreement with 6 of 11 data points. Prediction 2 appears to provide the best results during the summer and winter months. Spring and fall predictions varied significantly from recorded values.

Figure 63 shows predicted versus actual ammonia-N removal results using the three models developed by the author. Prediction 3 makes use of equations 41 through 43 in a given temperature range. Prediction 4 applies equation 46, and Prediction 5 illustrates use of equation 52. Predictions 4 and 5 provide results close to measured values for this pond. Therefore, either can be applied with confidence. However, use of Prediction 5 is
recommended since it was developed from a theoretical basis.

*Calculation of Blue Diamond Primary Pond Ammonia-N Removal Mass Transfer Coefficients*

As stated previously, it is expected that the Blue Diamond primary pond will exhibit overall flow characteristics approaching that of a plug flow reactor. This hypothesis is explored in Figure 64. Overall mass transfer coefficient values are displayed on the left-hand axis, and dispersion numbers are shown on the right-hand axis. Note that k_D values are typically in the middle of the range between plug flow (k_P) and well-mixed (k_M), with a slight tendency toward plug flow. This result is consistent with the stated hypothesis.

*Figure 64. Calculated Blue Diamond Primary Pond Overall Mass Transfer Coefficients and Dispersion Numbers for Various Assumed Flow Conditions*
though a closer correlation to plug flow conditions was expected. As noted for the other ponds, $k$ values tend to converge at low ammonia-N removal performance values and diverge at the higher performance values.

Dispersion numbers ranged from 0.41 to 0.54, showing an inverse relationship with temperature. These values indicate that pond geometry is such that relatively low dispersion will occur in this pond provided that other external factors do not influence flow conditions. One of these external factors is aeration. Mechanical aeration introduces localized dispersion effects. Therefore, it is suggested that the actual overall mass transfer coefficient for this pond will be in the range between the $k_D$ (plug flow with dispersion) and $k_M$ (well mixed) values shown in Figure 64.

The average overall ammonia-N removal performance for this pond was determined to be 65 percent. The calculated dispersion number and overall mass transfer coefficients corresponding to this average removal performance is as follows:

Blue Diamond primary well-mixed overall mass transfer coefficient, $k_M = 0.110 \text{ d}^{-1}$
Blue Diamond primary plug flow overall mass transfer coefficient, $k_p = 0.062 \text{ d}^{-1}$
Blue Diamond primary dispersion number, $D$, (dimensionless) = 0.45
Blue Diamond primary dispersive overall mass transfer coefficient, $k_D = 0.081 \text{ d}^{-1}$

From the preceding discussion, the actual overall mass transfer coefficient for 65 percent average ammonia-N removal performance is in the range between $k_M$ and $k_D$. An overall $k$ value of 0.09 $\text{d}^{-1}$ is, therefore, suggested.
Nitrate

Recorded nitrate values ranged from 0 to 0.03 mg/L, averaging 0.007 mg/L. These data indicate that nitrification can be ruled out as a viable mechanism for ammonia removal in this pond.

Blue Diamond Secondary Pond

Pond Properties

The Blue Diamond Secondary pond, a facultative pond, was operational while this study was being conducted for the time period August 1996 through March 1997. This pond was drained in March 1997 and was not put into operation by the time this study concluded in September 1997. Collected data associated with pond properties are depicted in Figure 65. Temperature, pH, and DO concentration is read from the right-hand axis.

Measured alkalinity ranged from 272 to 380 mg/L, a narrow range that is consistent with primary pond values, with the maximum value recorded in the summer and the minimum value recorded in the fall. Values for pH ranged from 8.8 to 9.8, a change in \([H^+]\) by a factor of 10. The 9.8 pH measurement, recorded on 8/23/96, corresponds to the high influent spike recorded on that date. However, the 17-day HRT of the Blue Diamond primary pond suggests the high pH wastewater would have entered the primary pond 2.5 weeks prior to entering the secondary pond unless short circuiting is occurring in the primary. Therefore, the high pH measurement must be attributable to other factors not explainable with the current data. Temperature ranged from 3 °C in the winter to 27
°C in the summer, a difference of 24 degrees. Surface DO concentrations varied from 2.5 to 19.2 mg/L, a surprisingly large difference of 16.7 mg/L. The lowest DO value was recorded in the early morning while the highest DO values were recorded around noon, as would be expected to account for algal photosynthesis. One of the lower data points, however, was recorded at 3:00 p.m. during early fall, a result that is unexplained with the current data available.

Figure 65. Blue Diamond Secondary Pond Properties.

The alkalinity/pH relationship of the Blue Diamond secondary pond is examined in Figure 66. Values for pH are read from the right-hand axis. Note that the pH mirrors alkalinity for the first three data points and then exhibits an opposing relationship.
thereafter. This opposing relationship is not explained by the current data. Measurement error may be responsible, however, the data points in question are backed up by duplicate measurements taken in the field and laboratory, the alkalinity values agreeing within 40 mg/L in all but one instance which showed an 80 mg/L discrepancy. The alkalinity prediction was developed using equation 6. The results obtained using this equation diverge significantly from measured values. Use of this equation is therefore not recommended for this pond.

