DISSERTATION

# ENVIRONMENTAL IMPACT AND LIMNOLOGICAL RESPONSE OF A DEEP WASTEWATER TREATMENT POND

Submitted by

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WE HEREBY RECOMMEND THAT THE DISSERTATION PREPARED UNDER OUR SUPERVISION BY SYED ALI MOHSIN ENTITLED ENVIRONMENTAL IMPACT AND LIMNOLOGICAL RESPONSE OF A DEEP WASTEWATER TREATMENT POND BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY.

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# ABSTRACT OF DISSERTATION

# ENVIRONMENTAL IMPACT AND LIMNOLOGICAL RESPONSE OF A DEEP WASTEWATER TREATMENT POND

The annual and seasonal response of water quality variables to the annual hydrometeorological variation is evaluated at the 10 ft. deep wastewater treatment pond no. 3 of Boxelder Sanitation District. Data of six water quality variables are collected, in one foot depth increments from the surface to the bottom of the pond, to investigate their temporal and spatial response to the seasonal variations in maximum-monthly solar radiation, air temperature, and peak wind gusts. Discrete Fourier series of the nine hydrometeorological variables are generated to study the maximum response of the water quality variables to changes in hydrological phenomena at the surface of the pond.

The inter-relationships among the variables under investigation are identified by performing multiple linear regression. The results of the Fourier and regression analyses aid in the identification of the variables which significantly affect the performance of the deep wastewater treatment pond, at an elevation of 5000 ft., operating under the widely varying climatic conditions experienced in Northern Colorado.

Analysis of the depth profiles of water temperature, dissolved oxygen, conductivity, and salinity reveal that the 10 ft. deep wastewater treatment Pond No. 3

functions as a shallow lake. The limnological behavior of the deep wastewater treatment ponds is signified by the formation of thermoclines, negative heterogrades, positive heterogrades, clinogrades, and chemoclines. The temporal and spatial observations of the dissolved oxygen, oxidation reduction potential, conductivity, and pH point toward the occurrence of photosynthetic activity, algae blooms, summer anoxia, eutrophication, aerobic, anoxic and anaerobic zones at various depths-and-times in the pond. The strongly aerobic and anoxic periods are the respective indicators of nitrification and denitrification-and-phosphorus releases in the pond. Formation of the winter ice cover and the subsequent warmup lead to the episodes of densimetric mixings as witnessed by the corresponding dissolved oxygen depth profiles. The pH depth profiles under the ice cover indicate acidification of the pond waters. The frequency of the process-altering limnological phenomena classify the 10 ft. Pond No. 3 as discontinuous cold polymictic.

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# TABLE OF CONTENTS

CHAPTER 1

CHAPTER 2

CHAPTER 3

CHAPTER 4

CHAPTER 5

CHAPTER 6

CHAPTER 7

CHAPTER 8

## LIST OF FIGURES

# LIST OF TABLES

# CHAPTER 1

# INTRODUCTION

## 1.1 Background

The majority of the world population remains under-served in terms of the provision of adequate water supply and sanitation facilities. An examination of water resource availability, the demands for water resource allocation and the limited population served by adequate water supply and sanitation, accentuates the severity of the water crisis.

In 1999, the world population exceeded 6 billion and by the year 2050 the global population is projected to reach 9.3 billion. The increase in population has resulted in deterioration of the already scarce surface and ground-water quality. It is estimated that less than half of the third world population has access to safe drinking water which results in about 35,000 deaths each day (Singh and Helweg 1990). The first International Drinking Water Supply and Sanitation Decade, instituted from 1981 to 1990, fell short of its target of providing universal coverage both for safe drinking water and for adequate sanitation to the world population. The current water-supply and sanitation situation clearly demands that the limited supplies of fresh water be protected and recycled to the maximum extent possible in order to help avert an even more serious water crisis.

Due to the increased demand for fresh water, effective wastewater treatment and recycling are increasingly important for the optimal and efficient utilization of the precious fresh water reserves. Everyday, water resource engineers are faced with the challenge of allocating the dwindling fresh water reserves among municipal, agricultural, and industrial users. By practicing effective and efficient recycling of wastewater, the limited freshwater reserves can be used to maximum advantage. As an appropriate technology, deep wastewater stabilization ponds (more than 3m deep) offer an economical and effective means of treating and recycling wastewater -- especially for smaller sized communities. This is in sharp contrast to the high costs of mechanical treatment systems.

An economical and efficient system of deep wastewater treatment ponds, developed in California, performs satisfactorily under moderate climatic conditions (Oswald 1996). It is notable that Oswald has not investigated the depth profiles of the water quality variables in the deep wastewater treatment ponds operating in California. The wide-spread use of deep wastewater stabilization ponds can be promoted once ample and credible data about the spatial and temporal impact of the hydrometeorological variables on key water quality variables become available. At the present time there is a dearth of significant process-altering hydrometeorological and water-quality data-sets for deep wastewater treatment ponds which operate under widely varying climatic conditions, and also experience very harsh and prolonged winters. Investigation of the depth profiles in small temporal and spatial increments of the key process-altering variables would provide a better understanding of the dynamics of deep wastewater treatment ponds. Utilization of the meteorological data would enable the development of reliable and easy to formulate site-specific water quality predictors which can be used, after proper calibration, for wastewater treatment pond design and operation in the various physiographic and geographic settings of the world.

Reliable predictions can be made about the periodically recurring limnological phenomena, once the key process-altering variables are identified for deep wastewater treatment ponds. Predictors of key process-altering variables can be developed along the same lines as those used for forecasting limnological behavior in lakes (Wetzel 1975).

Water use and water treatment have been practiced at different levels over time by the various civilizations of the world. The next section briefly examines the evolution of water use and water treatment and also outlines its importance to various civilizations.

### 1.2 History of Water Treatment

In order to protect and recycle the limited supply of water, it is essential to understand the historic development of water use and water treatment. The search for proper ways to dispose-of wastewater has been going on for thousands of years, particularly since the time mankind started to live in large communities and cities. One of the oldest proofs of this practice can be found in the city of Moenjodaro, unearthed in the Indus plain of Pakistan. The city is estimated to be 5000 years old. Its streets have an elaborate network of brick-covered drains (Amin 1982). There are manholes down the streets and soak-pits as disposal bins. In the ruins of Nippur of Sumeria, dating back to 5000 B.C., there is evidence of central water supply and wastewater disposal facilities (Oswald 1996). Evidence of water purification and water treatment systems has also been found in the older civilizations of Egypt, Yemen, and India.

Ancient Rome is known for aqueducts which brought water to the city. In 98 A.D., Julius Frontinus was the water commissioner of Rome. He is one of the first persons known for regulating a water supply network effectively. In the 8th century A.D., Jabber Bin Hayyan, an Arab alchemist, wrote a detailed text on distillation. No significant progress was made after this, until the 18th century when the city of Venice, Italy, developed a water filtration process (Oswald 1996).

The pollution caused to natural water bodies by large amounts of untreated domestic and industrial wastes, being discharged into streams or rivers, was of such alarming magnitude that regulations were needed for the treatment of wastewater prior to its disposal. Hence, wastewater treatment plants were built, initially in Europe and later in North America. Europe took the lead in providing its population with treated waters and also to serve them with wastewater treatment plants when compared to U.S.A. (Singh and Helweg 1990). It has been noted over time that countries employing adequate and efficient sanitation systems, show a marked increase in human longevity (Garber 1992; Platt 1996). Thus, regions with safe drinking water and adequate sanitation have eventually made giant strides in the realms of economic and social development.

Wastewater treatment ponds offer an inexpensive and effective means of treating wastewater. In the U.S., wastewater treatment ponds have been in use for about 100 years. The first documented wastewater treatment pond in the U.S. was constructed in San Antonio, Texas in the year 1901. By 1983, more than 7000 wastewater treatment ponds were functioning in the U.S. (EPA 1983). Most of these wastewater treatment ponds were shallow in depth, less than 2m deep. Since 1983, due to the incentives provided by the EPA, thousands of additional wastewater treatment ponds have been built. The guidelines governing the design and operation of wastewater treatment ponds do not examine the entire depth profiles of the water quality variables, -- especially in deep wastewater treatment ponds. As a consequence, the occurrence and impact of the important process-altering limnological phenomena in deep wastewater treatment ponds are not clearly understood. Thus, highlighting the need for conducting further research in order to better understand the periodic behavior of deep wastewater treatment ponds, especially in colder climatic regions. The next section looks at the prevalent benefits and disagreements regarding the widespread use of deep wastewater treatment ponds.

### 1.3 Advantages and Disadvantages of Using Deep Wastewater Stabilization Ponds

Deep wastewater treatment ponds, especially facultative and primary ponds, are more economical to build, operate, and maintain than the conventional wastewater treatment plants. In fact, when compared with the various state of the art wastewater treatment technologies, waste stabilization pond systems stand out as the least expensive wastewater treatment technology. Properly designed wastewater treatment ponds offer an economical and practical solution to the problem of affordable wastewater treatment. Deep wastewater treatment ponds have the following advantages over mechanical wastewater treatment plants.

1. Provide effective wastewater treatment and can help significantly to alleviate the water shortage if widely used.
2. Simple to design and involve low costs of construction, operation, and maintenance.
3. Being an appropriate technology, deep wastewater treatment ponds.are easy to operate and maintain, especially due to their high buffer capacity.
4. Deep wastewater treatment ponds are ideally suited for: (a) small sized communities;

(b) low income neighborhoods because of their affordable and yet effective operation.

It is notable that most of the shallow wastewater treatment ponds designed according to EPA guidelines, are having compliance difficulties with the regulatory agencies. The performance of wastewater treatment ponds is found to vary considerably with seasonal changes. In Colorado, many shallow wastewater stabilization ponds, which are less than 2m deep, go out of compliance for a significant part of the year. The same can be said for shallow wastewater treatment ponds in other regions of the U.S. (Richard 1996).

Apart from being an efficient means of treating wastewater, deep wastewater treatment ponds require very little energy for their operation. If desired, the methane gas released from the pond can be captured and used to meet the low-energy requirements for the effective and efficient operation of deep wastewater treatment ponds. Sludge production in deep wastewater treatment ponds is either eliminated or greatly reduced due to sludge digestion by anaerobic bacteria.

The afore-mentioned situation has led many communities, especially small to medium sized, to opt for low cost, sustainable, and alternative wastewater treatment systems. On a larger scale, there still remains a tendency among professionals to shy away from low-cost wastewater treatment technologies due to one or a combination of the following factors, (NSPE 1995; Oswald 1996):

1. Non-credible data on cost, operation, and maintenance
2. Lack of rational design guidelines
3. Lack of awareness among professionals and communities about the effectiveness of low-cost sustainable wastewater treatment systems

4. Lack of appropriate regulations and standards
5. Percentage based service fees
6. Fear of litigation
7. Obsolete legal standards

Lack of credible data about the occurrence and the affects of the key process-altering variables on the satisfactory performance of deep wastewater treatment ponds have highlighted the need to gain better insight into the various physical, meteorological, hydrological, chemical, and biological processes which affect the performance of the various natural wastewater treatment systems -- especially in deep wastewater treatment ponds. Boxelder Sanitation District offers a novel opportunity to investigate the behavior of a deep wastewater treatment pond system operating under the cold climatic conditions experienced in the foothills of Northern Colorado. The next section examines the utility of deep wastewater treatment ponds as an efficient and cost effective wastewater treatment method while operating under widely varying climatic conditions.

### 1.4 Purpose

In this research, an attempt has been made to identify the significant process-altering phenomena and to study their impact, in temporal and spatial terms, on the key water quality variables by identifying the occurrences of the following periodically occurring limnological phenomena in the 10 feet (3.048 m) deep settling pond of Boxelder Sanitation District for a one year period, which is located 5 miles East of Fort Collins Colorado, at an elevation of about 5000 ft.

(1) thermal stratification; (2) oxyclines; (3) acidic and elevated pH values; (4) chemoclines;

(5) density stratifications; (6) production under the ice cover; (7) eutrophications; and (8) algae blooms.

Identification of the afore-mentioned significant hydrological and meteorological process-altering phenomena will aid in the reliable prediction of the following annually and seasonally recurring processes which are of vital significance for the smooth and effective operation of deep wastewater treatment ponds:

(1) clinogrades; (2) negative heterogrades; (3) positive heterogrades; (4) Summer anoxia; (5) thermal stratifications; (6) Fall destratifications; (7) algae blooms; (8) DO super saturations; (9) Winter acidifications; (10) density driven mixings; and (11) seasonal turn-overs.

## 1.5 Objectives

The main objective of this research is to identify the significant process-altering limnological phenomena which occur in the 10 ft. deep settling pond at Boxelder Sanitation District, while operating under widely varying climatic conditions. The specific objectives of this research are the following:

1. To identify the following independent hydrometeorological variables, which have significant impacts on the performance, – especially limnological behavior, of deep wastewater treatment ponds.

   a. Solar Radiation, R

   b. Air Temperature, Ta

   c. Peak Wind Gusts, Vw

2. To utilize a new technology, which has recently become available to measure and record the following dependent water quality variables, in small increments of depth and

time, on a computer for a period of one year:

  a. Water Temperature, Tw

  b. Dissolved Oxygen, DO

  c. pH

  d. Salinity, S

  e. Conductivity, C

  f. Oxidation Reduction Potential, ORP

3. To formulate mathematical models which generalize the temporal behavior of the key hydrometeorological variables by generating their discrete Fourier series and measure the maximum response of the water quality variables to the hydrological variation at the pond's surface.

4. To derive statistical relationships between the above-stated independent and dependent variables by performing multiple linear regression.

5. To demonstrate the utility of the variable and harmonic selection criteria used to formulate both the discrete Fourier series and the Multiple linear regression predictors.

6. To evaluate and interpret the impact of the meteorological variables on the water quality variables identified in Sections 1.5.1 and 1.5.2 with respect to time and depth.

7. To apply principles of comparative limnology to investigate the behavior of deep wastewater treatment ponds and shallow lakes under widely varying climatic conditions. Classify the limnological phenomena identified in the 10 ft. deep wastewater treatment Pond No. 3 based upon the nature and frequency of their occurrence by utilizing the lake classification scheme of Lewis, which is inclusive of shallow lakes.

8. To ascertain how the information obtained in this research can be used to design and

operate deep wastewater treatment ponds in the future. Especially, the development of reliable predictors of water temperature Tw can lead to the accurate forecasting of the various temperature dependent phenomena that occur in Pond No. 3. The same approach can be extended to formulate reliable predictors of other water quality variables.

This investigation begins with the classification of the significant process-altering variables according to the nature of their occurrence as: (1) periodic over the annual cycle; (2) periodic with seasonal cycles; and (3) and non periodic. Use of the Hydrolab H-20 multi-parameter water quality probe facilitates the collection of water quality data in an efficient and economical fashion.

### 1.6 Scope

The focus of this dissertation is to study the impacts of the hydrometeorological parameters on key water quality variables in a 10 ft. deep wastewater treatment lagoon, located at 5000 ft. elevation under the widely varying climatic conditions of Northern Colorado, for a one year period. This involves investigation of the temporal and spatial behavior of the water quality variables in small increments. The next section outlines the significant reasons for the investigation and identification of the annually and seasonally recurring limnological behavior in the 10 ft. deep wastewater treatment pond.

### 1.7 Rationale

Wastewater treatment ponds offer many obvious benefits over other expensive means of wastewater treatment. The reasons for the identification of the limnological behavior of deep wastewater treatment ponds include:

1. There is a paucity of water quality data for wastewater treatment ponds. Conventionally, only a point sample is taken for recording water quality data. Temporally and spatially

varying water quality data-sets about deep wastewater treatment ponds are very hard to locate. Water quality data from lakes, both in small temporal and spatial increments, are abundant and are readily available. The availability of limnological data has enabled scientists to better understand and also to accurately forecast the annual and seasonal behavior of lakes. The paucity of water quality data in general, and particularly in the case of deep wastewater treatment ponds, makes it difficult to fully explain the annual and seasonal limnological behavior of deep wastewater treatment ponds.

2. The EPA manual for designing municipal wastewater stabilization ponds limits its recommendations only to shallow ponds, up to 2m deep, and does not study the depth profiles of the water quality variables (EPA 1983).

3. Deep wastewater treatment ponds, having a depth of 3m or more, function more efficiently and economically than shallow ponds (Oswald 1994). When properly designed and adequately operated, sludge production is either eliminated or is greatly reduced. Removals of $BOD_5$ and TSS of up to 90% have been reported from deep primary wastewater treatment ponds.

4. The use of Hydrolab H-20 multi parameter water quality probe for obtaining more comprehensive data results in the simultaneous and continuous data collection of six water quality variables, as mentioned in Section 1.5.2. Investigations of the these water quality variables are of critical importance in order to obtain a thorough understanding of the year-round temporal and spatial limnological behavior of deep wastewater treatment ponds.

5. Identification of the annually and seasonally recurring process-altering phenomena can lead to the efficient and effective management of deep wastewater treatment ponds by employing techniques similar to those used for lake management.

6. Water quality data collection was carried out when Pond No. 3, for most of the year, was functioning in compliance with the effluent discharge standards set forth by The Colorado Department of Public Health and Environment. Pond No. 3 was completely in compliance except for part of the month of August, when the effluent TSS exceeded the limits prescribed in the effluent discharge permit.

### 1.8 Summary

The significance of the impact of the hydrometeorological variables on the temporal and spatial variation of water quality variables in deep wastewater treatment ponds is realized. This raises the need to identify and investigate the occurrences and the impacts of the annually and seasonally recurring limnological phenomena on the performance of deep wastewater treatment ponds. It is found that despite the widespread use of wastewater treatment ponds, there is a lack of credible pond performance and design criteria for the construction and satisfactory operation of deep wastewater treatment ponds in the various physiographic and hydrological settings in the world. This lack of credible pond performance data has led to pond failures in the various settings. As a consequence of seasonal pond failures, professionals tend to shy away from using wastewater treatment ponds as a low-cost wastewater treatment alternative. As wastewater treatment ponds remain exposed to the natural environment, the various process-altering limnological variables which significantly impact deep wastewater treatment pond performance need to be studied in more detail. Hence, the periods of: (1) thermal stratifications; (2) oxycline formations; (3) acidifications; (4) photsyntheses; (5) DO super saturations; (6) chemocline formations; (7) algae blooms; and (8) seasonal turn-overs need to be identified and accurately forecasted.