![Blue Diamond Secondary Alkalinity vs pH](image)

*Figure 66. Blue Diamond Secondary Alkalinity and pH.*

The DO concentration profile of the Blue Diamond secondary pond by season is shown in Figure 67. This profile differs significantly from the primary pond profile.
showing the highest surface DO concentration occurring in the spring. An explanation for the lower summer surface DO concentration may be that the data supporting this data series was obtained in late summer. A mid-summer component is not included.

Supersaturated DO concentrations are present at the surface during spring, summer, and fall months. An interesting observation is that the extent of stratification is less for this facultative pond than that evidenced by the partially mixed aerated primary. This condition may be attributed to the shallower depth of the secondary pond. The winter

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**Figure 67. Blue Diamond Secondary Pond Seasonal DO Concentration Profile.**
DO profile is constant at near saturated concentrations, similar to that observed for the primary pond. In all cases, sufficient DO concentration is present to support aerobic processes throughout the pond depth.

*Organic Removal Characteristics*

No data on BOD removal were obtained from the Blue Diamond secondary pond. COD data obtained from this pond varied from 205 to 274 mg/L, averaging 238 mg/L. TSS data consists of one data point which recorded a value of 81 mg/L.

*Chemical Characteristics*

*Phosphorus*

The only phosphorus data collected for the Blue Diamond secondary pond was ortho-phosphate. This pond was inactive when complete phosphate testing capabilities was developed. An ortho-phosphate concentration, based on one data point, of 12 mg/L was recorded for this pond.

*Nitrogen*

*Ammonia-N Removal*

The Blue Diamond secondary pond has dimensions similar to that of the primary, but with a lower depth and no localized mixing. The lower depth would tend to decrease the pond HRT and increase dispersion. The greater dispersion would raise the overall mass transfer coefficient required for effective ammonia removal. Therefore, a lower
ammonia-N removal efficiency is expected from the secondary pond as compared to the primary pond.

**Measurement Data**

Measured ammonia-N concentrations, temperature, and pH are shown in Figure 68.

![Blue Diamond Secondary Pond Measured Ammonia-N Concentrations](image)

**Figure 68. Blue Diamond Secondary Pond Measured Ammonia-N Concentrations.**

Recorded pH values are indicated on the right-hand axis. Consistently low ammonia-N concentrations were recorded for this pond when it was in operation during the study time frame. Concentrations of 10 mg/L or greater were recorded on two occasions with all other data values recorded at less than 5 mg/L. The inverse temperature and pH
relationship is apparent. The effect pH has on ammonia concentrations is illustrated by examining the last two data points in Figure 68. An increase in pH approaching the ammonium dissociation constant value results in a dramatic decrease in ammonia-N concentration.

Blue Diamond Secondary Pond Ammonia-N Removal Performance

Blue Diamond secondary pond ammonia-N removal efficiencies are summarized in Figure 69 along with the results of applying the predictive models described by equations

![Blue Diamond Secondary Pond Performance](image)

Figure 69. Comparison of Actual Versus Predicted Ammonia-N Removal Performance for the Blue Diamond Secondary Pond (Predictions 1 and 2).

33 and 34 (Predictions 1 and 2). Pond performance averaged 89 percent during warm weather months and 45 percent during cool weather months, with an overall average of 70
percent. These values are higher than expected for this pond. An explanation for the higher than expected performance is that the high pH values recorded in this pond result in a greater fraction of ammonia present as NH$_3$, thus increasing the volatilization rate.

The predictive model based only on equation 33 (Prediction 2) provided closest agreement with recorded values, matching 4 of 8 data points. However, there is significant variability between predicted and measured values using Prediction 2, therefore. Prediction 2 in not recommended.

Figure 70 shows predicted versus actual ammonia-N removal results using the three models developed by the author. Prediction 3 makes use of equations 41 through 43 in a

![Blue Diamond Secondary Pond Performance](image)

*Figure 70. Comparison of Actual Versus Predicted Ammonia-N Removal Performance for the Blue Diamond Secondary Pond (Predictions 3 through 5).*

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given temperature range. Prediction 4 applies equation 46. and Prediction 5 illustrates use of equation 52. Predictions 4 and 5 provide results closest to measured values for this pond, with Prediction 4 slightly more accurate than Prediction 5. Prediction 5 is recommended by the author given its theoretical basis.

Calculation of Blue Diamond Secondary Pond Ammonia-N Removal Mass Transfer Coefficients

The Blue Diamond secondary pond is expected to exhibit greater dispersion than the Blue Diamond primary pond given its lesser depth. This expectation is explored in Figure 71 which depicts calculated overall mass transfer coefficients and dispersion numbers for

![Blue Diamond Secondary Ammonia-N Removal Coefficients](image)

**Figure 71. Calculated Blue Diamond Secondary Pond Overall Mass Transfer Coefficients and Dispersion Numbers for Various Assumed Flow Conditions**

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flow conditions between plug flow and well mixed. Dispersion numbers are shown on the right-hand axis. The calculated $k_D$ values tend to approach the plug flow regime. Dispersion numbers range from 0.45 to 0.59, a range similar to that calculated for the primary pond. This result indicates that the lesser depth in this pond did not significantly impact the dispersion number. The narrower pond width tends to compensate for the lesser depth.

The average overall removal efficiency of 70 percent was used to calculate a representative dispersion number and overall mass transfer coefficients. The calculated values are as follows:

- Blue Diamond secondary well-mixed overall mass transfer coefficient, $k_M = 0.175 \text{ d}^{-1}$
- Blue Diamond secondary plug flow overall mass transfer coefficient, $k_P = 0.090 \text{ d}^{-1}$
- Blue Diamond secondary dispersion number, $D$, (dimensionless) = 0.50
- Blue Diamond secondary dispersive overall mass transfer coefficient, $k_D = 0.123 \text{ d}^{-1}$

There is no mechanical aeration occurring in this pond, and the pond is shielded by mountains which limits dispersion by wind. Therefore, the $k_D$ value is the most appropriate parameter to apply to this pond.

**Nitrates**

Recorded nitrate values ranged from 0 to 0.04 mg/L, averaging 0.01 mg/L. These data suggest that nitrification can be ruled out as a significant contributor to ammonia-N removal in this pond.
Blue Diamond Overflow Pond

Pond Properties

Data on the Blue Diamond overflow pond was collected during the time period January through May 1997. The pond was in use prior to that time, however no data was collected. Data was collected from this pond when the pond depth increased above 3 feet and it became apparent that the pond was playing an important treatment role. Data collection was discontinued when the pond was drained. Data addressing pond properties are depicted on Figure 72.

Figure 72. Blue Diamond Overflow Pond Properties.
Measured alkalinity values range from 243 to 308 mg/L, the 65 mg/L difference being the smallest variation exhibited by any of the ponds studied. This stable alkalinity concentration is probably due to the relatively short time period over which data was gathered. Measured pH values varied from 8.8 to 9.6, a [H+] difference of a factor of 6.3. Note that these pH measurements were higher than that recorded for the primary or secondary ponds. These higher pH values are due to the longer wastewater residence time in which algal photosynthesis/respiration and microbial processes are occurring in addition to carbonate system interactions with this unlined pond. Pond temperatures ranged from 4 °C during the winter to 18 °C in the spring, a 14 degree variation. Surface DO concentrations varied from 2.0 to 11.2 mg/L. The primary pond also had a lower than expected DO value (2.25 mg/L) recorded on this date. Therefore, a DO meter error is suspected. Given the short time period over which data was collected for this pond, no DO profile data by season is available.

The relationship between alkalinity and pH is examined in Figure 73. In this figure, alkalinity values do not mirror pH values for any of the data points. An increase in pH is followed by a decrease or very slight increase in alkalinity. Conversely, a decrease in pH is followed by an increase in alkalinity. Application of equation 6 yields alkalinities that are significantly higher than measured values.
<table>
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</table>

**Figure 73. Blue Diamond Overflow Alkalinity and pH.**

**Organic Removal Characteristics**

Blue Diamond overflow pond BOD values ranged from 41 to 102 mg/L with an average concentration of 72 mg/L. The BOD concentrations in this pond were greater, on average, than the BOD concentrations in both the secondary and primary ponds. This result indicates that this pond produces BOD rather than consumes it. It is likely that the excess organic material in this pond is the result of algal respiration. Additional data addressing this issue is needed before a definitive conclusion can be developed. Recorded COD concentrations ranged from 282 to 3380 mg/L, averaging 331 mg/L. These concentrations are also greater than that recorded for the secondary and primary ponds. No TSS data on this pond was available.
Chemical Characteristics

Phosphorus

Data on inorganic and organic phosphorus was collected from this pond. Inorganic phosphorus measurements, in the form of ortho- and poly-phosphates, of 4 and 1 mg/L were recorded, respectively. These data indicate that the ortho-phosphate concentration was unchanged from the primary pond, and the poly-phosphates concentration decreased by approximately 3 mg/L as compared to the primary pond. Organic phosphate concentration averaged 11 mg/L, a significant increase from the 5.5 mg/L average recorded from the primary pond.

Nitrogen

Ammonia-N Removal

Blue Diamond System Ammonia-N Removal Performance Comparison

Ammonia-N removal performance of the ponds comprising the Blue Diamond pond system is summarized in Figure 74. Data on the secondary overflow pond is also presented, though no analyses is provided. The pond system performed very well, averaging 93 percent removal. The secondary overflow pond complemented ammonia-N removal during the winter months, providing the additional treatment needed to ensure satisfactory ammonia removal. Pond system performance averaged 82 percent without considering performance from the secondary overflow pond.
Figure 7.4. Blue Diamond Pond System Ammonia-N Removal Summary.
CHAPTER 9

SEARCHLIGHT POND SYSTEM DATA

Searchlight Primary Ponds

Pond Properties

The Searchlight primary ponds consist of two facultative ponds in series. Samples were collected from the westernmost pond opposite the inlet location. It is assumed that the southernmost primary pond will exhibit similar properties. Searchlight primary pond properties are depicted in Figure 75. Temperature, pH, and DO concentration are read from the right-hand axis.