Once the key process-altering limnological phenomena are identified, then guide lines for the important wastewater treatment pond design-variables can be established for the various hydrological and physiographic settings world-wide. Thus, the stage is set for the formulation of an input-output model to study the year-round temporal variation of the water quality and meteorological variables in a deep wastewater treatment pond. The successful application of the input-output modeling technique approach can be extended in small increments to the various depths of Pond No. 3. The interrelationships among the variables under investigation may be established by performing multiple linear regression. The spatial variation of the water quality variables when investigated while keeping in view the temporal behavior and the interrelationships among the causal meteorological variables can help to identify the limnological behavior in Pond No. 3.

In the next chapter, the literature related to the problem under investigation is reviewed.

# CHAPTER 2

# REVIEW OF LITERATURE

This chapter examines the literature associated with the design, construction, operation, and maintenance of the various commonly used wastewater treatment systems. The meteorological and water quality variables which have significant impacts on the performance of deep wastewater treatment ponds are identified by considering the periodically occurring process-altering limnological phenomena, observed over the annual cycle, in lakes and reservoirs. The experiences of wastewater treatment ponds, located in the various geographic and physiographic regions, are also reviewed.

## 2.1 Affordability and Effectiveness of Wastewater Treatment Systems

Advanced Integrated Wastewater Pond Systems (AIWPS) are found to be much less expensive than conventional secondary wastewater treatment plants in U.S.A. The costs of conventional egg-shaped sludge digesters are many times more expensive than the same size deep wastewater treatment ponds (Oswald 1996). Cost comparisons are made for the following wastewater treatment systems (Batchelor et al. 1991):

1. Waste stabilization system,
2. Aerated lagoon system,
3. Oxidation ditch system,
4. Biological filter system

Waste stabilization ponds are found to be the least expensive and yet they provide an acceptable degree of wastewater treatment. The affordable and sustainable nature of deep wastewater treatment ponds leads to the identification of the following periodically occurring limnological phenomena.

## 2.2 Periodically Occurring Process-Altering Limnological Phenomena

The following process-altering limnological phenomena significantly impact the various biological and chemical reactions which occur in lakes and reservoirs over the annual or seasonal cycles.

### 2.2.1 Thermal Stratification

Lakes and reservoirs exhibit distinct thermoclines in the summer season due to increased solar radiation and very high air temperatures. The thermoclines formed in late spring might be unstable and may erode due to interruptions caused by wind action and precipitation. The immediate effect of solar heating is confined to the surface waters of the reservoir. Any temperatures changes at depths below 6 ft. result from circulation of water within the reservoir (Linsley and Franzini 1992). Over an annual cycle, the surface water of the reservoir is heated by solar radiation and warm air. In general over the annual cycle, the peak in surface water temperatures lags the crest in air temperatures, depending upon the surface area of the reservoir. The formation of a distinct thermocline, which is a zone of rapid Tw change, prevents circulation between the overlying lighter waters and the underlying denser waters. Beneath the thermocline the water temperature stays fairly constant (Linsley and Franzini 1992). The decomposition and settling of plankton in this relatively stagnant and deep zone, most probably, depletes the dissolved oxygen, which creates undesirable anaerobic conditions. The classical summer thermocline divides a lake into the following three depth-regions as shown in Figure 2.1 adapted from (Wetzel 1975):

1. Epilimnion 2. Metalimnion 3. Hypolimnion

The epilimnion has the highest water temperature and is characterized by an upper stratum of more or less uniformly circulating and fairly turbulent water. The metalimnion lies below the epilimnion and is defined as a stratum of steep thermal gradient with respect to depth. The hypolimnion is the relatively deepest, coldest, and almost an isothermal region of the thermally stratified water body. The summer thermocline gets eroded due to the establishment of the Fall cooling conditions and the entire depth profile once again becomes isothermal. The wide variations in the water temperature over the annual cycle, make it imperative to examine the impact of seasonality on the various dissolved oxygen depth profiles found in lakes and reservoirs.

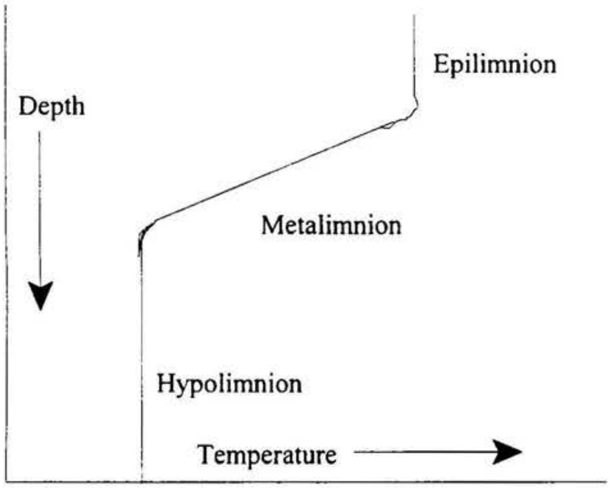

Fig 2.1 Reservoir Thermal Stratification Model (Wetzel 1975)

### 2.2.2 Oxyclines

The behavior of dissolved oxygen depth profiles is primarily in response to the annually and seasonally occurring meteorological and biochemical phenomena. Lakes and reservoirs exhibit the following typical formations of DO depth profiles (Wetzel 1975).

1. Negative Heterograde 2. Summer Anoxia 3. Positive Heterograde
4. Clinograde

The negative heterograde forms as a consequence of the summer warm-up. The DO concentrations at the water surface are mostly supersaturated due to algae blooms. A little distance below, the DO concentrations sharply reduce almost to zero, because the settling of degradable matter greatly slows down at the interface of the lighter-overlying and the heavier-underlying strata of water (Wetzel 1975).

In this nutrient rich zone, there seems to be a very high concentration of aquatic life forms, which results in increased respiration that causes DO depletion. Below the metalimnetic oxygen minimum, the DO profile once again follows the general trend of the initial DO gradient (Wetzel 1975). The increased DO values in the metalimnion gradually decrease almost to zero at the sludge water interface, see Figure 2.2.

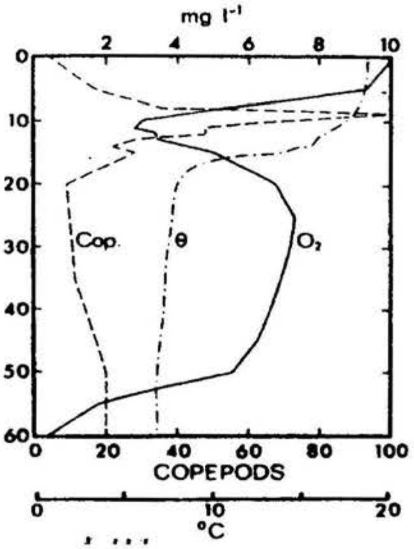

Figure 2.2 Negative Heterograde, Thermal Stratification and Copepod Microcrustaceans Adapted from (Wetzel 1975)

The continued decrease of the DO concentrations observed in the negative heterograde usually leads to the formation of a very strong clinograde. The water body starts to turn anoxic first in the hypolimnion and eventually the entire depth profile experiences summer anoxia. These anoxic conditions create an environment, in the entire water body, suitable for denitrification and phosphorus release (Goldman 1983). The anoxic conditions prevail until the resumption of circulation after the erosion of the summer thermocline.

The positive heterograde forms in lakes due to a decrease in the solubility of the epilimnion because of increasing summer temperatures (Wetzel 1975). Oxygen consumption in the hypolimnion results in the formation of a typical clinograde profile. The result is an absolute oxygen maximum in the metalimnion which could be above saturation. Algal photosynthesis is recognized as a contributor in the formation of positive heterograde due to increased oxygen production, see Figure 2.3 (Goldman 1983). As photosynthesis varies with the time of the day, positive heterogrades are very sensitive to the time at which readings are taken.

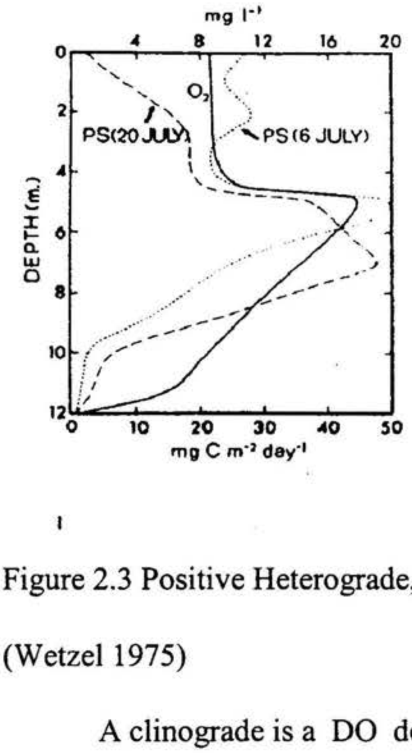

Figure 2.3 Positive Heterograde, and Phytoplanktonic Photosynthesis, Adapted from (Wetzel 1975)

A clinograde is a DO depth-profile formed due to the oxidative processes which occur in the hypolimnion (Goldman 1983). Intensity of the clinograde reflects the amount of organic matter reaching the hypolimnion from the productive zones of the lake. As a consequence, the DO concentration of the hypolimnion is reduced and stays under saturation (Wetzel 1975). Oxygen consumption is most intense at the sediment water interface due to: (1) bacterial respiration and (2) accumulation of undigested organic matter in the hypolimnion. While the upper layers of the water column such as the epilimnion and metalimnion experience renewal mechanisms of oxygen production mostly due to photosynthesis, see Figure 2.4 (Goldman 1983). The highly aerobic conditions experienced after the spring thaw facilitate for nitrification to occur in the lake. After the spring thaw, very intense photosynthesis takes place in the upper layers of the lake and is signified by elevated pH values and supersaturated DO readings. The wide variations in DO and pH values suggest to examine the fluctuations in the hydrogen ion availability in a water body.

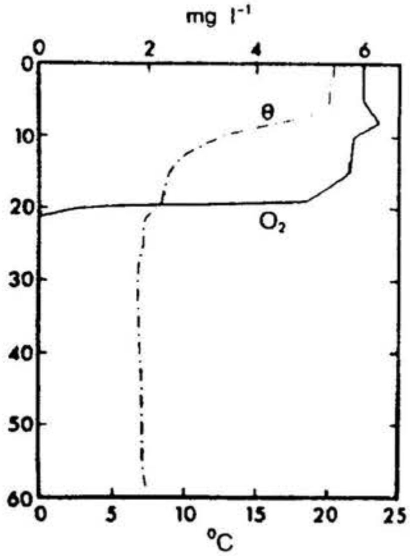

Figure 2.4 Clinograde and Thermal Stratification, Adapted from (Wetzel 1975)

### 2.2.3 Acidic and Elevated pH Values

The reaeration of DO to the surface waters of the lake is cut off after the formation of an ice sheet at the lake's surface. The cycling of carbon gets significantly affected in instances where the water is rich with dissolved carbon. The ice cover at the lake's surface causes the entrapment of carbon dioxide gas, mostly released at the sludge water interface, in the lake.

The solubility of carbon dioxide gas in water increases with a decrease in water temperature. Under conditions of high solubility, the carbon dioxide gas reacts with water to form carbonic acid. Formation of carbonic acid leads to a drop in pH values and acidic conditions prevail in the lake. Lake acidification reduces the availability of dissolved inorganic carbon and photosynthesis by periphyton (Leavitt et. al 1999). The cycling of inorganic carbon in water is shown in Figure 2.5.

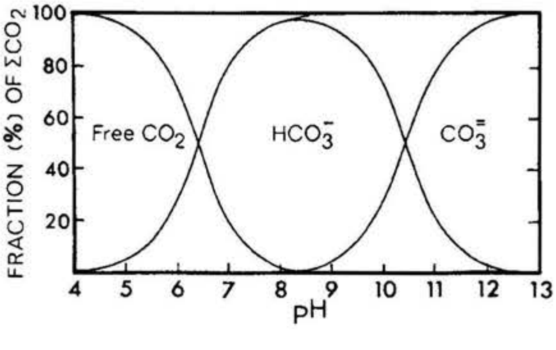

Figure 2.5 Relation Between pH and species of inorganic carbon (Wetzel 1975)

The dissolved organic carbon (DOC) in water also declines in acidified lakes (Williamson et al. 1999). Dissolved organic carbon is the primary factor which regulates the penetration of ultra violet radiation (UVR) in lakes (Leavitt et al. 1999). A decrease in DOC results in increased penetration of UVR. As a consequence of the increased UVR penetration, the predators and prey communities in a lake get altered. Increased UVR penetration also facilitates the increased habitable area for deep water phytoplankton and periphyton in an acidified lake (Burkhardt et al. 1999). Changes in DOC also alter the nutrient and metal availability in an acidified lake (Leavitt et al. 1999). Episodes of algae blooms result in increased photosynthetic and heterotrophic activities and are accompanied first by an increase and then a decrease in the pH and DO readings at and near the surface of a lake (Schoemann et al. 1998). These significant changes in the pH of a water column, found especially in acidified lakes, point toward the study of the seasonal behavior of chemoclines of salinity and conductivity in lakes, which provide a measure about the concentrations of solids in a water column.

### 2.2.4 Chemoclines

Conductivity and salinity readings at the surface of a lake show periodic fluctuations. Annual time series of salinity and conductivity are analyzed to identify the episodes of spring algae blooms, spring photosyntheses, spring chlorophyll-a maxima, Mn and Fe cycling (Schoemann et al. 1998). The concentrations of salinity and conductivity serve as direct indicators of the total dissolved solids in water (Metcalf and Eddy 1991). Chemoclines of salinity and conductivity occur along with the formation of distinct thermoclines in lakes (Leclerc and Texier 1999; Bronk and Ward 1999). Thus, giving an indication about the settlement rates of dissolved solids (Lewis 1983). The uneven distribution of solids in a water column lead to the examination of the role played by density in the seasonal circulations in the bodies of water.

### 2.2.5 Density Stratification

Reservoirs and shallow lakes exhibit circulations in the Spring, Fall, and Winter seasons. The frozen ice cover on a lake's surface melts due to the Spring thaw caused by the accompanying warm-up. If the water temperature in winter goes below 4°C, then the surface waters warm-up to 4° C first, and cause the denser and oxygen-rich overlying surface water to plunge to the lake bottom (Linsley and Franzini 1992). During the peak of the Summer season the lake becomes stably stratified with the formation of a distinct thermocline. The cooling effect of the Fall season results in heat loss from the surface waters of the lake (Nurnberg 1999). With the establishment of the isothermal conditions, the entire lake becomes unstable, and the wind action at the surface can cause the surface water to circulate to the bottom of the lake (USGS 1978). The cooling phenomena of lake waters continue into the Winter season. In regions which experience extremely cold winters, the surface waters are likely to approach the 4°C mark first and result in another episode of density driven circulation. The seasonal variations of the key physiochemical variables in lakes warrant an investigation into the accompanying temporal and spatial behavior of the key biochemical variables in a lake.

### 2.2.6 Production in a Permanently Ice-covered Lake Fryxell

The production of phytoplankton in Lake Fryxell, located 77° 35' S, 163° 15' E at an altitude of 22m, occurs under the ice cover on November 20 1979 (Vincent, W.F. 1981). Vertical profiles of: (1) water temperature, (2) dissolved oxygen, (3) conductivity, and (4) chlorophyll-a are recorded up to a depth of 19 meters. Water temperature is found to vary from 0° C below the ice cap to a maximum of 3.6° C midway between the water column. Dissolved oxygen levels are above saturation at the surface waters of the lake. Dissolved oxygen concentrations are maximum in the region 6.5 meters to 8.0 meters and decline abruptly below 8.5 meters to zero at a depth of 9.5 meters. Chlorophyll-a concentrations are 3-4 mg/m$^3$ (typically mesotropic) near the surface of Lake Fryxell but rise sharply to a defined maximum of 27 mg/m$^3$ at 9.0m depth.

The lake is further stabilized by conductivity and salinity gradients, which increase toward its bottom because there is no direct wind induced turbulence. As a consequence, its phytoplankton are distributed down the pronounced and relatively stable gradients of light, temperature and nutrient regime. Four regions with distinct algal distribution are identified down the water column with respect to algal contents. The first zone of algal concentration ranges from 4.5m to 6.5m. The next depth-region of algal concentration exists from 6.5m to 8.5m. The third profile of algal concentration is observed from a depth of 8.5m to 9.5m. The fourth and the deepest zone, ranging from 9.5m to 19.0m is found to be devoid of algae. At the bottom of Lake Fryxell's euphotic zone, nutrient availability may be more typical of enriched waters. The gradients in nitrogen and phosphorus concentrations from 9.0m to 10.0m are extreme, and therefore molecular and turbulent diffusion may be important in recharging the lower euphotic zone with nutrients over winter. Bacterial biomass is maximal for the oxygenated water column in this region and consequently nutrient resupply by bacterial mineralization may have been highest here. Photosynthetic rates are highest in the 8.5m to 9.5m stratum. Dissolved oxygen levels are very low and indicate either extreme activity by heterotrophs or very high respiration by autotrophs. The existence of biological and chemical gradients, observed under the extreme cold climatic conditions of Lake Fryxell, warrant a review of the eutrophication phenomena in lakes.

### 2.2.7 Eutrophication

Eutrophication results from the enrichment of a water body with nutrients, which in the presence of sunlight stimulate the growth of algae and other aquatic plants (Linsley and Franzini 1992). The increased nutrient load provoke an intense cycle of production, consumption, and decay. In shallow waters, the stimulated development of epiphytic and planktonic algae reduce light availability for rooted plants (Van Straten 1986). Large growth of these plants show undesirable effects, although smaller quantities of these plants may be helpful for aquatic life.

In wastewaters, the compounds of nitrogen and phosphorus control the extent of algae growth especially when the influent is composed of agricultural and industrial runoffs. The recycling of nitrogen, phosphorus, carbon and heavy metals such as mercury, copper, zinc, iron, and manganese are identified with the annually and seasonally occurring limnological phenomena (Burkhardt et al. 1999; Herrin et al. 1998; Nurnberg 1999).

The factors which regulate eutrophication have been studied extensively in dimictic soft-water, temperate lakes but remain poorly understood in polymictic, hard-water, prairie lakes of the Northern Great Plains of Canada which lie in large fertile agricultural catchments (Hall et al. 1999).

Food web manipulation has been successfully applied to control eutrophication by altering the nutrient input in three lakes in Wisconsin U.S.A. These lakes experience the formation of a strong thermocline along with anoxia in the hypolimnetic waters and increased concentrations of P in the lake waters during the summer season (Carpenter, S. R. 1999). Algal bloom, which is another important periodically recurring limnological phenomenon, is described in the next section.