Alkalinity ranged from 256 to 392 mg/L with the lowest values occurring during the winter, and the highest values occurring during the summer. Measured pH values experienced a large variation, ranging from 8.0 to 10.3. This variation represents a change in $[H^+]$ of a factor of 20, a much greater difference than the other pond locations. The pH variability may be attributed to the extremely high summer density of algae in this pond resulting in higher pH values in the summer. Surface water temperature ranges from 5 °C in the winter to 30 °C in the summer, a 25 degree temperature swing. The warmer
summer temperatures in the pond tend to promote conditions for algae growth. Surface DO concentrations varied from 4.2 mg/L to over 20 mg/L. The DO meter used for this study had a maximum scale reading of 20 mg/L. Readings that surpassed this maximum were assigned a value of 21 mg/L. Of particular interest are the supersaturated DO values recorded during the winter. This result indicates a year-round contribution to DO concentration by algae photosynthesis.

The pond properties evaluated in this study vary by month-to-month and throughout the day. The bulk of this analysis has focused on month-to-month variations. However, day-to-day (i.e., diurnal) variations are also important, particularly with regard to algal

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**Searchlight Primary Alkalinity vs pH, Temperature, and DO**

*Figure 75. Searchlight Primary Pond Properties.*
photosynthetic processes, and hence DO concentration. In order to gain an understanding of this diurnal fluctuation, Searchlight pond properties were measured at approximate 3-hour intervals over a 24-hr period in early September 1997. Results obtained from the primary pond are shown in Figure 76.

![Searchlight Primary Pond Diurnal Behavior Characteristics](image)

**Figure 76. Searchlight Primary Pond Diurnal Properties.**

In the early morning hours, DO concentrations are depressed due to algal respiration. This process tends to produce carbon dioxide, thus lowering the pH and decreasing alkalinity. In addition, the die-off of algae increasing the organic loading in the pond, further suppressing the DO concentration. As the sun rises in the morning, the pond begins to heat up and algae photosynthesis commences. This process consumes carbon
dioxide (an acid), raising the pH and alkalinity. Maximum DO concentration is reached in
the late afternoon after prolonged exposure to the sun decreasing dramatically after the
sun goes down. The pH values recorded during this 24-hr sampling did not fluctuate to
the extent expected. This finding may be due to the buffering capacity of the wastewater.
the ability to resist changes in pH when acidity is added.

The alkalinity/pH relationship is further explored in Figure 77. In general, alkalinity
can be seen to mirror pH. Alkalinity predictions using equation 6 provide good results
for 5 of 13 data points. However, this equation is not recommended as it does not
account for alkalinity contributions due to total carbonic species and algal photosynthetic
and respiratory processes.

![Searchlight Primary Alkalinity vs pH](image)

*Figure 77. Searchlight Primary Alkalinity and pH.*

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Seasonal DO concentration profiles are depicted in Figure 78. The Searchlight primary pond exhibits similar DO profiles as that shown for the other ponds examined in this study. Summer DO concentrations are the highest with the greatest level of stratification. Conditions approaching anoxic levels are present in both the summer and fall. Winter DO concentrations are supersaturated at the pond surface decreasing to saturated levels at the pond bottom, indicating that photosynthetic processes are occurring during the winter months. A somewhat surprising result is the fall DO profile showing DO concentrations less than expected. This profile may be explained by noting that fall values were recorded in the morning hours, and an increased organic loading is expected in the fall as temperatures change and algae die off to a lower density.

Figure 78. Searchlight Primary Seasonal DO Concentration Profile.
Organic Removal Characteristics

Recorded BOD and COD data obtained from the Searchlight primary pond are depicted in Figure 79. BOD data varied from 70 to 155 mg/L, with an average of 100 mg/L. The average BOD removal efficiency was 60 percent. COD data varied from 240 to 743 mg/L, averaging 492 mg/L. The trend over the study period was increasing COD concentrations. COD concentrations in the primary pond were, on average, greater than concentrations measured in the influent. TSS data varied from 112 to 342 mg/L, averaging 250 mg/L.

Searchlight Primary BOD and COD Values

Figure 79. Searchlight Primary Pond BOD and COD Data.
Chemical Characteristics

Phosphorus

Data on inorganic and organic phosphorus was collected from this pond. Inorganic phosphorus concentrations, in the form of ortho- and poly-phosphates, averaged 9 and 2.5 mg/L, respectively. These data indicate that, on average, 4 mg/L of ortho-phosphate was consumed in the primary pond (when compared to influent concentrations), and the poly-phosphates concentration remained unchanged when compared to the primary pond. Organic phosphate concentration averaged 5.5 mg/L, an increase of 3 mg/L as compared to the influent organic phosphate concentration.

Nitrogen

Ammonia-N Removal

The Searchlight pond system consists of two facultative primary and two facultative secondary ponds in series. The secondary ponds are approximately twice the size of the primary ponds. The pond system HRT of 52.5 days provides sufficient time for adequate ammonia-N removal. In addition, high wind conditions are often present at this location. The high wind provides mixing and increases the wastewater interfacial surface area in contact with air, thus enhancing volatilization. Therefore, it is expected that this pond system will exhibit high ammonia-N removal efficiencies.

The primary pond geometry is square, rather than rectangular, suggesting that flow conditions will approach well mixed in this pond. The secondary pond geometry is rectangular, but shallower than the primary pond. Flow conditions should also approach
well-mixed in this pond. Dispersion numbers are anticipated to be high, given these geometries.

**Measurement Data**

Searchlight primary pond ammonia-N concentrations, temperatures, and pH are depicted in Figure 80. The pH values are shown on the right-hand axis. The ammonia-N concentrations follow the expected pattern of low values during the summer months and relatively high values during the winter months. The inverse temperature and pH relationships are also apparent. The pH values have been observed to exceed the equilibrium value for the \( \text{NH}_4^+ - \text{NH}_3 \) reaction during the summer months, thus increasing volatilization and further lowering ammonia-N concentrations.

![Searchlight Primary Ammonia-N VS Temperature and pH](image)

*Figure 80. Searchlight Primary Pond Measured Ammonia-N Concentrations.*
Searchlight Primary Pond Ammonia-N Removal Performance

Actual and predicted Ammonia-N removal performance of the Searchlight primary pond using the published models is illustrated in Figure 81. High removal efficiencies were achieved during the warm weather months (average of 92 percent), and moderate removal efficiencies were achieved during the cool weather months (average of 56 percent). The overall pond average was 84 percent.

![Graph showing searchlight primary pond performance](image)

Figure 81. Comparison of Actual Versus Predicted Ammonia-N Removal Performance for the Searchlight Primary Pond (Predictions 1 and 2).

The predictive models using equations 33 and 34 provided results that were consistently lower than the measured values. Reasonable agreement with actual values...
was achieved for 6 of the 13 data points using equation 33 only (Prediction 2). However, neither model is recommended for providing accurate ammonia-N removal predictions. The higher than expected performance may be attributed to the high wind conditions at this pond location. The higher winds provide aeration by increasing the interfacial surface area in contact with the air. This added aeration enhances volatilization, and therefore, ammonia removal.

Figure 82 shows predicted versus actual ammonia-N removal results using the three models developed by the author. Prediction 3 makes use of equations 41 through 43 in a given temperature range. Prediction 4 applies equation 46. and Prediction 5 illustrates use of equation 52. Prediction 5 provides results closest to measured values and is, therefore.

Figure 82. Comparison of Actual Versus Predicted Ammonia-N Removal Performance for the Searchlight Primary Pond (Predictions 3 through 5).
recommended for predicting ammonia-N removal from this pond.

*Calculation of Searchlight Primary Pond Ammonia-N Removal Mass Transfer Coefficients*

The square geometry and high wind conditions experienced at the Searchlight primary pond suggests well-mixed conditions. This hypothesis is explored in Figure 83. Dispersion numbers are read from the right-hand axis. A relatively wide range of overall $k$

![Searchlight Primary Ammonia-N Removal Coefficients](image)

*Figure 83. Calculated Searchlight Primary Pond Overall Mass Transfer Coefficients and Dispersion Numbers for Various Assumed Flow Conditions*

values was calculated for this pond. The $k_{M}$ and $k_{P}$ values are an order of magnitude greater than values calculated at the other three pond locations. This fact implies that a
greater rate of volatilization is occurring in this pond due primarily to the higher pH values and surface aeration caused by high winds. Note the high calculated dispersion numbers, ranging from 2.0 to 2.8, indicating close to well-mixed conditions.

The average removal efficiency determined for this pond was 84 percent. The overall k values and dispersion number calculated for this removal efficiency are as follows:

Searchlight primary well-mixed overall mass transfer coefficient, $k_M = 0.282 \text{ d}^{-1}$
Searchlight primary plug flow overall mass transfer coefficient, $k_P = 0.099 \text{ d}^{-1}$
Searchlight primary dispersion number, D (dimensionless) = 2.30
Searchlight primary dispersive overall mass transfer coefficient, $k_D = 0.219 \text{ d}^{-1}$

Given the high wind conditions experienced at this pond location, an overall ammonia-N removal mass transfer coefficient between the $k_D$ and $k_M$ values is suggested (e.g., $0.24 \text{ d}^{-1}$).

*Nitrates*

Measured nitrate concentration ranged from 0 to 0.2 mg/L, averaging 0.06 mg/L. These data indicate nitrification is not occurring, and this mechanism can be ruled out as contributing to ammonia-N removal in this pond.

**Searchlight Secondary Ponds**

**Pond Properties**

The secondary ponds at Searchlight consist of two ponds in parallel of similar physical dimensions. Samples were obtained from the westernmost pond since it was
assumed that acquired data would be characteristic of either pond. This pond contains the greatest algae density of any of the ponds analyzed in this study. This greater algae density can be explained by noting that the Searchlight pond system is exposed to weather conditions advantageous to algae growth, the wastewater residence time is longer in this pond system (approximately 34 days) providing ample time for algae to proliferate. Measured pond properties are illustrated in Figure 84. Temperature, pH, and DO concentrations are read from the right-hand axis.