### 2.2.8 Algae Blooms

Intense algae blooms observed during the Spring season control the concentrations of iron and manganese in the shallow coastal waters of the North Sea (Schoemann et al. 1998). The increased photosynthetic and phytoplanktonic activity is accompanied with increased DO and pH readings in the surface waters. The cooling phenomena occurring in early Fall, after the destratification of the Summer thermocline under quiescent climatic conditions, most likely provides an environment conducive for the formation of algae blooms at the water surface. Recognition of the various periodically-occurring process-altering limnological phenomena lead to the review of a lake classification scheme, which also incorporates shallow lakes.

### 2.3 Modified Lake Classification Scheme

A revised scheme of classifying lakes incorporates shallow lakes by identifying the following inadequacies in the most commonly used lake classification scheme forwarded by Hutchinson (Lewis 1983):

1. Exclusion of shallow lakes from the classification scheme
2. Unsatisfactory relationship between meromixis and the six basic lake types
3. Excessively complex treatment of tropical lakes
4. Difficulties in the classification of cold lakes resulting from 4° C temperature boundary on cold meromixis

The revised lake classification forwarded by Lewis includes the following features:

1. Based on seasonal mixing, the meromixis/ holomixis dichotomy is combined with the six lake types based on seasonal mixing in such a way that the two systems are hierarchical and universal; meromictic lakes are assigned to a seasonal type on the basis of the behavior of upper water column
2. Oligomixis is eliminated from the revised lake classification scheme
3. Shallow lakes are brought under the classification by definition of four polymictic

Table 2.1 Revised Lake Classification Scheme (Lewis 1983)

| Lake Type | Lake Description |
|---|---|
| Amictic | Always ice covered |
| Cold Monomictic | Ice covered most of the year, ice free during warm season but does warm above 4° C. |
| Continuous Cold Polymictic | Ice covered for part of the year, ice free above 4° C and stratifies during warm season at most on a daily basis during warm season. |
| Discontinuous Cold Polymictic | Ice covered part of the year, ice free above 4° C and stratifies during warm season for periods of several days to weeks but with irregular interruption by mixing. |
| Dimictic | Ice covered part of the year and stably stratified part of the year with mixing once each year. |
| Warm Monomictic | No seasonal ice cover, stably stratified part of the year, and mixing once each year. |
| Discontinuous Warm Polymictic | No seasonal ice cover, stratifying for days or weeks at a time, but mixing more than once a year |
| Continuous Warm Polymictic | No seasonal ice cover, stratifying at most for a few hours at a time. |

types based on ice cover and frequency of mixing

4. The eight mixing types of the revised lake classification scheme depend on latitude, elevation, and depth estimated from existing data

The revised lake classification by Lewis is summarized in Table 2.1. For regions where deep lakes are cold monomictic, shallow lakes are either continuous or discontinuous polymictic. The heat absorbing capacity of a deep lake is found to be much higher than that of a shallow lake before Tw exceeds the 4° C mark. Where as in a shallow lake, much less water needs to be heated before Tw in the lake exceeds the 4° C mark. This heat absorbing phenomenon places shallow lakes in one of the polymictic categories.

Thus, middle to high latitudes are likely to be rich in cold polymictic lakes in those regions where deep lakes are classified as dimictic. Below 40° adjusted latitude, deep lakes will be warm monomictic with one annual period of deep mixing. The shallowest lakes between 0° and 40° adjusted latitude are most likely to be continuous warm polymictic. While discontinuous warm polymictic lakes are speculated to exist mostly in the middle latitudes ranging from 20° to 40°. In discontinuous warm polymictic lakes, there is very little density difference between the surface and lower layers of the water column. This increases the likelihood of change in mixing depth due to strong winds during the season of stratification. Chemoclines representing concentrations of dissolved solids are formed during periods of stratification. Consideration of the shallow-lake classification scheme warrants a review of the various process-altering factors which are known to significantly affect wastewater treatment.

## 2.4 Factors Affecting Wastewater Treatment

The factors which significantly impact wastewater treatment pond performance, either favorably or adversely, have been grouped as (WHO EMRO #10 1987; EPA 1983; Pescod, M. B.; and Arar, A. 1988):

1. Natural 2. Physical 3. Chemical

The natural factors are essentially meteorological events uncontrollable by humans. Natural factors affecting pond performance include the following phenomena:

1. Wind action 2. Temperature 3. Solar radiation
4. Evaporation 5. Seepage 6. Rainfall

The following physical factors have more pronounced affect than any of the above on pond operation and include:

1. Surface area 2. Water depth 3. Short-circuiting

The following chemical factors significantly affect the performance of wastewater treatment ponds:

1. pH 2. Salinity 3. Dissolved Oxygen
4. Oxidation Reduction Potential 5. Conductivity

The next sections describes those variables which have been identified to significantly impact the periodic behavior of the process-altering limnological phenomena observed in lakes.

### 2.4.1 Water Temperature, Tw

Water temperature is identified as the most important parameter affecting treatment in wastewater treatment ponds. A technique to compute the plug flow ratio coefficient and the reaction rate constant is also presented (Zhao and Zhiang 1992). Tw is noted to be the principal indicator of heat transfers occurring into and from wastewater treatment ponds. Water temperature as a function of depth can be indicative of limnological behavior in deep water bodies which may include deep wastewater treatment ponds (APHA 1992). Tw directly affects the: (1) chemical and biological reactions; (2) reaction rates; (3) aquatic life; (4) bacterial mortality rates; and (5) oxygen solubility in water. The values of Tw depend heavily on climatic factors such as R and Ta.

### 2.4.2 Dissolved Oxygen, DO

Dissolved oxygen is required for the respiration of aerobic bacteria and also by all other aerobic life forms. The DO concentrations directly influence the rate of biological reactions which occur in a water body (APHA 1992). The temporal and spatial DO profiles provide valuable information about the state of the pond, such as: aerobic, anaerobic, and facultative. The quantity of DO in water is directly influenced by: (1) water temperature; (2) partial pressure of the gas; (3) solubility of the gas; (4) salinity and suspended solids in water; (5) biochemical reactions occurring in the water body; (6) ORP; and (7) photosynthesis (APHA 1992).

Low dissolved oxygen values in wastewater indicate that the liquid wastes require treatment before being discharged into a receiving body. Oxygen uptake rates could be determined once the DO concentrations are known, which in turn can provide a measure of biological activity. DO levels lower than 4 mg/l to 5 mg/l are noted to lead to adverse effects on aquatic life (Wetzel 1975).

### 2.4.3 Inverse Log of Hydrogen Ion Concentration, pH

pH, is the negative logarithm, to the base 10, of hydrogen ion concentration (Metcalf and Eddy 1991). The pH significantly affects the survival and growth of bacteria, algae, and fungi. The optimum pH for bacterial growth ranges from 6.5 to 7.5. Most bacteria cannot tolerate pH levels above 9.5 or below 4.0. High pH conditions could also occur in wastewater treatment ponds which experience photosynthesis under low alkalinity (Wetzel 1975). The pH significantly affects the nutrient regime in a wastewater treatment pond by influencing the nitrification and denitrification processes. pH also strongly influences the removal of phosphorus. Low pH values lead to large releases of carbon dioxide gas in water bodies which are rich in carbon (Wetzel 1975).

### 2.4.4 Salinity, S

Salinity is a concentration of solids on a mass per mass basis and is expressed either as parts per thousand or grams of dissolved solids per kg of seawater (Maidment 1993). Salinity is another measure of dissolved solids, used primarily in studies of irrigation waters and in oceanographic investigations. Salinity is measured from conductivity measurements which are temperature dependent. Information of salinity can be used to calibrate predictors of total dissolved solids in a water column.

### 2.4.5 Specific Conductivity, C

Specific conductivity of water is its ability to conduct electric current and is dependent on total ionic solids. Specific conductivity is defined as a reciprocal of the electrical resistance of a 1 $cm^3$ of a material at 25° C (Maidment 1993). It is customary to report specific conductivity in millisiemens per m, $mS\ m^{-1}$. Specific conductivity approximately doubles in a 0.01 molar solution of KCl from 0° C to 35° C, indicating its temperature dependence.

### 2.4.6 Oxidation Reduction Potential, ORP

Oxidation reduction potential, also known as redox potential, is equivalent to the free energy change per mole of electrons associated with a given reduction (Wetzel

1975). Free electrons and protons are not found in aqueous solutions. Proton activity is defined by the pH of the solution. Electron activity pE is defined by the negative logarithm, to the base 10, of the $[OH]^-$ ion concentration and is denoted as: $pE = -\log[e^-]$. The pE is large and positive in strongly oxidizing solutions. Likewise, pH is high in strongly alkaline solution. Thus, both pE and pH are intensity factors of free energy levels. Positive redox values are indicative of aerobic conditions in the water body. Negative redox potential readings indicate the existence of either anaerobic or anoxic conditions. The state of the wastewater treatment pond can be ascertained from its ORP profiles. The ORP values are also indicative of the nitrification and denitrification processes occurring in the pond. The ORP values also depend upon the DO and pH readings in the water body.

The performance of anaerobic lagoons as sewage treatment lagoons in Melbourne Australia, South Africa, and India are investigated and it is found that the bacteria in an anaerobic pond, responsible for breakdown of organics, operate in the absence of both free oxygen and oxygen contained in inorganic compounds (Pescod, M. B. 1995). The ORP values are found to be helpful in the identification of the reaction types occurring in the pond. The ORP values at which the most sensitive organisms, the methanogenic bacteria, grow most favorably are found to be in the range of approximately -490 mv to -570 mv, although anaerobic conditions are known to exist at -200 mv. In an anoxic system, free oxygen is absent but oxygen is available to some anaerobic bacteria, such as the denitrifiers and sulphate-reducers, in the form of nitrates and sulfates. An ORP range of -100 mv to -300 mv is identified for the existence of anoxic conditions. It is further explained that even an ORP of -100 mv is sufficient for the existence of sulphate-reducing bacteria. The organic loading level usually accepted as the minimum required to achieve totally anaerobic conditions in a pond is 100 g $BOD_5$ /$m^3$.d. Facultative conditions depend on the ambient water temperature but, in volumetric organic loading terms, the maximum loading is not normally in excess of 15 g $BOD_5$ /$m^3$.d. Therefore, the range of anoxic pond loading might be expected to be between 15 and 100 g $BOD_5$ /$m^3$.d.

The affect of ORP on the performance of 32 constructed wetlands operated to treat wastewater by the Tennessee Valley Authority is investigated and the ORP and DO values in and around the roots of the plants are found to greatly affect the biochemical reactions occurring in the cell by influencing aluminum and heavy metal removals (Hauck, R. D. 1992).

Forty seven percent and 62% reductions in the respective consumption of chlorine and sulfur dioxide, in the chlorination and dechlorination processes, are reported at a wastewater treatment plant in California U.S.A. which utilizes ORP as a coliform inactivation parameter (Kim and Hensley 1997). Laboratory scale studies show that ORP plays a critical role in the enhanced nutrient removal in controlled-aeration extended aeration treatment system (Lo, C. K. et al. 1994). The ORP values have been found to identify nitrification, denitrification, and phosphorus removal processes in lakes, reservoirs, and ponds (Lie et al. 1994; Schon et al. 1993).

### 2.4.7 Solar Radiation, R

Solar radiation represents the net radiative fluxes arriving at the earth's surface.

Radiation from the hot sun is referred to as short wave radiation while radiation from the cooler earth is called long wave radiation (Maidment 1993). The amount of radiation received at the earth's surface varies with the latitude, day, season of the year, and the shape of earth. The cyclic variation in solar radiation leads to seasonal warming and cooling cycles. Wastewater treatment ponds are directly influenced by climatic variations occurring over the annual hydrological cycle.

### 2.4.8 Air Temperature, Ta

Air temperature is an indicator of the degree of warmth of the atmosphere surrounding the earth. Air temperatures are altered due to the periodic patterns of the annual hydrological cycle in the region (Maidment 1993). Solar radiation is the primary cause of change in air temperature. Air temperature plays an important role in heat transfers occurring at the pond's surface.

### 2.4.9 Peak Wind Gusts, Vw

Wind action should be taken into consideration at the design stage of the stabilization pond, by orienting the long pond direction, or the long diagonal, in the direction of the prevailing wind (WHO EMRO #10 1987). If wind directions alter with seasonal changes then the summer wind direction should be chosen. Wind fetch help to induce mixing in the pond which is very helpful for aerobic and facultative ponds by providing dissolved oxygen to the surface waters. Strong winds can cause erosion of the embankment slopes if proper slope protection like armor, grass or linings are not provided.

### 2.5 Experiences of Wastewater Treatment Ponds

Wastewater treatment ponds have been in use all over the world for a significant period of time. The experiences of operating wastewater treatment ponds, lakes and reservoirs are stated in the sections which follow.

#### 2.5.1 Wastewater Stabilization Ponds in U.S.A.

Several facultative waste stabilization pond design equations are evaluated to outline pond performance from actual field data (Finney and Middlebrooks 1980). Evaluation of the design equations indicate them to be inadequate for wide range applications. Instead, the design equations are found to be site specific. The EPA manual on waste stabilization pond design is authored by collecting twelve month performance data from the following four shallow lagoons, 1.2 m to 2 m deep (EPA 1983):

1. Peterborough, NH 2. Kilmichael, MS 3. Eudora, KS 4. Corinne, UT

The data collection includes four separate 30 days of consecutive sampling periods once in the season. For the remainder of months, a minimum of 7 days are sampled representing 24 hour composites. The parameters monitored include: (1) influent and effluent areal BOD loading rate; (2) influent COD; (3) hydraulic detention time; (4) flow rate; (5) effluent suspended solids; (6) influent and effluent fecal coliform concentrations; (7) wind speed; (8) solar radiation; (9) relative humidity; (10) pond temperature; and (11) air temperature.

#### 2.5.2 Seasonal Behavior of Flaming Gorge Reservoir

Flaming Gorge Reservoir located on the Green river in northeastern Utah and southwestern Wyoming with a maximum storage of 4674 $hm^3$ extends 145 km upstream from the dam and has the deepest point at 133 meters below maximum pool altitude. It is observed for Flaming Gorge reservoir that circulation is mostly caused by insolation, inflow-outflow relationships and by wind induced disturbances during the period ranging from 1970 to 1975 (USGS 1978). The reservoir, in 1970, exhibits the formation of a hypolimnion. The existence of summer stratification is noted when dissolved oxygen in the bottom of the reservoir goes to zero. The depletion of dissolved oxygen results in a metalimnetic oxygen minimum in the reservoir. A massive algal bloom, observed in September 1975, disappeared by October 1975. The nutrient loading is noted to be insufficient to maintain a rate of algal production which would be disastrous to the reservoir ecosystem.

### 2.5.3 Hydrothermal Processes in Lake Calhoun, Minnesota

A dynamic simulation model (MINLAKE) is used to predict the year-round effects of both summer and winter on lake water temperature by taking into account the unsteady hydrothermal processes at Lake Calhoun in Minnesota (Gu, R. and H. G. Stefan 1995). The two special modules of the model include:

(1) Module for winter ice-cover simulation

(2) Module for heat exchange with lake sediments

The thermal state of the lake is found with a high degree of accuracy by applying the law of conversion of energy in the form of a one-dimensional heat transfer equation.

### 2.5.4 Wastewater Treatment Ponds in Alberta, Canada

Guidelines to plan and design wastewater treatment lagoons for the cold regions of Canada, i.e. for the northern and western provinces, are established (G. W. Heinke

1991). Use of short-term detention lagoons followed by long term detention lagoons is advocated to allow for longer storage of influent in order to accomplish an acceptable degree of wastewater treatment.

### 2.5.5 Wastewater Treatment Lagoons North of 45th Parallel

The performance of a sewage lagoon system located in Yellowknife, NWT Canada, is evaluated over a period of one year. It is noted that during the winter months, when there is an ice cover, wastewater treatment is almost minimal (Soniassy and Lemmon 1986). While during the summer months, June to September, a satisfactory degree of wastewater treatment is obtained.

### 2.5.6 Wastewater Treatment Lagoons of Lima, Peru

The water quality parameters of oxidation lagoons of San Juan De Miraflores in Lima, Peru are investigated (Bartone 1983). The lagoons range in depth from 1.3 meters to 1.5 meters and receive an average sewage flow of 360 liters per second.

Data of the following variables are collected for six months: (1) dissolved oxygen; (2) temperature; (3) alkalinity; and (4) pH.

Other process affecting parameters monitored at the ponds include: (1) daily inlet and outlet flows; (2) monthly infiltration studies; (3) daily temperature measurements of raw sewage and all pond effluents; (4) daily Secchi disk measurements; (5) daily meteorologic information of wind speed and direction; (6) ambient temperature; (7) solar radiation; (8) evaporation; and (9) hours of sunshine.

The following variables are measured in the laboratory from grab samples: (1) chemical oxygen demand COD; (2) $BOD_5$; (3) suspended solids and residue (total, volatile and fixed); (4) alkalinity; (5) hardness; (6) calcium; (7) pH; (8) potassium; (9) sodium; (10) conductivity; (11) chlorides; (12) sulfates; (13) ammonia nitrogen; (14) organic nitrogen; (15) nitrate; (16) nitrate nitrogen; (17) total phosphate; and (18) orthophosphate.

Microbiologic determinations include: (1) identification and counting of algae; (2) identification and counting of pathogenic protozoa and helminths; (3) enumeration of total and fecal coliforms by most probable number (MPN) techniques; and (4) isolation of salmonella with complete biochemical and serotype identification.

Based on the prevailing average air temperatures, regression expressions are derived to predict the average and maximum water temperatures at the pond's surface. Water temperature based expressions for BOD removal and bacteria die off rates are also developed. Results of the research indicate the importance of accurate estimation of water temperatures for the reliable prediction of the year-round pond performance.

Effective removal of pathogens and parasites from the wastewater is reported, both for the summer months and the winter months, as the treated wastewater is about to leave the polishing lagoons. The epidemiologic data from Lima indicate that acute diarrheal diseases and parasite infections are prevalent in the population served by the wastewaters from the lagoons of San Juan De Miraflores. The prevalence of water-borne diseases calls for more thorough removal of infectious bacterial and viral organisms.

The experiences with lakes, reservoirs, and ponds warrant for an investigation into the techniques of mathematical and statistical modeling in order to develop reliable predictors of the variables of interest, as outlined in the next section.

## 2.6 Mathematical and Statistical Modeling Techniques

The following techniques of temporal modeling for numerous physical variables have found wide application in the various branches of science and engineering.

### 2.6.1 Fourier Transform

J.B.J. Fourier in the early 19th century postulated that it is possible to approximate a periodic function by a combination of trigonometric functions (Bloomfield 1973). A combination of sine and cosine functions, known as Fourier series, is used to represent a periodic function. A Fourier series can appear either in the trigonometric or in the exponential form (Ingle and Proakis 1997; Chatfield, C. 1996).

The Fourier transform DFT is used to model discrete data sets. The continuous Fourier transforms give a continuous frequency spectrum while the frequency spectra of the Fourier series is discrete. In real time, data collection is of finite length and sampling is carried out at discrete time interval (Lynn and Fuerst 1998). Thus, it is easy and practical to transform the discrete data set into a discrete frequency spectrum. The discrete Fourier transform comes in handy for providing such transformations. The discrete Fourier Transform is given as:

$$X(i) = \frac{1}{N} \Sigma_{k=0}^{N-1} x(k) \exp(\frac{-2\pi jik}{N}) \qquad (i = 0,1,....,N-1) \qquad (2.1)$$

In trigonometric form, discrete Fourier transform is given as:

$$x_t = \frac{a_o}{N} + \Sigma_{j=1}^{(N/2)-1} [a_j \cos(\frac{2\pi jt}{N}) + b_j \sin(\frac{2\pi jt)}{N})] + a_{N/2} \cos \pi t \qquad (2.2)$$
$$where\ t = 1,2,....,N$$

### 2.6.2 Multiple Linear Regression Techniques

The general multiple linear regression model is outlined as:

$$\hat{y}(t) = \beta_0 + \beta_1 x_1(t) + \beta_2 x_2(t) + \dots\dots\dots\dots + \beta_n x_n(t) \tag{2.3}$$

The use of more than one variable selection procedure has been recommended in order to eliminate discrepancies in the final form of predictive models (Graybill and Iyer 1994; Rawlings 1986). Details of these methods have been provided in the above cited references. The two variable selection procedures in common use are stated below (Graybill and Iyer 1994; Rawlings 1986).

(1) Backward Elimination (2) Best Subset Regression

### 2.6.3 Statistical Tests used in Modeling

The following statistical tests are used in the evaluation of the Fourier models developed by the theory described above. These tests are standard statistical tests and can be found in standard books on time series analysis, see (Fuller 1976).

(1) F-Test for the selection of number of harmonics

(2) Fisher's Test of Periodicity to evaluate periodic or nonperiodic nature of data

(3) Chi Squared Test for goodness of fit

Some times the independent variables have been combined in an attempt to obtain a stable solution of the variable of interest, as shown in the following section.

### 2.6.4 Combination of Variables

It has been demonstrated that some of the problems which are solved using either finite difference methods or finite element methods exhibit instability in their solutions (Lee et al. 1982). The solutions to the finite difference and finite element approximations are made stable by combining the variables involved in the problem. The combined variables apart from increasing the stability to solutions also preserve the laws of energy and momentum conservation. Combinations of the various hydrometeorological variables led to the formulation of reliable multiple linear regression based predictors of the incoming and outgoing $BOD_5$ concentrations for a series of wastewater treatment ponds operating in the Cayman Islands (Ellis and Rodrigues 1995).

### 2.6.5 Parameter Variation in Hydrologic Time Series

The periodic models require a large number of parameters and their estimation is more difficult than the estimation required for non periodic models. Parameter estimation is of more concern when dealing with within-the-year periodicity (Yevjevich and Harmancioglu 1989). Fourier series fits are successfully used to describe within-the-year periodicity in basic parameters. Several methods exist for determining the number of parameters required to model stationary stochastic processes. These methods are only an approximation in the case of parameter selection for periodic stochastic models. Until the time of publication of this paper, the methods of parameter estimation and techniques of model selection have not been clearly defined for periodic stochastic processes.

Functional description of periodic parameters by their fitted Fourier coefficients is found to be more parsimonious than its nonfunctional description. The Fourier series method requires careful judgement to estimate the significant number of harmonics in periodic functions which describe the basic parameters of the hydrologic time series. There remains a need to determine more accurate methods for estimating the significant harmonics in the Fourier description.

### 2.6.6 Advantages of Fourier Series

Fourier series and its partial sum are presented as a solution to polynomial nonlinear differential equations and nonlinear wave equations. It is observed that finding exact closed form solutions to both nonlinear ordinary differential equations and partial differential equations is a popular though difficult area of research (Yan 1997). Although, a variety of algebraic and transformation methods exist to find the solutions with closed form, however the problem is that many of the found solutions are less meaningful physically. A fairly simple and direct method which utilizes the discrete Fourier transform both as a transformation and as a solution is presented and may carry more physical significance.

## 2.7 Summary

In summary, it is noted that wastewater treatment ponds are an affordable and effective means of wastewater treatment. The performance of deep wastewater treatment ponds is impacted by the various process-altering phenomena, recognized earlier in the chapter. The identification of the periodically occurring limnological phenomena and the factors affecting wastewater treatment is of vital importance in the investigation of their impact on pond performance. The limnological behavior of various lakes and reservoirs are discussed and a lake classification scheme, inclusive of shallow lakes, is also presented. The mathematical and statistical modeling techniques used to investigate the temporal behavior and the interrelationships among the variables investigated are also outlined. In the next chapter, the pertinent theory is developed and a research plan is laid out to investigate the limnological behavior of deep wastewater treatment ponds.

# CHAPTER 3

# THEORY DEVELOPMENT AND RESEARCH DESIGN

In this chapter, the input-output system modeling approach is extended to simulate the temporal behavior of the hydrometeorological variables and to measure the response of the water quality variables at the pond's surface. The investigational methodology presented for the collection and analysis of the key water quality variables and the significant causal meteorological factors help to identify the key process-altering limnological phenomena in the pond. Based on the year-round temporal and spatial behavior of the key pond performance variables, limnological classifications can be assigned to the 10 ft. deep wastewater treatment pond. The site description highlights its uniqueness for the design and operation of deep wastewater treatment ponds at higher elevations and under widely varying climatic conditions -- especially for regions experiencing prolonged and harsh winters.

## 3.1 Introduction

A review of design procedures for wastewater treatment ponds, presented in Chapter 2, reveals a lack of consensus on the uniform and concrete scientific principles used to design deep wastewater treatment ponds. Numerous authors have concluded that wastewater treatment ponds are the most economical means of effectively treating wastewater. The combinations of environmental factors and water quality variables which contribute toward environmental impact are termed as hydrometeorological variables. These variables which significantly affect the water quality variables in wastewater treatment ponds have been identified in the literature. In the next section, a systemic approach is applied to simulate the temporal behavior of the various process-altering variables and the impacted water quality variables at the surface of Pond No. 3.

### 3.2 Deep Wastewater Treatment Pond as a System

The 10 ft. deep wastewater treatment Pond No. 3 is viewed as a system comprised of the incoming and outgoing discharges, $Q_i$ and $Q_o$, as constant inputs and outputs to the closed system. The main energy inputs into the pond system are comprised of solar radiation R; air temperature Ta; and wind velocity Vw. R and Ta mostly influence heat transfers into and from the pond. Vw imparts energy to the surface waters by causing mixing. The following state variables are critical for the identification and evaluation of the impact of limnological behavior in the wastewater treatment pond: Tw; DO; pH; C; S; and ORP. The energies transferred into and from the pond tend to transform the incoming values of the state variables into the output values of the state variables. The various process-altering variables, identified in Section 3.5, significantly impact the water quality variables in the pond and are classified as:

(1) hydrological (2) meteorological (3) chemical

(4) biological

The systemic approach when applied to the settling pond of the Boxelder Sanitation District results in the input-output system shown in Figure 3.1. In general terms, a deep wastewater treatment pond is viewed to constitute a system of hydrometeorological and biochemical input and output signals. The hydrological, meteorological, chemical, and biological inputs arriving in a wastewater treatment pond

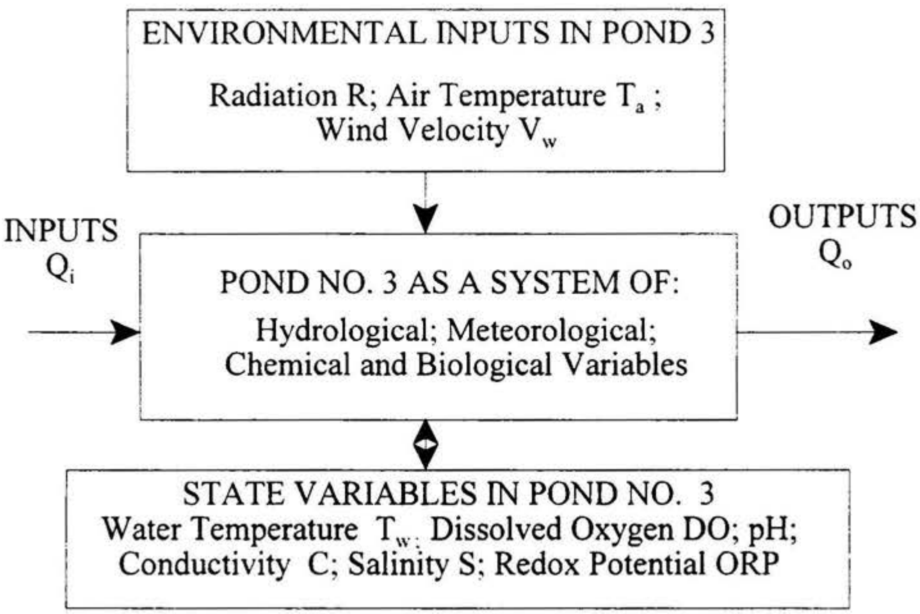

Figure 3.1 Systemic Representation of Wastewater Treatment Pond No. 3

simultaneously interact with each other. The complex hydrometeorological and biochemical interactions in the pond wastewaters result in transformed water quality output variables. In simple terms the complex reactions, which take place in a wastewater treatment pond, serve as transfer functions to transform the input-variables into output-variables. The temporal modeling and spatial analyses of the significant process-altering variables lead to the identification of the periodically recurring limnological phenomena as outlined below.

### 3.3 Periodically Occurring Limnological Phenomena Observed in Lakes

Lakes and reservoirs functioning under widely varying climatic conditions, including freezing winters -- especially located in the mid latitudes and at higher elevations -- exhibit the occurrence of the following seasonal limnological phenomena.

### 3.3.1 Spring Season Limnological Phenomena

Lakes located at higher elevations in the mid latitudes are covered by a solid ice sheet in the freezing winter season. The spring warm-up leads to the melting of the ice sheet and can also result in the circulation of oxygen-rich waters to the lake bottom. The effect of the spring warm-up also results in the formation of unstable thermoclines which are susceptible to oscillations caused by the intermittent episodes of precipitation. The nice and quiescent spring climate facilitates for algae blooms in the surface waters of the pond. The increased algal activity results in elevated DO and pH levels at the Pond surface. The DO depth profile in the pond may vary due to: (a) density driven mixing, (b) the renewal mechanisms experienced at and near the lake's surface, and (c) the clinograde curve which significantly affects the oxidative processes at the sludge-water interface. The spring warmup, – especially at higher altitudes, leads to increased heat storage, which in turn yields faster reaction rates for the various chemical and biological reactions which occur in the lake. The ORP profiles in the spring season are most likely to signify aerobic behavior, such as the occurrence of the nitrification process.

### 3.3.2 Summer Season Limnological Phenomena

The peak of the summer season, under prolonged hot and dry spells, witnesses the formation of stable and distinct thermoclines. The distinct and stable summer thermoclines are likely to be accompanied with chemoclines of conductivity and salinity in the water column. In some cases, a negative heterograde signifying the metalimnetic DO minimum is also likely to form near the interface of the two density strata. The stable thermal stratification and the negative heterograde profile in the water column can also cause nearly the entire water depth to become anoxic. The stable thermocline, formed at the peak of the summer season, also yields the fastest reaction rates for the various biochemical reactions that occur in the lake. The cycling of nutrients and heavy metals in the water column are most likely to be significantly impacted by this increase in the reaction rates. The faster consumption of DO can result in anoxic conditions to prevail in a wastewater treatment pond. The anoxic conditions may prove beneficial for denitrification and phosphorus releases to occur in the pond.

### 3.3.3 Fall Season Limnological Phenomena

The onset of the fall season witnesses the erosion of the stable summer thermocline and the lake starts to lose heat, primarily into the surrounding atmosphere. Once again, the isothermal conditions are restored in the water column. The nice and quiescent climatic conditions in the early part of the fall season facilitate for algae blooms to occur at the water surface. The algae blooms are accompanied with elevated DO and pH readings at and near the surface of the lake. When the surface water temperatures fall below the underlying water temperatures, another episode of density driven mixing, which is highly susceptible to wind blown disturbances, occurs and results in increased DO values in the entire water column. After the fall destratification and the establishment of cooler climatic conditions, the rates of biochemical reactions greatly slow down and sludge starts to accumulate at the lake bottom.

### 3.3.4 Winter Season Limnological Phenomena

During the winter season, the water temperatures in the entire lake keep decreasing at least until the winter solstice, after which the water temperature begins to increase due to the increase in the incoming solar radiation. Lakes in the mid latitudes, --especially at higher altitudes, form an ice cover when the water temperature falls below 4° C. Once again, due to the heavier water overlying lighter water, density driven mixing takes place. The DO readings at the lake surface get sharply reduced, while DO values near the lake bottom are most likely to show an increase. The decreased water temperatures cause the reaction rates to significantly slow down, which leads to the accumulation of undigested matter at the lake bottom. The ice cover entraps the carbon dioxide gas, released mostly at the sludge-water interface, in the underlying lake waters. This leads to the formation of carbonic acid and the entire lake turns acidic. Acidification of the lake significantly influences the cycling of carbon in carbon-rich waters under the solid ice cover primarily due to increased UVR penetration. The identification of these periodically recurring limnological phenomena identify the significant contributions made by the following process-altering variables on the year-round limnological performance of deep wastewater treatment ponds.

## 3.4 Significant Process Altering Variables

The above stated periodically recurring limnological phenomena are found to depend upon the following significant process-altering variables.

### 3.4.1 Water Temperature, Tw

Tw is the principal indicator of heat transfers that occur into and from wastewater treatment ponds. Tw as a function of depth is indicative of the limnological behavior in deep water bodies which may include deep wastewater treatment ponds. Water temperature depends heavily upon climatic factors such as R and Ta. Tw directly affects the following parameters: (1) chemical and biological reactions; (2) reaction rate constants; (3) bacterial mortality rates; (4) thermal stratification; (5) destratifications; (6) density driven circulations; (7) oxygen solubility in water; and (8) aquatic life. These influences of Tw render it as an indispensable parameter, both temporally and spatially, for the smooth and effective operation of deep wastewater treatment ponds.

### 3.4.2 Dissolved Oxygen, DO

Dissolved oxygen is required for the respiration of aerobic bacteria and also by all other aerobic life forms. The DO concentrations directly influence the rate of biological reactions occurring in the wastewater treatment pond. The temporal and spatial DO profiles provide valuable information about the state of the wastewater treatment pond such as: aerobic, anaerobic, and facultative. The quantity of DO in water is directly influenced by: (1) water temperature; (2) partial pressure of the gas; (3) solubility of the gas; (4) salinity and suspended solids in the water; and (5) biochemical reactions which occur in the water body. Variations of DO concentrations along the depth lead to the formation of: (1) clinogrades; (2) negative heterogrades; (3) positive heterogrades; and (4) anoxic DO profiles in lakes. Dissolved oxygen is categorized as a dependent variable which seems to rely heavily on: (1) Tw; (2) ORP; (3) nutrient availability; and (4) photosynthesis. The reliance of DO on the above-mentioned factors leads to the classification of DO, both temporally and spatially, as one of the important process-altering dependent variables in deep wastewater treatment pond operation.

### 3.4.3 Inverse Log of Hydrogen Ion Concentration, pH

The pH significantly affects the survival and growth of bacteria, algae and fungi. The optimum pH for bacterial growth ranges from 6.5 to 7.5. Most bacteria cannot tolerate pH levels above 9.5 or below 4.0. High pH conditions result in wastewater treatment ponds which experience photosynthesis under low alkalinity. The pH significantly affects the nutrient regime in a wastewater treatment pond by influencing the nitrification and denitrification processes. pH also has a strong influence on the removal of phosphorus and other minerals. Low pH values lead to large releases of carbon dioxide gas and cycling of carbon, especially in ice-covered water bodies which are rich in carbon. The various chemical, biological, and physical processes which periodically occur in lakes have the tendency to significantly alter its pH values. The pH serves as a vital indicator of lake acidification and its crucial role as a temporally and spatially varying process-altering variable qualifies it for detailed sampling in this investigation.

### 3.4.4 Salinity, S

The utility of salinity as an indicator of total suspended solids TSS in water and its fitness for reuse for non-potable purposes qualifies it, both temporally and spatially, for sampling as a dependent variable over the annual hydrological cycle.

### 3.4.5 Specific Conductivity, C

The temperature-based variation of conductivity renders it useful for temporal and spatial investigation as an independent variable over the annual hydrological cycle.

### 3.4.6 Oxidation Reduction Potential, ORP

Oxidation reduction potentials in a wastewater treatment pond are indicative of the aerobic, anoxic, and anaerobic states in the various zones of the pond. The ORP readings are of critical importance in the identification of the nitrification and denitrification processes, monitoring of phosphorus releases, cycling of metals in lakes, determination of the optimal dosages of chlorine and sulfur dioxide in the chlorination and dechlorination processes in a water body. The oxidation and reduction of several elements and many chemical and biological reactions are also influenced by the redox potentials in the water body. Due to the year-round importance of ORP as an indicator of the wide array of reactions which also occur in deep wastewater treatment ponds, it is included as a dependent variable in the temporal and spatial data collection scheme.

### 3.4.7 Solar Radiation, R

The direct and indirect impact of R on the various hydrometeorological and biochemical variables in a wastewater treatment pond qualify it as a significant causal variable in the changes that occur in the hydrometeorological variables under investigation.

### 3.4.8 Air Temperature, Ta

Air temperatures play an important role in heat transfers which occur at the lake surface. The strong seasonality exhibited by air temperature and its impact on: Tw, DO, and photosynthesis, qualify it as a causal independent variable among the various variables investigated.

### 3.4.9 Peak Wind Gusts, Vw

Peak wind gusts are included as an independent causal meteorological variable in order to determine their impact on the DO and ORP concentrations at the surface of the wastewater treatment pond.

The above stated systemic approach, the periodically occurring limnological phenomena, and the process-altering variables lay the foundation for the research methodology described as under.