Figure 84. Searchlight Secondary Pond Properties.
Measured alkalinity values ranged from 490 to 1153 mg/L. This variation is by far the greatest of any of the ponds evaluated. These high alkalinity values are attributed to high algae density and carbonate system interactions. Alkalinity is highest during the summer months when algae density is the greatest. It should also be noted that alkalinity values measured in the summer of 1997 are significantly higher than the alkalinity values measured during the summer of 1996, a difference of approximately 200 mg/L. This observation holds even though pH did not increase in response to the higher alkalinity values. Measured pH ranged from 8.4 to 10.6, a shift in [H⁺] by a factor of 158. This large pH variation can be attributed to algae activity, consuming carbon dioxide during photosynthesis. The highest pH values were recorded in the summer, and the lowest pH values were recorded in the winter, further evidence of the algae influence on pond properties. Temperatures ranged from 5 °C in the winter to 32 °C in the summer, a 27 degree temperature swing. Surface DO concentrations were also recorded over a wide range of values, varying from 0.4 to 21 mg/L.

A further understanding of these properties is obtained through examination of diurnal behavior. This behavior is illustrated in Figure 85. The data depicted in Figure 85 were gathered in September 1997. Alkalinity is seen to decrease during the early morning hours reaching a minimum value around 8:00 am and increased to a maximum during late afternoon when carbon dioxide consumption by algae is the greatest. Alkalinity concentration tails off once the sun goes down. Recorded pH values stayed within a relatively narrow band, varying from 9.3 to 9.8. This small response to large alkalinity fluctuations attests to the buffering capacity of the pond. Surface DO concentration is at
near zero levels during the morning hours increasing to supersaturated values when the sun comes up with the maximum value recorded, as expected, in late afternoon. A decrease in DO concentration was recorded around noon, however, indicating a localized change or a measurement error in the 8:00 am or noon measurement. Supersaturated DO values were recorded during the daylight hours, an expected result.

![Searchlight Secondary Pond Diurnal Behavior Characteristics](image)

**Figure 85. Searchlight Secondary Pond Diurnal Properties.**

The alkalinity/pH relationship is further explored through examination of Figure 86. In general, pH does not appear to mirror alkalinity. In some instances, an increase in pH results in a corresponding increase in alkalinity, but in other instances, an increase in pH results in a decrease in alkalinity. Use of equation 6 to predict alkalinity provides
reasonable agreement with measured values in 4 out of 13 data points. In all instances but one, equation 6 predicts alkalinity concentrations that are low by as much as 700 mg/L. This result is due to the fact that equation 6 does not account for carbonate system interactions or algal photosynthetic and respiratory processes. Equation 6 is, therefore, not recommended for estimating alkalinity in this pond.

![Searchlight Secondary Alkalinity vs pH](image)

*Figure 86. Searchlight Secondary Alkalinity and pH.*

Seasonal DO concentration profile data is presented in Figure 87. These profiles show constant DO concentration profiles during fall, winter, and spring months and a stratified profile during summer months. The fall profile is based on data collected during
October and is indicative of the depressed oxygen levels characteristic of morning hours as well as increased organic loading due to algae die off to a new equilibrium density that can be accommodated by cooler water temperatures and shorter daylight hours. The supersaturated winter conditions imply greater saturated concentration limits due to cooler water temperatures and an algae DO contribution. The explanation for the lower DO concentrations below saturated values during the spring is less clear. Warmer wastewater temperatures during the spring would lower the DO saturated concentration value, and morning data collection (around 7:30 am) would limit the DO contribution by algae. The combination of these two factors may explain the lower recorded spring values.

![Searchlight Secondary DO Profile](image)

*Figure 87. Searchlight Secondary Seasonal DO Concentration Profile.*
Organic Removal Characteristics

Recorded BOD, COD, and TSS data obtained from the Searchlight secondary pond are depicted in Figure 88. BOD data varied from 77 to 151 mg/L, with an average of 119 mg/L. BOD concentrations were, on average, greater than concentrations measured in the primary pond. Therefore, BOD removal is not occurring in this pond. This result may be attributed to the high algae density in this pond, a hypothesis supported by the correspondingly high TSS concentrations (see below). COD data varied from 117 to 1490 mg/L, averaging 943 mg/L. The trend over the study period was increasing COD concentrations. COD concentrations in the secondary pond were significantly higher than concentrations measured in the primary pond. TSS data varied from 252 to 576 mg/L.

Figure 88. Searchlight Secondary Pond BOD, COD, and TSS data.

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averaging 415 mg/L. The trend is towards increasing TSS concentrations, an expected result given the increasing pond COD concentration. This upward trend may be due to increasing algae density in this pond, a hypothesis further supported by the trend of increasing pond alkalinity. However, data on algae density is required before a definitive conclusion on the cause of these upward trends can be posited.