### 3.5 Research Design

The main thrust of the research design is aimed at detecting the occurrence of periodically recurring limnological phenomena in the 10 ft. deep settling pond of Boxelder Sanitation District. The periodically occurring limnological phenomena, such as: (1) clinogrades; (2) negative heterogrades; (3) positive heterogrades; (4) summer anoxia; (5) thermal stratifications; (6) fall destratifications; (7) algae blooms; (8) super saturations; (9) winter acidifications; (10) elevated pH values; (11) density driven mixings; and (12) seasonal turn-overs need to be identified before the behavior of Pond No. 3 could be deduced as limnological. Once the limnological behavior in Pond No. 3 is established, over the annual hydrological cycle, then the frequency of the various process-altering limnological phenomena can be used to assign Pond No. 3 a limnological category based upon Lewis' lake classification scheme, which is inclusive of shallow lakes.

The process-altering variable-types observed in lakes can further be grouped as: hydrometeorological and biochemical. Figure 3.2 illustrates that the variations in the hydrometeorological variables tend to influence the behavior of the biochemical variables. Thus, it is of critical importance to identify the key hydrometeorological variables which significantly influence deep wastewater treatment pond performance.

Data collection in short temporal and spatial increments most likely provide a better opportunity to study the impact of the environmental factors on the temporal and spatial variations of the water quality variables under investigation in Pond No. 3. A 1 ft. depth interval is chosen to record the readings of the water quality variables from the surface to the bottom of Pond No. 3.

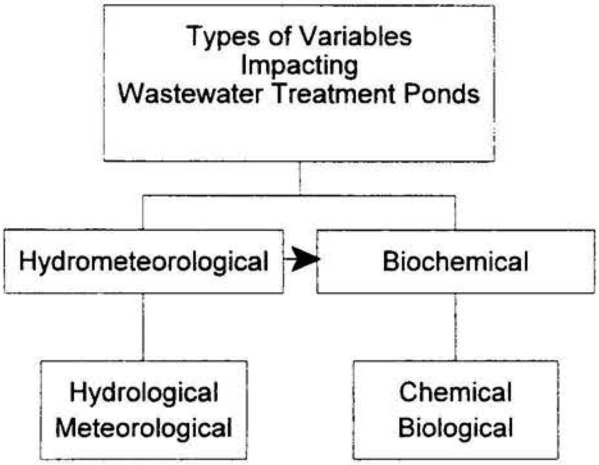

Figure 3.2 Process Altering Variables in Wastewater Treatment Pond

The time series of the water quality data are used to generalize their temporal behavior over the annual hydrological cycle. While spatial variation of the water quality variables, when measured in small depth increments, are likely to provide valuable information leading to the identification of the periodically recurring limnological phenomena in deep wastewater treatment ponds. The water quality data from Pond No. 3 of Boxelder Sanitation District are collected in two-week increments from January through December 1995. The two-week time increment is chosen on the assumption that it is representative of the period sampled. It is also assumed that the evenly spaced data collection in two-week time increments does not miss significant changes in water quality variables due to seasonal changes in the climatic parameters. If a reading is missed due to inclement weather, then it is replicated by the preceding reading. Data are initially collected at one foot depth intervals, at the five stations 3A to 3E, in Pond No. 3. If negligible spatial variability is observed, then regular data collection is to continue at one foot depth intervals for rest of the year at stations 3A, 3C, and 3E. Hence, the annual time series of each of the nine hydrometeorological variables consist of 26 observations in two-week time increments.

The meteorological data of: (1) R; (2) Ta; and (3) Vw are obtained from the nearest weather stations. The monthly data of solar radiation are furnished by the Colorado Climate Center at Colorado State University. Data of monthly air temperatures and peak wind gusts are gathered from the Rocky Mountain Weather Service which is located near Boxelder Sanitation District. The meteorological data series in two-week time increments are interpolated from their respective monthly data series.

Two individuals set out in a boat to collect data each time. The functions performed by the first person include: (a) operates the boat, (b) lowers the probe from the reel, and (c) records the depth of the probe in one foot increments. The second individual performs the following tasks: (a) down-loads the water quality data onto a lap-top computer and (b) also records the water quality readings on standard forms.

### 3.6 Modeling Techniques

The main focus of the modeling techniques is to study the response of the water quality variables, collected in two-week time increments, in terms of the amplitude of the discrete Fourier series at the pond's surface, caused by the periodic variation of the meteorological variables.

Time series of the hydrometeorological data variables are obtained after generating their discrete Fourier series using the 26 data points, 15 days apart, over a one year period. The ease of application of Fourier series in modeling within the year periodicity justify the generation of discrete Fourier series, after performing the discrete Fourier transform on the discrete and finite data sets, of the variables under investigation.

The temporal behavior of the nine variables under investigation are most likely to exhibit any of the following behavior over the 26 two-week fundamental period:

(1) Periodic over the Annual Cycle

(2) Periodic with Seasonality

(3) Nonperiodic

Fishers's test of periodicity is applied to ascertain whether the temporal behavior of the data is periodic or nonperiodic. The number of significant harmonics for the discrete Fourier series are obtained by applying the F-test on the discrete Fourier transform of the variables investigated (Fuller 1976). A significance level of 95% is used to select the number of significant harmonics. The discrete Fourier models, of those variables which give high correlations between the original and the fitted data sets, are tested for goodness of fit by performing the Chi-squared goodness of fit test (Rawlings 1986).

The inter-relationships among the nine variables under investigation are explored by performing multiple linear regression. The following two variable selection schemes are used to rule out inconsistencies among the independent variables retained by the statistical models (Draper and Smith 1998):

(a) stepwise backward elimination (b) best sub set regression

Standard error of estimate is used to place 95%, upper and lower, confidence limits (UCL and LCL) on the generated data series. The various combinations of the independent and dependent variables investigated in this research are listed in Table 3.1.

The product the maximum solar radiation and maximum air temperatures recorded in Fort Collins, Colorado in two-week increments R*Ta is used as an independent variable in an attempt to obtain better correlations between the original and the simulated data series.

The adequacy of the statistical models, obtained by multiple linear regression, is tested by plotting the normal score plots of their respective residuals (Graybill and Iyer 1994). The next section outlines the salient features which make Pond No. 3 a unique research site for this investigation.

Table 3.1 Dependent and Independent Variables used in Multiple Linear Regression

| **Dependent Variable** | **Independent Variables** |
|---|---|
| Water Temperature, Tw | Ta, R, R*Ta, Vw, DO, ORP, pH, C, S |
| Dissolved Oxygen, DO | Tw, Ta, R, R*Ta, Vw, ORP, pH, C, S |
| Oxidation Reduction Potential, ORP | Tw, Ta, R, R*Ta, Vw, DO, pH, C, S |
| pH | Tw, Ta, R, R*Ta, Vw, DO, ORP, C, S |
| Salinity, S | Tw, Ta, R, R*Ta, Vw, DO, ORP, pH, C |

### 3.7 Site Description

Pond No. 3 of Boxelder Sanitation District offers a novel opportunity to study the year-round behavior of a deep wastewater treatment pond, located 40° N of the equator at an elevation of about 5000 ft. above mean sea level (MSL), under widely varying climatic conditions. The 10 ft. pond depth sets it apart from the shallow ponds (1.2m to 2m deep) investigated in the EPA Wastewater Stabilization Pond Design manual. The composition of the wastewater entering the Boxelder Sanitation District's wastewater treatment ponds is a mixture of agricultural, commercial, and domestic effluent. The nutrient-rich influent provides an opportunity to observe if nutrient enrichment also leads to summer eutrophication in deep wastewater treatment ponds at higher elevations. Heavy metal removal can also be studied to ascertain the effectiveness of deep wastewater treatment ponds in the cycling of important minerals.

Pond No. 3 has a design capacity of storing up to 7 MG of water. The areal dimensions of the pond are 300 ft by 200 ft at the top surface and its design depth is 10 feet. The side slopes of the inner pond embankments are 1V:3H. The pond has a detention time of 4.52 days. Figure 3.3 shows the layout of wastewater treatment ponds at Boxelder Sanitation District. A 1/4 inch $\phi$ steel cable is stretched across Pond No. 3, at a location 200 ft. East, from the West end of the pond as shown Figure 3.4.

Five data collection stations, namely 3A, 3B, 3C, 3D, and 3E about 30 feet apart, are marked permanently on the steel cable, also shown in Figure 3.4. The operational standards complied by The Boxelder Sanitation District for the year 1995 are listed below.

Table 3.2 lists the effluent discharge standards set forth for Boxelder Sanitation District by The Colorado Department of Public Health and Environment. Table 3.3 lists the: (1) 30 day averages for discharge Q; (2) biochemical oxygen demand $BOD_5$; (3) total suspended solids TSS; (4) water temperature Tw; (5) dissolved oxygen DO; and (6) pH as reported by The Boxelder Sanitation District in their DMR reports. The instruments used to collect water quality data are described in the following section.

## 3.8 Instruments Used

Data of the six water quality parameters under investigation are collected with the help of a Hydrolab H-20 multi-parameter water quality probe. The H-20 probe is 3.5 inches in diameter and is 24 inches long. Sensors for the following water quality parameters are attached on the H-20 water quality probe.

(1) Water Temperature, Tw
(2) Dissolved Oxygen, DO
(3) pH
(4) Specific Conductivity, C
(5) Salinity, S
(6) Oxidation Reduction Potential, ORP

Only DO and pH probes require calibration before each data collection. Details

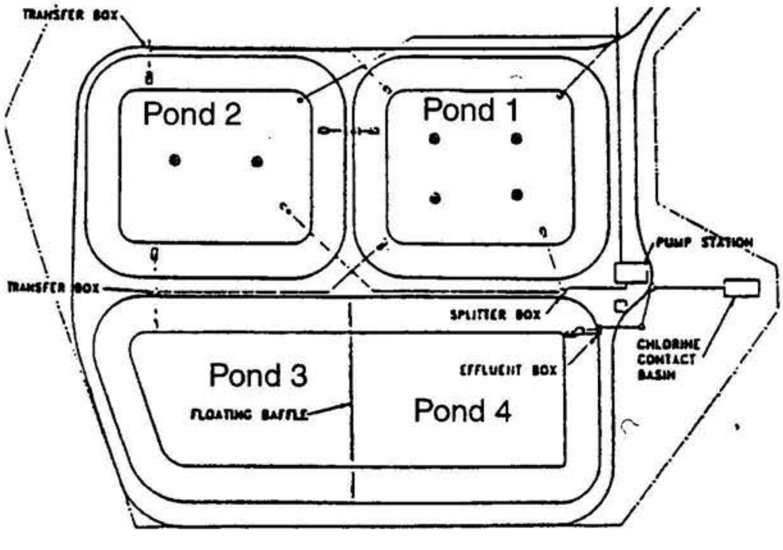

Figure 3.3 Site Layout of Boxelder Sanitation District Ponds

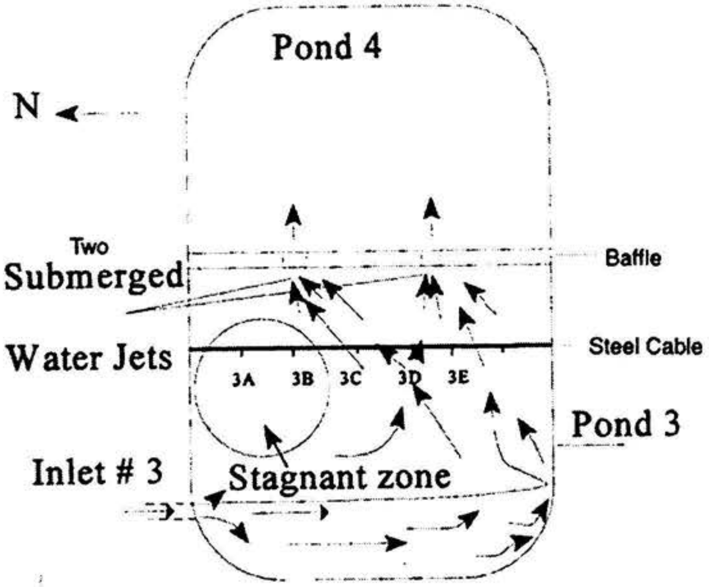

Figure 3.4 Plan View of Ponds Nos. 3 & 4
at Boxelder Sanitaion District

Table 3 .2 Discharge Limitations at BSD: Maximum Permissible Concentrations

| Effluent Parameter | 30 day Avg. | 7-Day Avg. | Daily Max. |
|---|---|---|---|
| Flow, MGD | $2*10^6$ | N/A | Report |
| $BOD_5$ mg/l | 30 | 45 | N/A |
| TSS mg/l | 75 | 110 | N/A |
| Fecal Coliform number/100ml | 3710 | 7420 | N/A |
| Total Residual Cl mg/l | N/A | N/A | 0.08 |
| pH min.-max. | N/A | N/A | 6.5-9 |
| Oil and Grease mg/l | N/A | N/A | 10 |

of the calibration and maintenance procedures are documented in the Hydrolab H-20 owners manual (Hydrolab 1991). The salient features of the sensors attached with the H-20 water quality probe are shown in the Table 3.4 (Godfrey 1996). The remaining sensors need very infrequent calibration. By July's end when the entire depth profiles of Pond No. 3 exhibited zero DO values, the H-20 probe was sent back to Hydrolab Corporation, located in Austin TX, for routine maintenance and calibration of all its sensors. A fiber glass boat, with a seating capacity of two persons, is used to collect data from the stations marked on the cable. A depth measuring reel, borrowed from USGS, is used to lower the probe and to record depth readings in feet. The research methodology presented above is most likely to meet the objectives stated in Section 1.5.

### 3.9 Summary

In summary, the hydrometeorological data are collected in two-week time increments for one year. The twenty six data sets, at the pond's surface, of the nine

Table 3.3 Influent and Effluent Summary at Boxelder Sanitation District for 1995

| Month | 30 Day Avg Flow, MGD | | 30 Day Avg BOD mg/l | | BOD Removal % | 30 Day Avg TSS mg/l | | Tw °F | DO mg/l monthly Average | pH | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Influent | Effluent | Influent | Effluent | | Influent | Effluent | | | Min | Max |
| Jan. | 1.23 | 1.23 | 76 | 10 | 87 | 137 | 29.2 | 40.04 | 7.12 | 7.4 | 7.8 |
| Feb. | 1.26 | 1.25 | 103 | 11.7 | 89 | 140 | 33 | 43.85 | 6.66 | 7.5 | 7.8 |
| Mar. | 1.29 | 1.22 | 12.6 | 1.22 | 88 | 158.6 | 38.1 | 47.24 | 6.61 | 7.6 | 7.9 |
| Apr. | 1.26 | 1.21 | 108 | 11.8 | 89 | 166 | 32.6 | 48.35 | 5.75 | 7.7 | 7.8 |
| May | 1.86 | 1.72 | 73 | 12.2 | 83 | 146 | 32.4 | 53.30 | 4.48 | 7.6 | 7.9 |
| Jun. | 2.32 | 1.98 | 75.6 | 10.0 | 86 | 92.4 | 21.6 | N.A. | N.A. | N.A. | N.A. |
| Jul. | 1.84 | 1.77 | 97 | 12.6 | 87 | 151 | 28.6 | 68 | 3.72 | 7.1 | 7.9 |
| Aug. | 1.73 | 1.71 | 119 | 14.3 | 88 | 154 | **86.7** | 69.47 | 3.86 | 7.3 | 7.9 |
| Sep. | 1.62 | 1.59 | 66.2 | 13 | 82 | 118.8 | 34.4 | 62.09 | 5.23 | 7.4 | 8.1 |
| Oct. | 1.48 | 1.45 | 113 | 13.4 | 88 | 119 | 24 | 51.27 | 5.39 | 7.4 | 8.1 |
| Nov. | 1.37 | 1.34 | 97 | 11.9 | 88 | 100 | 30.2 | 44.5 | 5.48 | 7.4 | 7.9 |
| Dec. | 1.34 | 1.27 | 98.2 | 11.8 | 88 | 100.8 | 29 | 40.28 | 6.11 | 7.3 | 7.9 |

Table 3.4 Salient Features of Hydrolab H-20 Water Quality Probe (Godfrey 1996)

| Parameter | Range | Accuracy | Resolution | Response Time |
|---|---|---|---|---|
| Temperature | -5° C to 50° C | ±0.15° C | 0.01° C | < 1 min. |
| pH | 0 to 14 units | ±0.2 units | 0.01 unit | < 1 min. |
| Conductivity | 0 to 100 mS/cm | ± 1 % | 4 digits | < 1 min. |
| Salinity | 0 to 70 ppt | ± 0.2 ppt | 0.1 ppt | < 1 min. |
| DO | 0 to 20 mg/l | ± 0.2 mg/l | 0.01 mg/l | < 1 min. |
| ORP | -999 to 999 mv | ± 20 mv | 1 mv | < 1 min. |

variables under investigation are analyzed by formulating their input-output models to generate their discrete Fourier series and multiple linear regression predictors. The interrelationships among the various hydrometeorological variables are also examined by performing multiple linear regression. The theoretical concepts introduced in this chapter are applied to the hydrometeorological data sets collected from the field in an attempt to establish limnological behavior in Pond No. 3. Reliable prediction of the key pond performance indicators and process-altering variables may become possible when the data modeling techniques introduced in this chapter are used. Results of the mathematical and statistical modeling at the pond's surface are presented in the next chapter.

# CHAPTER 4

# RESULTS OF MATHEMATICAL AND STATISTICAL MODELING

The results of the input-output modeling approach, outlined in Chapter 3, are presented along with the graphs of the data and the predictors simulated by employing discrete Fourier series and multiple linear regression. The statistical tests applied to arrive at the resulting models are also tabulated later in the chapter.

## 4.1 Introduction

The maximum response of the water quality variables to the variation in meteorological phenomena was examined by performing discrete Fourier series analysis on the surface water quality data sets. The interrelationships between the variables under investigation were examined by employing multiple linear regression. Equally spaced time series of the hydrometeorological variables were generated to study the impact of the environmental factors on the water quality variables due to the seasonal changes in the meteorological phenomena. Water quality data collected from Boxelder Pond No. 3 and meteorological data acquired from the Colorado Climate Center and the Rocky Mountain Weather Service, shown in Table 4.1, were used to generate the mathematical and statistical models for these variables. The following data modeling techniques were employed to generate the original hydrometeorological data series at the pond's surface:

Table 4.1, Hydrometeorological and Water Quality Variables Used in Analysis of Pond No. 3 at Boxelder Sanitation District, For Year 1995

| Date 1995 | Obs. No. | Tw °C | Ta °C | R MJ/$m^2$-d | Vw mph | DO mg/l | ORP mv | C mS/m | S ppt | pH | R*Ta MJ/$m^2$-d C |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 01/02 | 0 | 3.78 | -1.44 | 9.50 | 13.86 | 3.14 | 246.33 | 2.03 | 1.10 | 6.13 | -13.72 |
| 01/11 | 1 | 6.58 | -0.22 | 10.99 | 17.43 | 4.16 | 278.33 | 1.99 | 1.07 | 7.69 | -2.44 |
| 02/23 | 2 | 7.53 | 1.00 | 12.47 | 21.01 | 1.27 | 99.00 | 1.91 | 1.00 | 7.42 | 12.47 |
| 02/23 | 3 | 7.53 | 2.61 | 14.80 | 23.69 | 1.27 | 99.00 | 1.91 | 1.00 | 7.42 | 38.63 |
| 03/09 | 4 | 6.26 | 4.22 | 17.12 | 24.59 | 0.00 | 77.00 | 1.90 | 1.00 | 7.80 | 72.78 |
| 03/28 | 5 | 6.68 | 5.36 | 18.98 | 22.35 | 14.62 | 236.00 | 1.95 | 1.00 | 8.06 | 101.73 |
| 04/13 | 6 | 7.89 | 6.06 | 20.83 | 20.12 | 10.21 | 497.00 | 1.94 | 1.00 | 8.20 | 126.14 |
| 04/13 | 7 | 7.89 | 7.94 | 21.41 | 21.91 | 10.21 | 497.00 | 1.94 | 1.00 | 8.20 | 170.09 |
| 05/02 | 8 | 10.71 | 9.83 | 21.99 | 23.69 | 4.36 | 349.00 | 1.86 | 1.00 | 7.71 | 216.24 |
| 05/22 | 9 | 10.07 | 11.74 | 22.57 | 22.80 | 0.00 | 372.00 | 1.84 | 1.00 | 8.09 | 264.88 |
| 06/07 | 10 | 22.38 | 13.64 | 23.84 | 21.91 | 3.70 | 114.00 | 2.01 | 1.10 | 7.56 | 325.19 |
| 06/14 | 11 | 19.85 | 15.54 | 25.12 | 21.01 | 3.20 | 154.33 | 2.06 | 1.10 | 7.33 | 390.35 |
| 06/22 | 12 | 21.94 | 17.44 | 26.39 | 20.12 | 1.66 | 39.33 | 2.03 | 1.10 | 7.47 | 460.36 |
| 07/13 | 13 | 24.06 | 19.22 | 25.72 | 17.88 | 1.87 | 116.33 | 1.99 | 1.10 | 7.68 | 494.30 |
| 07/26 | 14 | 26.11 | 21.00 | 25.04 | 15.65 | 7.73 | 214.67 | 1.56 | 0.87 | 8.10 | 525.84 |
| 08/09 | 15 | 20.79 | 22.44 | 23.46 | 14.98 | 0.00 | 168.67 | 1.97 | 1.07 | 7.78 | 526.43 |
| 08/15 | 16 | 20.58 | 21.72 | 21.87 | 14.31 | 0.00 | 139.67 | 2.00 | 1.10 | 7.64 | 475.07 |
| 09/03 | 17 | 17.69 | 18.78 | 20.18 | 14.75 | 2.10 | 129.33 | 1.97 | 1.07 | 7.51 | 378.84 |
| 09/24 | 18 | 12.20 | 15.11 | 18.48 | 15.20 | 2.05 | 125.00 | 1.92 | 1.03 | 7.44 | 279.25 |
| 10/01 | 19 | 13.66 | 13.21 | 16.97 | 17.29 | 1.54 | 179.00 | 1.13 | 0.63 | 7.46 | 224.14 |
| 10/15 | 20 | 11.55 | 11.29 | 15.47 | 19.37 | 8.29 | 128.67 | 2.00 | 1.10 | 7.32 | 174.69 |
| 10/29 | 21 | 8.41 | 9.39 | 13.96 | 21.46 | 7.01 | 198.67 | 1.98 | 1.10 | 7.64 | 131.07 |
| 11/12 | 22 | 7.02 | 6.83 | 11.92 | 21.01 | 5.34 | 165.33 | 2.00 | 1.10 | 7.58 | 81.45 |
| 11/26 | 23 | 7.93 | 4.28 | 9.88 | 20.56 | 0.00 | 379.67 | 1.96 | 1.07 | 7.69 | 42.26 |
| 12/10 | 24 | 3.20 | 2.03 | 9.09 | 19.45 | 4.16 | 278.33 | 1.99 | 1.07 | 7.69 | 18.42 |
| 12/24 | 25 | 2.82 | -0.22 | 8.29 | 18.33 | 2.04 | 258.00 | 2.00 | 1.10 | 4.38 | -1.82 |

(1) Discrete Fourier Model (2) Multiple Linear Regression Model

The first step in the model formulation process included identification of the model parameters used to represent the time series of the water quality and the meteorological variables.

### 4.2 Model Identification

The model identification procedure involved parameter calibration for the two types of models investigated to simulate the sampled hydrometeorological data series. Parameter calibration for the two model types are illustrated in the following sections.

### 4.2.1 Discrete Fourier Model

The following general form of the discrete Fourier model was used to simulate the nine hydrometeorological variables.

$$\hat{y}(t) = \frac{a_o}{N} + \Sigma_{j=1}^{\frac{N}{2}-1} [a_j \cos(\frac{2\pi j t}{N}) + b_j \sin(\frac{2\pi j t}{N})] + a_{\frac{N}{2}} \cos(\pi t) \qquad (4.1)$$

$$\begin{aligned} \textit{Where } t &= 0,1,2,\ldots\ldots,N-1 \\ j &= 1,2,\ldots,\frac{N}{2}-1 \end{aligned}$$

For the 26 time intervals of the nine variables investigated, the discrete Fourier model took the following form:

$$\hat{y}(t) = \frac{a_o}{26} + \Sigma_{j=1}^{12} [a_j \cos(\frac{2\pi j t}{26}) + b_j \sin(\frac{2\pi j t}{26})] + a_{13} \cos(\pi t) \qquad (4.2)$$

$$\begin{aligned} \textit{Where } t &= 0,1,2,\ldots\ldots,N-1 \\ N &= 26 \\ j &= 1,2,\ldots,\frac{N}{2} - 1 \end{aligned}$$

Where $a_{13}\cos(\pi t)$ is the error term from hereon is replaced by $\epsilon_t$.

The following parameters of the discrete Fourier model needed calibration in order to simulate the nine hydrometeorological series:

(1) $a_0$ (2) $a_j$ (3) $b_j$

The calibration procedure began by performing the discrete Fourier transform. Matrices of cosines and sines were generated for each hydrometeorological variable under investigation. The following equations were used to estimate the parameters used in the discrete Fourier model.

$$a_o = \Sigma_{t=0}^{N-1} x(t) \tag{4.3}$$

$$a_{\frac{N}{2}} = \Sigma(-1)^t \frac{x_t}{N} \tag{4.4}$$

$$a_j = 2[\Sigma x_t \cos(\frac{2\pi j t}{N})] \tag{4.5}$$

$$b_j = 2[\Sigma x_t \sin(\frac{2\pi j t}{N})] \tag{4.6}$$

$$Where\ j = 1,\ldots\ldots,(N/2) - 1$$

The significant frequencies were separated by applying the F-test on the ratio of each squared modulus to the sum of the remaining squared modulii obtained after performing discrete Fourier transform on the original data sets. A significance level of 95%, along with the appropriate degrees of freedom was used to test the significance of the frequencies. The degrees of freedom for each parameter were computed by using the following equation:

$$\nu = 26 - 2\,n - 1 \tag{4.7}$$

Where $\nu$ is the degrees of freedom

n is the number of significant terms

The F-values with appropriate degrees of freedom were read from F-tables for: $(0.95, 0.05, \nu_1, \nu_2)$. Two sided 95% confidence limits were placed above and below each simulated data series by multiplying the standard error of estimate (SEE) of the generated Fourier series by ±2 and adding it to the respective simulated series. Standard error of estimates for all the variables, generalized by the discrete Fourier models, were obtained after calculating the sum of squared errors. The SEE was computed by using the following statistical formula:

$$SEE = \sqrt{\frac{\Sigma_{t=1}^{n}(\hat{y} - y_i)^2}{\nu}} \tag{4.8}$$

Where $\nu$ is the degrees of freedom given as: $\nu = n - p - 1$,

p is the number of significant terms.

Table 4.2 displays the Fourier series coefficients obtained after performing discrete Fourier transform. The F-test provides an estimate of the number of significant harmonics required to generate the discrete Fourier series of the various hydrometeorological variables. The Fourier series expressions used to model the various hydrometeorological variables are presented in the sections which follow.

**a. Water Temperature, Tw**

The F-test indicated that five significant harmonics were needed to adequately model the discrete Fourier series of water temperature with an $r^2$ of 97.8%. Utilization

Table 4.2 Fourier Coefficients Evaluated from Discrete Fourier Transform

| variable<br>Coefficient | Tw | DO | pH | S | C | ORP | R | Ta | Vw |
|---|---|---|---|---|---|---|---|---|---|
| $a_0$ | 12.11 | 3.84 | 7.5103 | 1.033 | 1.9166 | 213.06 | 17.93 | 9.94 | 19.41 |
| $a_1$ | -8.94 | | | | | 34.88 | -7.52 | -9.68 | 0.95 |
| $b_1$ | -1.31 | | | | | 55.57 | 2.45 | -2.93 | 2.71 |
| $a_2$ | 2.48 | | | | | -50.70 | -0.52 | -0.16 | -1.51 |
| $b_2$ | 0.97 | | | | | -55.32 | 0.68 | 1.37 | -1.60 |
| $a_3$ | -1.19 | | | | | 40.32 | -0.84 | -0.66 | -1.56 |
| $b_3$ | 0.98 | | | | | -97.95 | 0.16 | -0.49 | 0.93 |
| $a_4$ | | | | | | 42.89 | 0.26 | 0.44 | -1.19 |
| $b_4$ | | | | | | 25.16 | -0.03 | 0.79 | 0.20 |
| $a_5$ | | | | | 0.0798 | | 0.08 | -0.15 | -0.66 |
| $b_5$ | | | | | 0.1022 | | 0.19 | -0.16 | -0.46 |
| $a_6$ | | | | | | -21.64 | | | |
| $b_6$ | | | | | | 32.87 | | | |
| $a_7$ | | | | | | | | | |
| $b_7$ | | | | | | | | | |
| $a_8$ | | | | | | 11.80 | | | |
| $b_8$ | | | | | | 6.57 | | | |
| $a_9$ | -0.35 | | | | | | 0.04 | -0.11 | |
| $b_9$ | -0.77 | | | | | | 0.11 | 0.01 | |
| $a_{10}$ | | | | 0.0133 | | | | | |
| $b_{10}$ | | | | 0.0250 | | | | | |
| $a_{11}$ | | | | | | | 0.05 | | |
| $b_{11}$ | | | | | | | 0.06 | | |
| $a_{12}$ | -0.88 | | | | | | | | |
| $b_{12}$ | -0.76 | | | | | | | | |

of only the first two significant harmonics and the average term yielded an $r^2$ of 92.0% as shown in Equation 4.9. Figure 4.1 displays the original Tw series, the Fourier series of Tw and its 95% confidence limits.

$$\hat{y}(t) = \frac{a_o}{26} + a_1\cos[\frac{2\pi t}{26}] + b_1\sin[\frac{2\pi t}{26}] + a_2\cos[\frac{(2\pi)(2t)}{26}] + b_2\sin[\frac{(2\pi)(2t)}{26}] \quad (4.9)$$

*Where t goes from* 0 *to* 25

**b. Dissolved Oxygen, DO**

The F-test indicated that all the harmonics in the DO data series were insignificant. Results of the F-test also indicated that the DO data series was too erratic. The Discrete Fourier model of DO consisted only of the average term as shown in Equation 4.10. Plots of the original DO data series, its discrete Fourier model and its 95% confidence limits are shown in Figure 4.2.

$$\hat{y}(t) = \frac{a_o}{26} \quad (4.10)$$

*Where t goes from* 0 *to* 25

**c. pH, pH**

The pH discrete Fourier model included only the average term as shown in Equation 4.11. Plots of the original and generated pH series along with its 95% confidence limits are shown in Figure 4.3.