Chemical Characteristics

Phosphorus

Data on inorganic and organic phosphorus was collected from this pond. Inorganic phosphorus concentrations, in the form of ortho- and poly phosphates, averaged 1 and 13.5 mg/L, respectively. These data indicate that, on average, 8 mg/L of ortho-phosphate was consumed in the secondary pond (when compared to primary pond concentrations), and 11 mg/L of poly-phosphates were produced in the secondary pond when compared to the primary pond. Organic phosphate concentration averaged 7 mg/L, an increase of 1.5 mg/L as compared to the primary pond organic phosphate concentration.

Nitrogen

Ammonia-N Removal

Measurement Data

Ammonia-N concentrations, temperatures, and pH values measured in the Searchlight secondary pond are illustrated in Figure 89. The pH values are shown on the right-hand axis. Consistently low ammonia-N concentrations, exhibiting an inverse temperature relationship, were recorded in this pond. These low concentrations are
primarily due to the long pond HRT and high pH values forcing the \( \text{NH}_4^+ \)-\( \text{NH}_3 \) reaction to proceed to the gaseous (\( \text{NH}_3 \)) phase in accordance with equation 37.

![Searchlight Secondary Ammonia-N VS Temperature and pH](image)

*Figure 89. Searchlight Secondary Pond Measured Ammonia-N Concentrations.*

**Searchlight Secondary Pond Ammonia-N Removal Performance**

Actual and predicted ammonia-N removal efficiencies of the Searchlight secondary pond using the published models are displayed in Figure 90. High removal efficiencies were achieved, averaging 89 percent during warm weather months and 53 percent during cool weather months. The overall pond average was 77 percent from volatilization and nitrification processes, and 71 percent from volatilization alone.
Figure 90. Comparison of Actual Versus Predicted Ammonia-N Removal Performance for the Searchlight Secondary Pond (Predictions 1 and 2).

The predictive models provide a reasonable agreement with actual values, agreeing with 7 of 12 data points. Statistical correlation coefficients are 0.81 for both predictive models. The best fit to the data is for spring and summer values.

Figure 91 shows predicted versus actual ammonia-N removal results using the three models developed by the author. Prediction 3 makes use of equations 41 through 43 in a given temperature range, Prediction 4 applies equation 46, and Prediction 5 illustrates use of equation 52. Predictions 3 through 5 provide similar results with none of the models showing consistent accuracy over the entire study period. Predictions 2 and 5 provide the best results during the summer months while Prediction 4 provides the best results over the winter months.
Figure 91. Comparison of Actual Versus Predicted Ammonia-N Removal Performance for the Searchlight Secondary Pond (Predictions 3 through 5).

Calculation of Searchlight Secondary Pond Ammonia-N Removal Mass Transfer Coefficients

The Searchlight secondary pond is expected to experience similar flow conditions as the primary pond. The lesser depth in this pond, as compared to the primary, may increase the degree of dispersion. Calculated overall mass transfer coefficients and dispersion numbers are displayed in Figure 92. Overall mass transfer coefficients were not calculated for days when 100 percent removal was achieved since the endpoint (C_{out}) value was not available for the calculation. The calculated kD values indicate conditions that are close to well mixed. Dispersion numbers, shown on the right-hand axis, range
from 2.0 to 2.8, high values consistent with those calculated for the primary pond and indicative of a well-mixed pond.

![Searchlight Secondary Ammonia-N Removal Coefficients](image)

**Figure 92. Calculated Searchlight Secondary Pond Overall Mass Transfer Coefficients and Dispersion Numbers for Various Assumed Flow Conditions**

The Searchlight secondary pond averaged 71 percent ammonia-N removal efficiency through volatilization. Pond overall mass transfer coefficients and dispersion number, based on this average removal efficiency are as follows:

Searchlight secondary well-mixed overall mass transfer coefficient, $k_M = 0.072 \text{ d}^{-1}$

Searchlight secondary plug flow overall mass transfer coefficient, $k_P = 0.036 \text{ d}^{-1}$
Ammonia-N Removal Performance Comparison

The Searchlight pond system ammonia-N performance summary is shown in Figure 93. The Searchlight pond system exhibited high ammonia-N removal performance, averaging 94 percent. Warm weather performance averaged 99 percent, and cool weather performance averaged 82 percent. The long HRT and high pH values in this pond system were the primary factors governing this high performance.

Figure 93. Searchlight Pond System Ammonia-N Removal Summary.
The \( k \) values reported for the secondary pond are significantly lower than the values calculated for the primary pond (this observation holds even at the average removal efficiency achieved for the primary pond). This result implies that more efficient mass transfer is occurring in the primary pond as compared to the secondary pond. The explanation for this observation is unclear given that both ponds experience essentially well-mixed conditions. A potential explanation is that the high algae density in the secondary pond suppresses the interfacial surface area exposed to air, and thus results in a lower mass transfer coefficient. Additional data is required before a definitive explanation for these differing coefficient values can be posited.