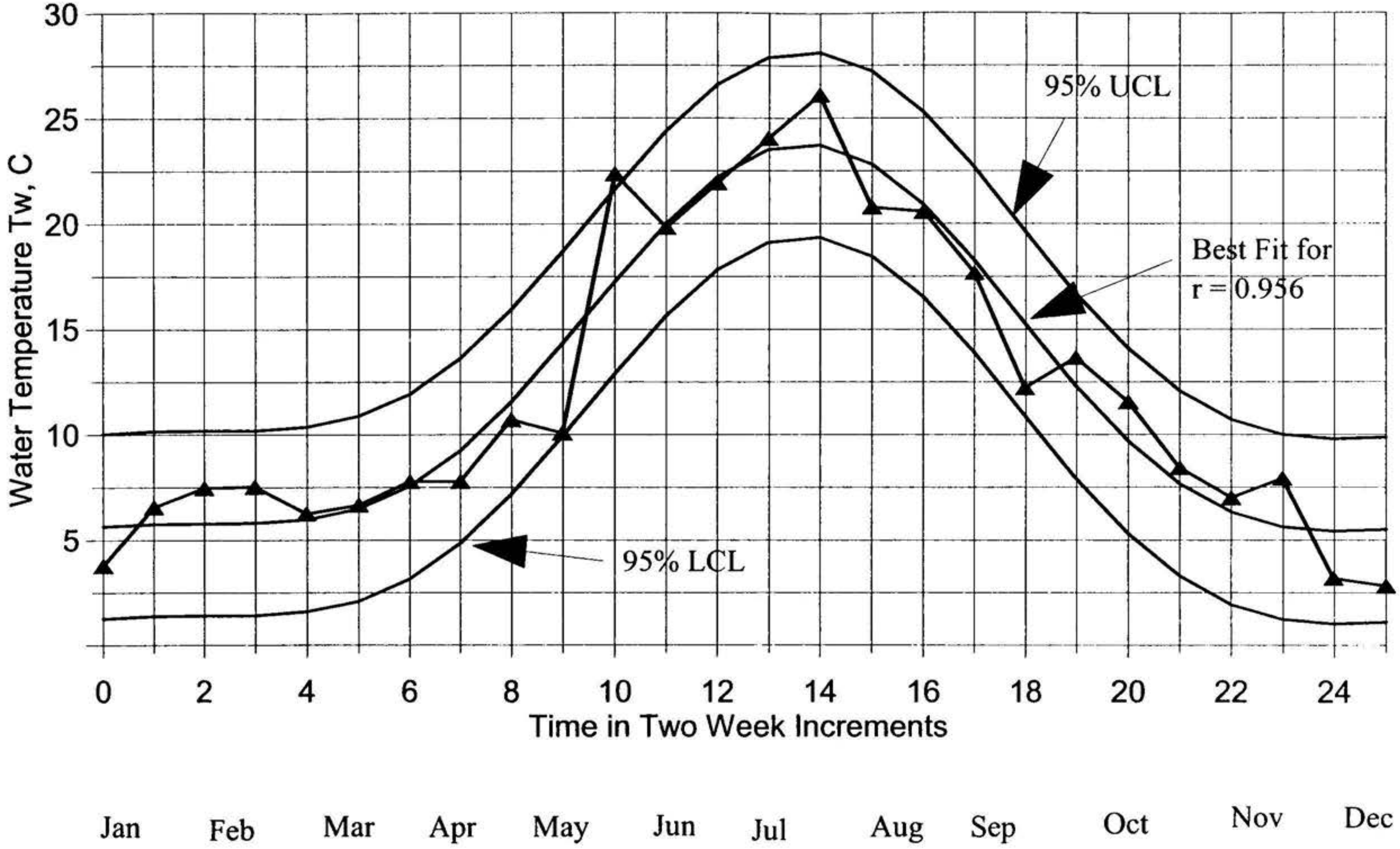

Figure 4.1, Water Temperature Fourier Series N=2, 95% Confidence Limits

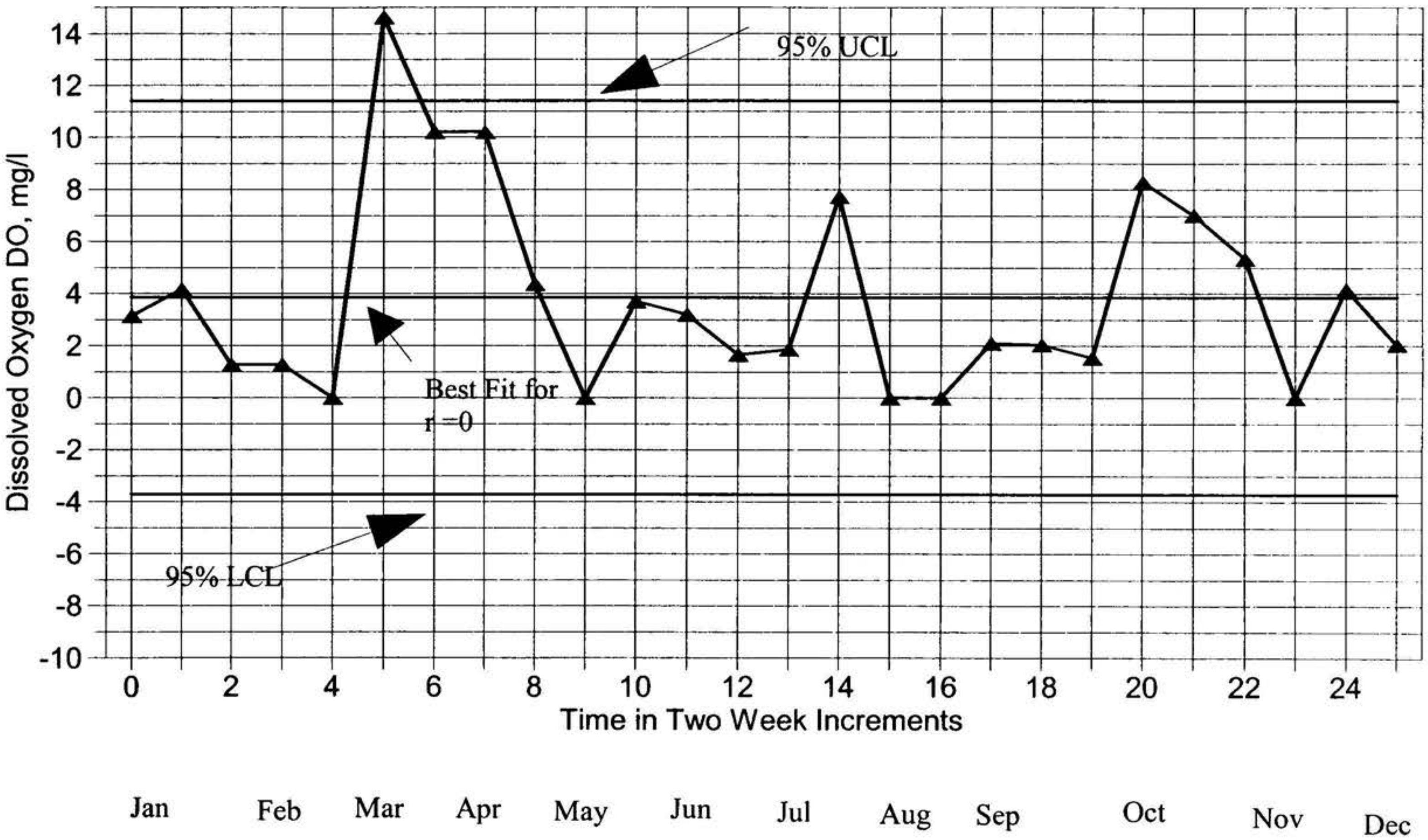

Figure 4.2, Dissolved Oxygen Fourier Series, N=0, 95 % Confidence Limits

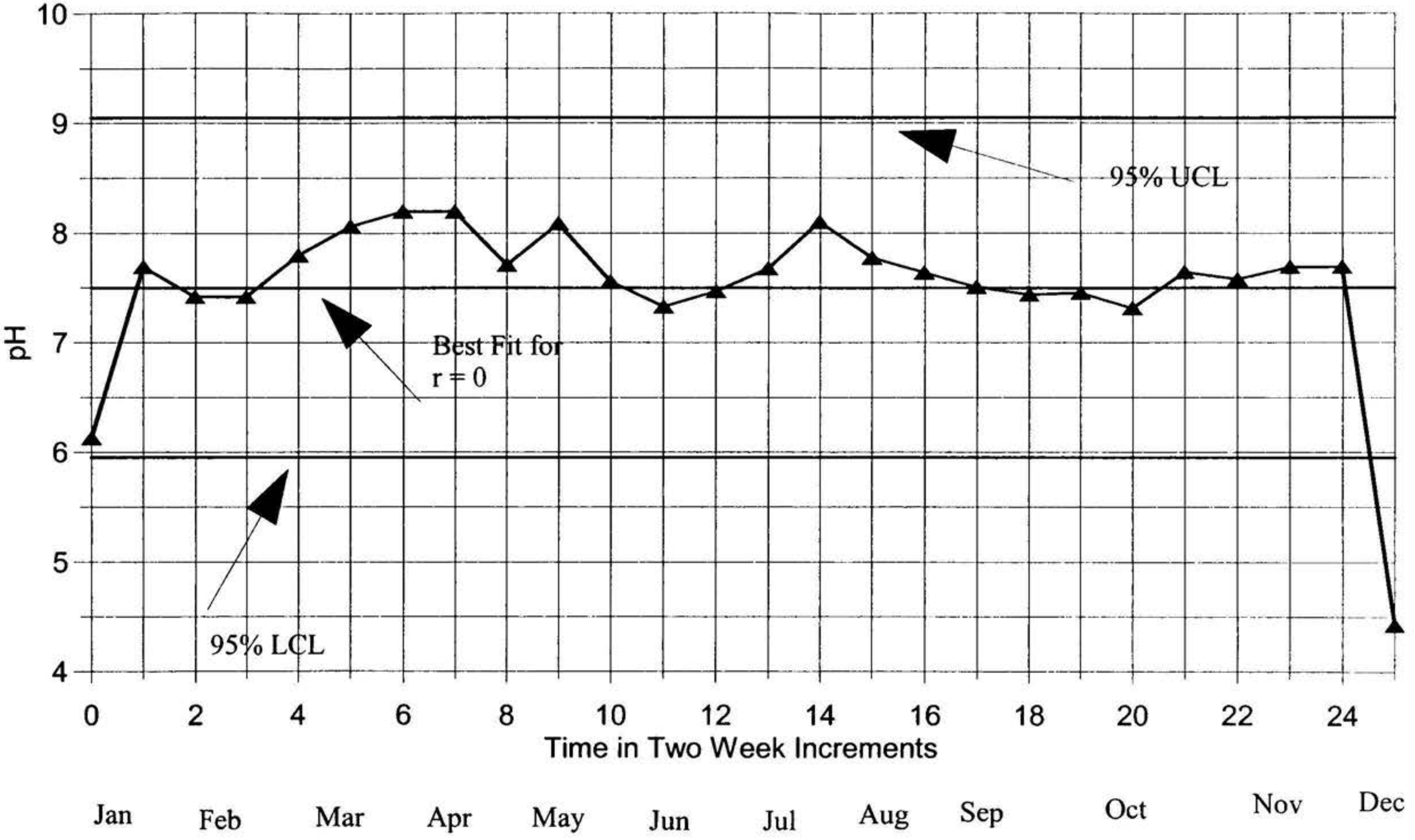

Figure 4.3, pH Fourier Series, N=0
95 % Confidence Limits

$$\hat{y}(t) = \frac{a_o}{26} \tag{4.11}$$
*Where t goes from* 0 *to* 25

### d. Salinity, S

For the salinity data series, the F-test showed only the tenth harmonic was significant but it gave a poor correlation of merely 25%. Only the average term was used to model the Fourier series of S, as shown in Equation 4.12. Figure 4.4 displays the salinity discrete Fourier model along with its 95% confidence limits and the original data series.

$$\hat{y}(t) = \frac{a_o}{26} \tag{4.12}$$
*Where t goes from* 0 *to* 25

### e. Conductivity, C

The application of the F-test to determine the number of significant harmonics needed to simulate the conductivity data set, yielded only the fifth harmonic as significant with an $r^2$ of 12.25%. The discrete Fourier model of conductivity, comprising only the average term, was used to generate the discrete Fourier series of C, shown in Equation 4.13. Figure 4.5 exhibits the original and Fourier series of conductivity along with the 95% confidence limits.

$$\hat{y}(t) = \frac{a_o}{26} \tag{4.13}$$
*Where t goes from* 0 *to* 25

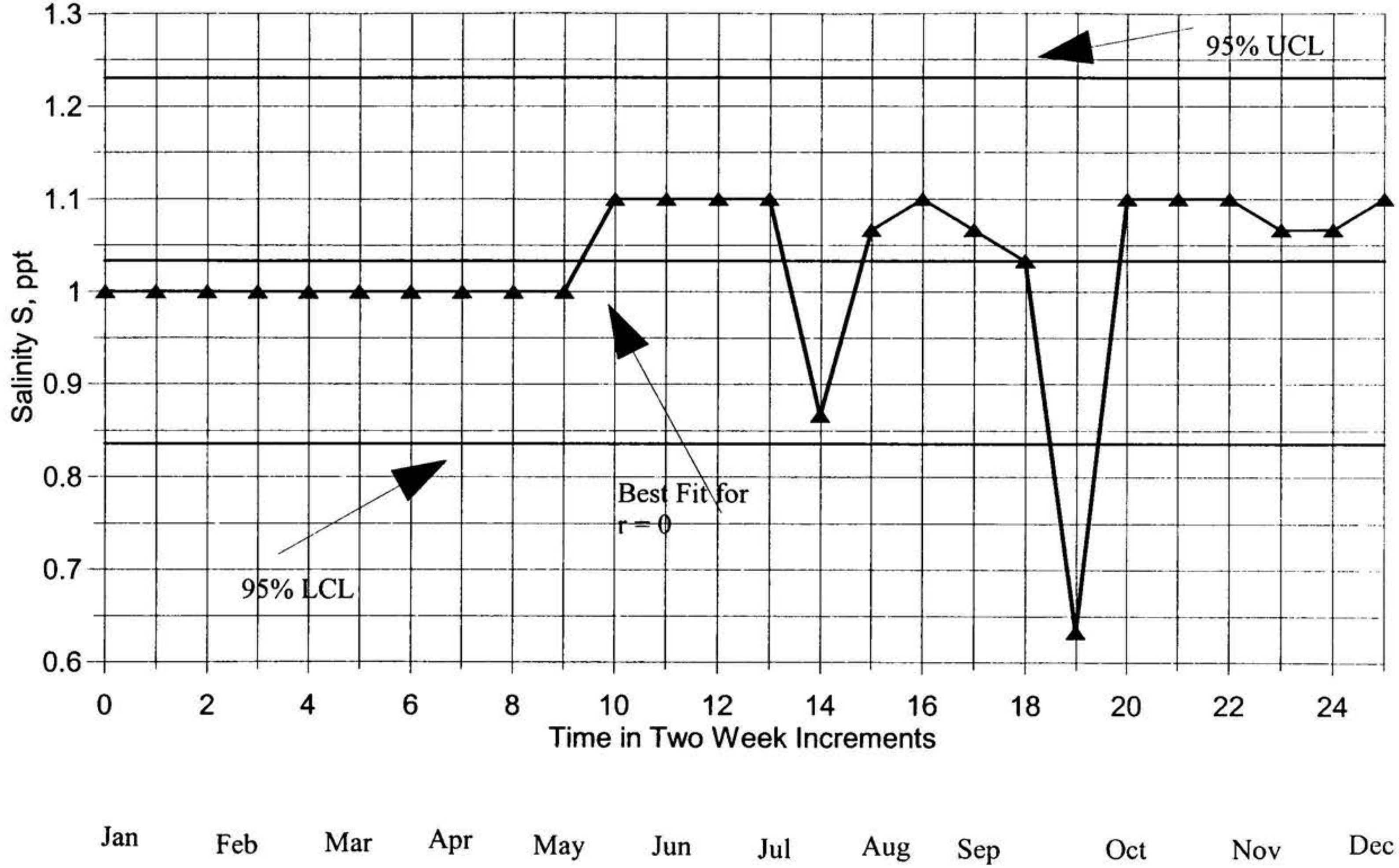

Figure 4.4, Salinity Fourier Series
N=0, 95% Confidence Limits

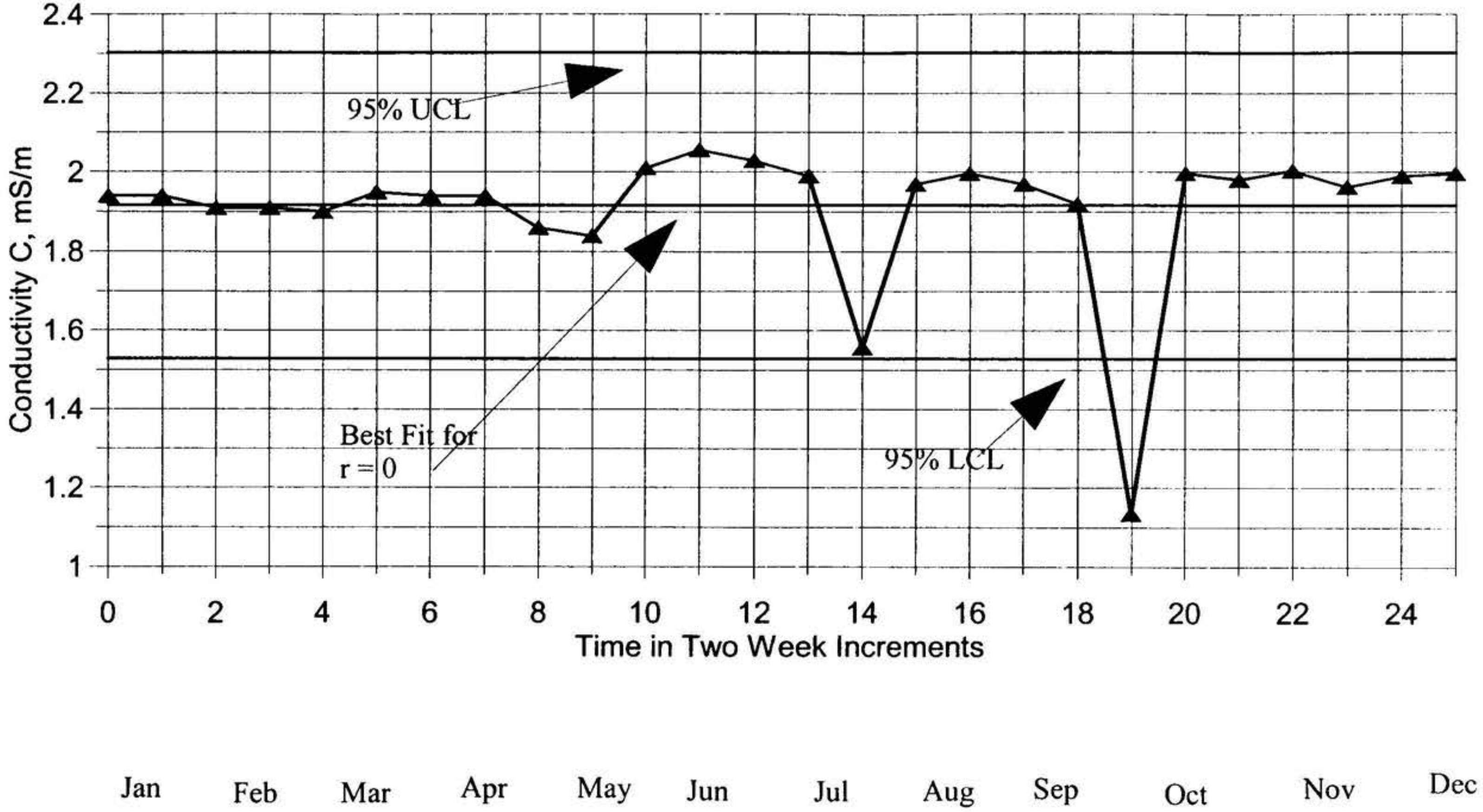

Figure 4.5, Fourier Series, N=0
Conductivity, 95 % Confidence Limits

### f. Oxidation Reduction Potential, ORP

The F-test predicted the discrete Fourier model of ORP to comprise 6 significant terms. The six harmonic Fourier model gave an $r^2$ of 88.5%. While the use of the first four significant harmonics gave an $r^2$ of 81.9%, which is computationally more efficient than using 6 harmonics. The expression for the discrete Fourier model of ORP is shown in Equation 4.14. The ORP discrete Fourier model along with 95% confidence limits and the original data series are plotted in Figure 4.6.

$$
\begin{aligned}
\hat{y}(t) = \frac{a_o}{26} &+ a_1 \cos\frac{(2\pi t)}{26} + b_1 \sin\frac{(2\pi t)}{26} + a_2 \cos\frac{[(2\pi)(2t)]}{26} \\
&+ b_2 \sin\frac{[(2\pi)(2t)]}{26} + a_3 \cos\frac{[(2\pi)(3t)]}{26} + b_3 \sin\frac{[(2\pi)(3t)]}{26} \\
&+ a_4 \cos\frac{[(2\pi)(4t)]}{26} + b_4 \sin\frac{[(2\pi)(4t)]}{26} \qquad (4.14) \\
&\textit{Where } t \textit{ goes from } 0 \textit{ to } 25
\end{aligned}
$$

### g. Solar Radiation, R

The F-test showed the solar radiation data series contained seven significant terms. The Fourier model of R consisting of seven significant terms gave an $r^2$ of 99.99%. By utilizing only the first two harmonics, an $r^2$ of 96.4% was obtained. The Fourier model comprising only two significant terms is not only highly accurate but it is also computationally efficient. The two-harmonic R-model is also very easy to apply. The discrete Fourier model for solar radiation comprising the average term and the first two frequency terms is given in Equation 4.15. Figure 4.7 shows the Fourier model of solar radiation along with 95% confidence limits and the plot of original solar radiation data series.