**Nitrates**

Measured nitrate concentrations ranged from 0 to 7.4 mg/L, averaging 2.6 mg/L. These data indicate that significant nitrification does occur in this pond during the winter months, the time period when appreciable nitrate concentrations were recorded. Pond organic loading resulting from algae respiratory processes may be less during the winter, providing the high DO concentration/low organic loading conditions necessary for nitrification to occur. However, no data were collected to support this assertion. It is also conceivable that nitrification/denitrification processes could be occurring in this pond during the summer months. The high algae concentration during the day provides sufficient excess DO to support nitrification, and the anoxic conditions observed during the evening hours may be adequate to support denitrification. However, this possibility
is speculation not supported by hard data. Future sampling of the bacteria distribution in this pond is suggested to arrive at a definitive conclusion on this matter.
The data and information presented in this paper is intended to further the current state of knowledge concerning wastewater pond characteristics in arid climates. Pond operators of the systems analyzed in this study can use this information as a baseline against which to track trends and formulate strategies to improve pond performance. Perhaps the most significant result achieved from this work is the ammonia-N removal models that are derived from data obtained from each of the pond systems. In particular, the model indicated in this paper as Prediction 5 (equation 52) achieved useful results. Equation 52 was shown to be applicable to the Alamo, Searchlight, and Blue Diamond pond systems, with the closest agreement to measured values obtained for the Blue Diamond primary pond. This finding is encouraging given that equation 52 was derived from theoretical considerations. Validation of equation 52 through application to other arid wastewater pond system sites is recommended. Closing comments and recommendations concerning the pond systems analyzed in this study are provided below.
Alamo Pond System

The Alamo pond system was shown to provide adequate BOD removal. This finding is important given the primary purpose of these wastewater pond systems is BOD removal. Ammonia-N removal, on the other hand, is not as effective in this system. This finding could become a concern if limiting ammonia-N concentrations to groundwater becomes an important consideration. One way of achieving more effective ammonia-N removal is to add additional surface aeration to the primary pond. Surface aeration will increase the pond interfacial surface area that comes in contact with air, thus increasing the overall mass transfer coefficient and, therefore, enhancing volatilization. Another recommendation is to remove extraneous sources of ammonia by clearing out the vegetation in the secondary pond. Decreasing the flow velocity through the secondary pond should also enhance ammonia-N removal. A decreased velocity will push flow conditions towards plug flow, thus reducing the overall mass transfer coefficient required for efficient ammonia-N removal. This result can be achieved by increasing the depth in the secondary pond.

Beatty Pond System

The Beatty pond system was shown to provide fair BOD removal. Given the high flow rates and correspondingly short HRT experienced by this pond system, this result is encouraging. Improved performance would be obtained if the HRT could be increased. The short HRT also negatively impacts ammonia-N removal performance. Ammonia-N removal is poor in this pond. Any improvements in the HRT must be accomplished
within the existing pond footprint. One approach is to add a baffling system to the pond facultative region. The baffling system would channel the wastewater increasing the effective length the wastewater must travel and thus, increasing the HRT. This improvement would also push flow conditions closer to plug flow, resulting in a lower required overall mass transfer coefficient for efficient ammonia-N removal. Another way to improve both BOD and ammonia-N removal performance is to increase the well mixed zone in this pond. Additional surface aeration will enhance volatilization as well as increase the wastewater volume experiencing near saturated conditions. This improvement will enhance conditions for efficient aerobic processes and accommodate a greater organic loading.

Blue Diamond System

The Blue Diamond system achieves BOD removal from the primary pond. The secondary and overflow ponds add additional BOD sources to the wastewater. Therefore, approaches should be explored that focus on enhancing BOD removal in the secondary and overflow ponds. Adding aeration to the secondary pond may promote BOD removal in this pond. Another approach, in addition to adding aeration to the secondary pond, is to run the primary and secondary ponds in parallel, making the secondary pond another primary pond. The overflow pond could then be used as the secondary pond. Wastewater recycle approaches should also be explored.
High ammonia-N removal efficiencies are achieved by the Blue Diamond pond system, particularly if the overflow pond is in use. If ammonia-N removal becomes a concern, running all three ponds in series is recommended.

Searchlight Pond System

The Searchlight pond system, like the Blue Diamond pond system, accomplishes BOD removal in the primary pond. The secondary pond introduces an additional BOD source. This additional source is most likely due to algae. The high alkalinity, COD concentration, and TSS concentration in the secondary pond suggests that the additional source may be due to algae. Of particular concern is the trend of increasing alkalinities, COD concentrations, and TSS concentrations. Evaluation of the cause for this upward trend is recommended.

Overall ammonia-N removal efficiency in the Searchlight pond system is the highest of the four pond systems included in this study. This high efficiency is due to the long HRT and high pH conditions in this system.
APPENDIX

MEASUREMENT AND ANALYTICAL METHOD ERRORS

An inherent aspect of obtaining measurement and analytical data is the introduction of error. The methods used in this study introduced a nominal error in the reported values. The observed error associated with obtaining the pond parameters reported in this study are summarized below.

Field Alkalinity = ± 20 mg/L
Laboratory alkalinity = ± 5 mg/L
pH = ± 0.02 pH units
Ammonia-N = ± 1 mg/L
Nitrate-N = ± 0.05 mg/L
Phosphorus = ± 1 mg/L
Dissolved oxygen = ± 0.1 mg/L
Temperature = ± 0.5 °C
COD = ± 25 mg/L
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