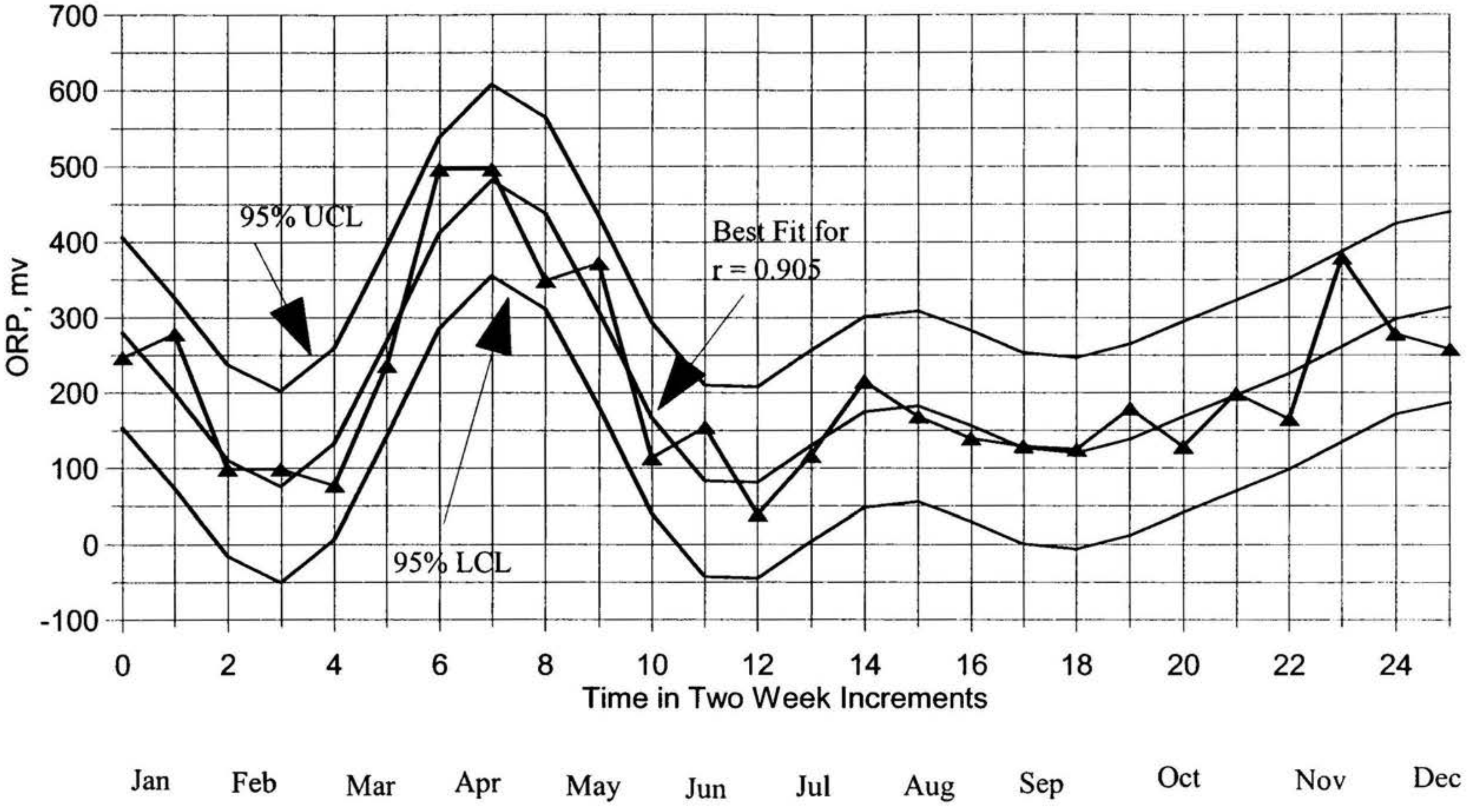

Figure 4.6 Oxidation Reduction
Potential, Fourier Series, N=4

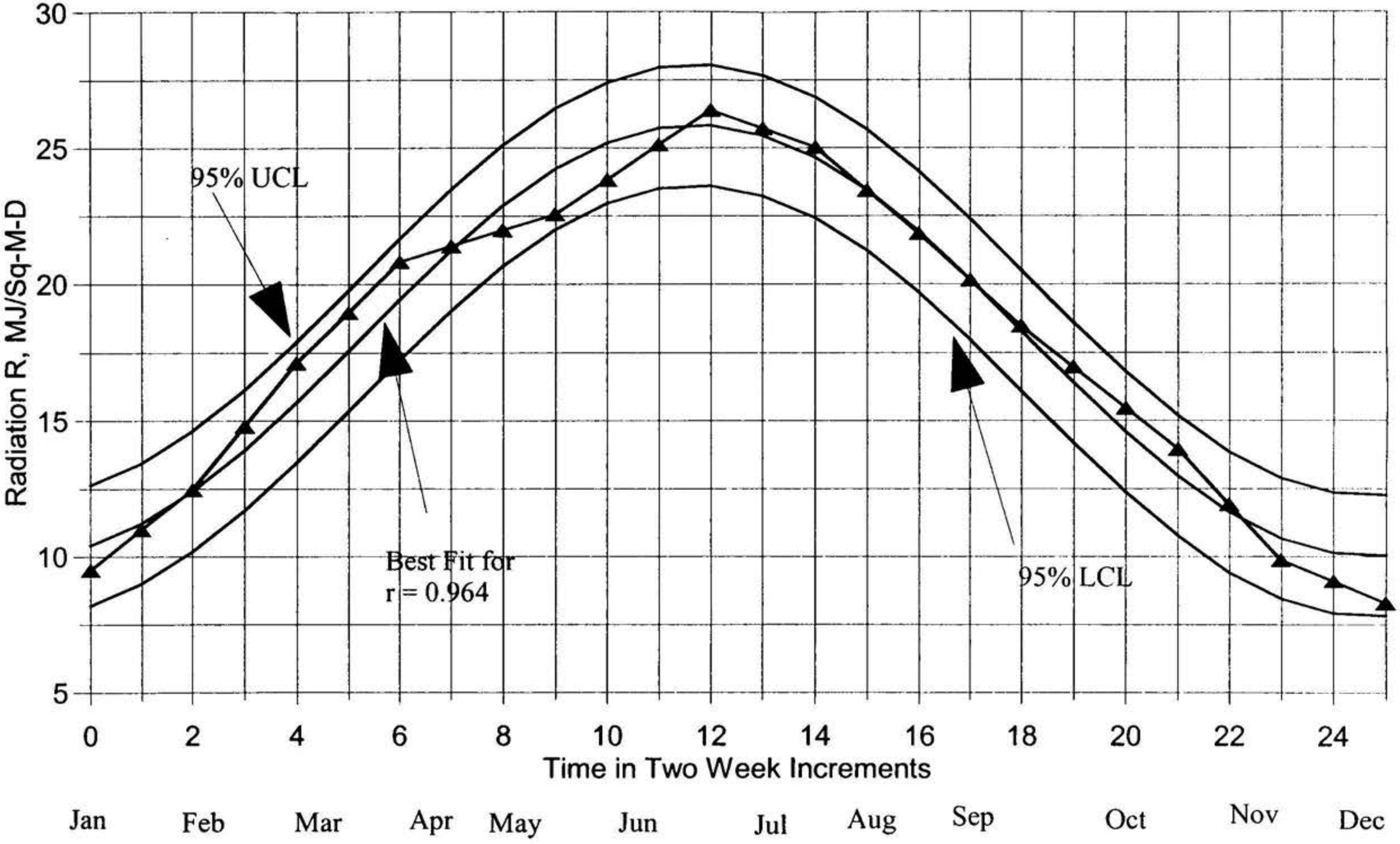

Figure 4.7, Fourier Series, N=2
Solar Radiation, 95% Confidence Limits

$$\hat{y}(t) = \frac{a_o}{26} + a_1\cos[\frac{2\pi t}{26}] + b_1\sin[\frac{2\pi t}{26}]$$
$$+ a_2\cos[\frac{(2\pi)(2t)}{26}] + b_2\sin[\frac{(2\pi)(2t)}{26}] \qquad (4.15)$$
$$\textit{Where } t \textit{ goes from } 0 \textit{ to } 25$$

**h. Air Temperature, Ta**

Results of the F-test indicated that the air temperature data series contained six significant terms which yielded an $r^2$ of 99.9%. The discrete Fourier model of air temperature is shown in Equation 4.16. Use of the first two significant terms still gave a very high $r^2$ of 99.2%. Figure 4.8 displays the original Ta data series, the Fourier model of the Ta data series and its 95% confidence limits.

$$\hat{y}(t) = \frac{a_o}{26} + a_1\cos[\frac{2\pi t}{26}] + b_1\sin[\frac{2\pi t}{26}] + a_2\cos[\frac{(2\pi)(2t)}{26}] + b_2\sin[\frac{(2\pi)(2t)}{26}] \quad (4.16)$$
$$\textit{Where } t \textit{ goes from } 0 \textit{ to } 25$$

**i. Peak Wind Speeds, Vw**

The peak wind gusts data series contained five significant terms and gave an $r^2$ of 95.1%. Use of the first three significant harmonics still gave an $r^2$ of 84.2%, as shown in Equation 4.17. Computational efficiency and ease of application by retaining less number of harmonics are worth consideration when generating discrete Fourier series with a slightly lower $r^2$. The occurrence of peak wind gusts is a relatively random phenomenon. So it is more appropriate to use fewer harmonics in the discrete Fourier model of Vw than those suggested by the F-test criteria. Figure 4.9 displays the original and the

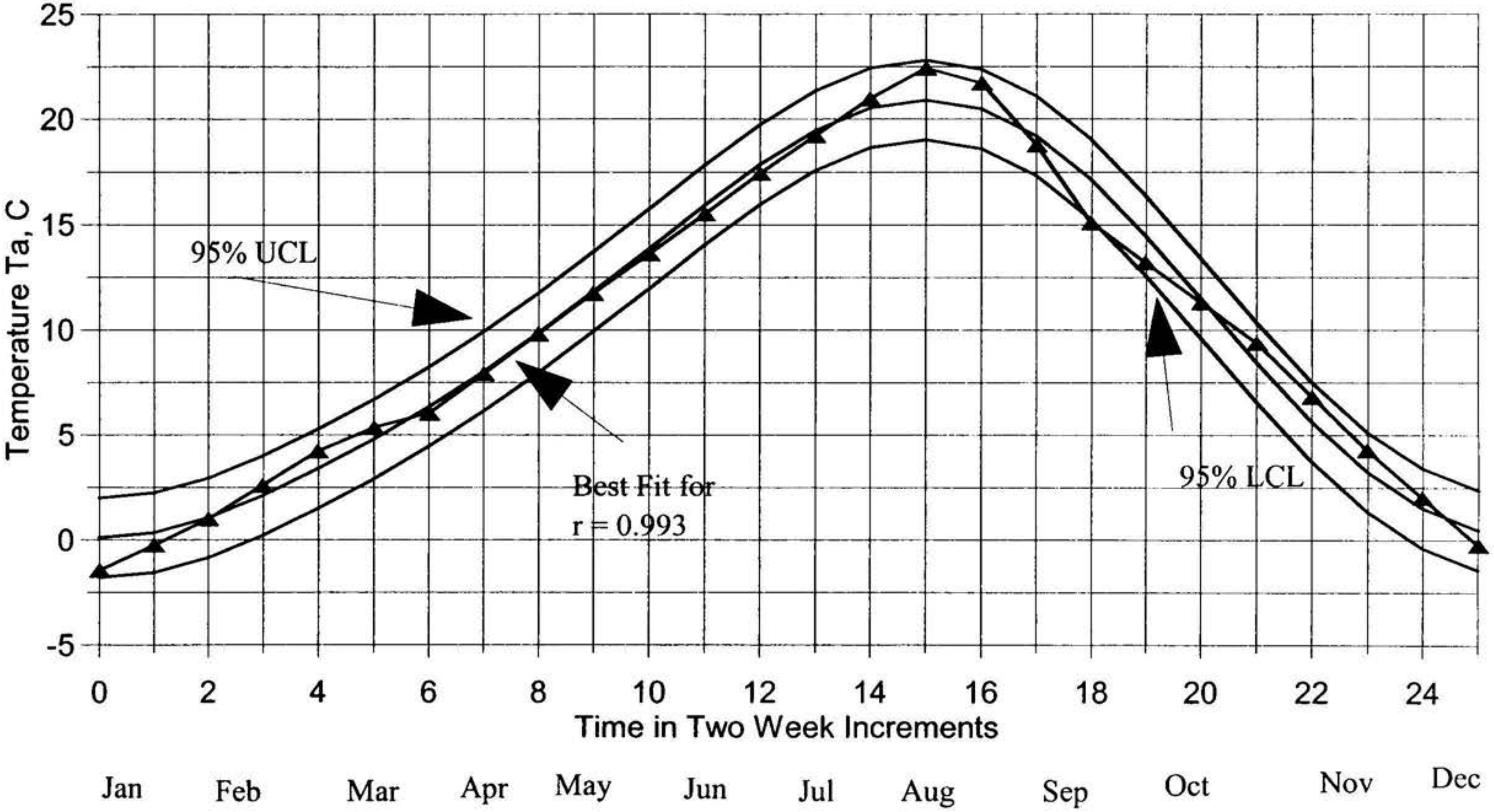

Figure 4.8, Air Temperature Fourier
Series N=2, 95% Confidence Limits

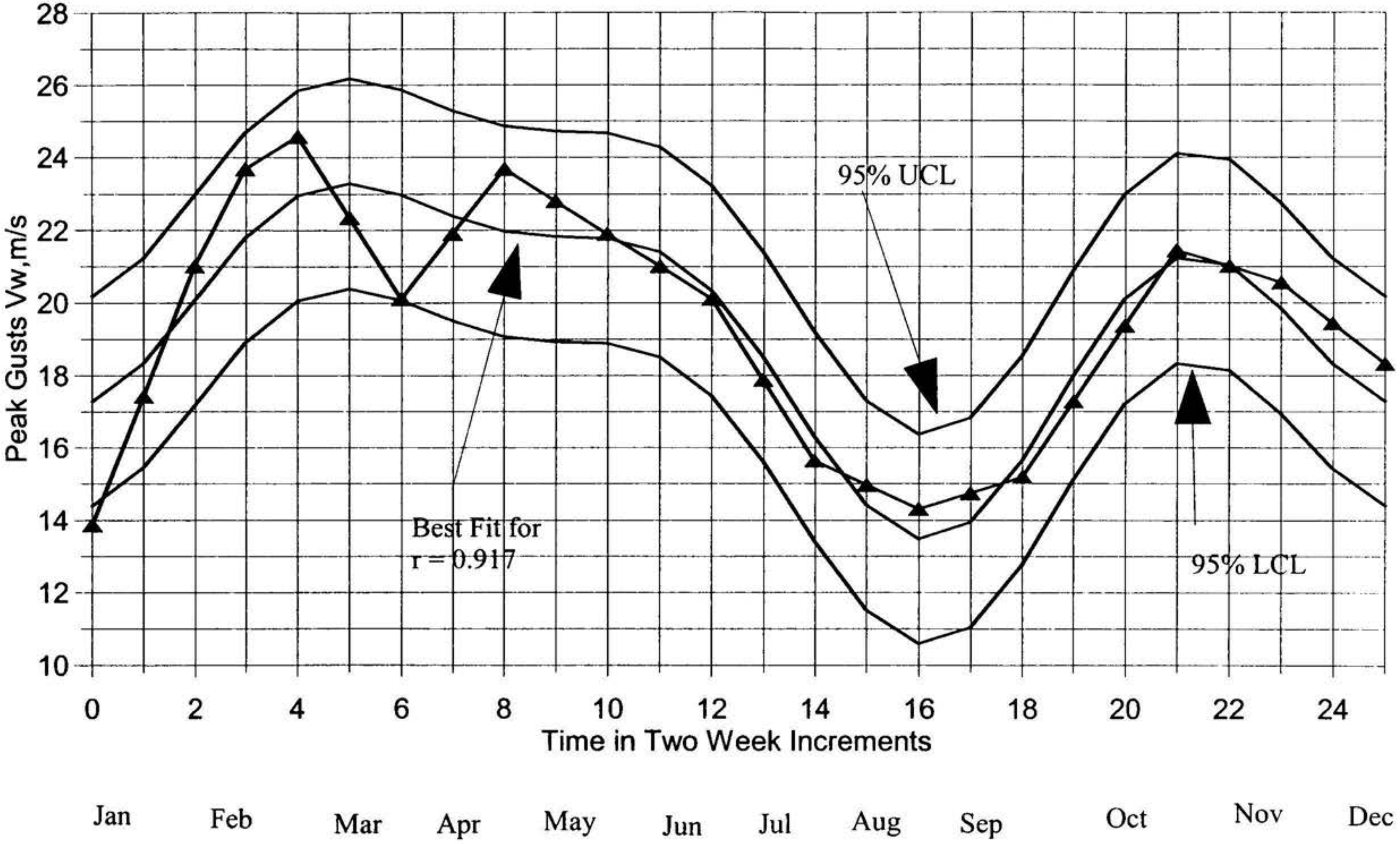

Figure 4.9, Fourier Series, N=3
Peak Wind Gusts, 95% CLs

generated data series of Vw along with its 95% confidence limits.

$$\hat{y}(t) = \frac{a_o}{26} + a_1\cos[\frac{2\pi t}{26}] + b_1\sin[\frac{2\pi t}{26}] + a_2\cos[\frac{(2\pi)(2t)}{26}] + b_2\sin[\frac{(2\pi)(2t)}{26}]$$
$$+ a_3\cos[\frac{(2\pi)(3t)}{26}] + b_3\sin[\frac{(2\pi)(3t)}{26}] \quad \textit{Where t goes from } 0 \textit{ to } 25 \quad (4.17)$$

The errors between the original and the generated discrete Fourier series, obtained by using the significant harmonic selection criteria, are discussed below.

### 4.2.2 Error Analysis of Discrete Fourier Models

The errors related to each discrete Fourier model were obtained by plotting the difference between the simulated series and the original data series, observed over time. The plots of the residuals are shown in Figures A-1 to A-9 in Appendix A. The chi squared goodness of fit test was successfully applied on the simulated data series of Tw, Ta, and R. These data series had shown very strong periodic behavior over the annual cycle and also provided very high correlations between the original and the data series. The results of the chi squared tests, presented in Table 4.3, showed these variables to be coming from a normal distribution.

### 4.2.3 Correlation Analysis of Discrete Fourier Models

Results of the Fourier analysis, consisting of the F-tests used to determine the number of harmonics, Fisher's test of periodicity, and the correlations between the original and the simulated data series are shown in Table 4.4.

Table 4.3, Chi Squared Tests for Goodness of Fit

| Parameter | Chi-Square(0.95, 5) | Sum Chi-square |
|---|---|---|
| Water Temperature | 11.07 | 4.75 |
| Air Temperature | 11.07 | 9.207 |
| Solar Radiation | 11.07 | 2.958 |

Table 4.4 Fisher's Test of Periodicity, F-Test Results, Significant Terms and $r^2$ of Discrete Fourier Series Suggested for Hydrometeorological and Water Quality Variables

| Variable | Fishers Periodicity Index | | Classification | F Test, | $r^2$ |
|---|---|---|---|---|---|
| | Statistic Value | Table Value | per Fisher's Test of Periodicity | Significant Terms | % |
| **Tw** | **10.98** | **4.67** | **Periodic** | **5** | **97.9** |
| DO | 2.427 | 4.67 | Non Periodic | 0 | 0 |
| pH | 2.216 | 4.67 | Non Periodic | 0 | 0 |
| S | 2.759 | 4.67 | Non Periodic | 1 | 12.25 |
| C | 2.985 | 4.67 | Non Periodic | 1 | 25 |
| **ORP** | **4.841** | **4.67** | **Periodic** | **6** | **88.5** |
| **R** | **11.70** | **4.67** | **Periodic** | **7** | **99.9** |
| **Ta** | **11.62** | **4.67** | **Periodic** | **6** | **99.9** |
| **Vw** | **5.092** | **4.67** | **Periodic** | **5** | **95.1** |

Correlations between the discrete Fourier models and their related original data series were computed for each parameter under investigation. After identification of the discrete Fourier models, the errors and squared errors were evaluated between the original and the simulated series of the variables under investigation. Fisher's test of periodicity was performed on all original data sets to get an idea about the nature of data series being studied.

Table 4.5 lists the number of significant terms actually used to generate the discrete Fourier series of the meteorological and water quality data sets, the F-test results, and $r^2$ between the simulated and the original data series investigated.

Table 4.5, Fisher's Test of Periodicity, F-Test Results, significant Terms Used and $r^2$ of Discrete Fourier Series of Hydrometeorological and Water Quality Variables

| Variable | Fishers Periodicity Index Statistic Value | Table Value | Classification per Fisher's Test of Periodicity | Significant Terms Used to Generate Fourier Series | $r^2$ % |
|---|---|---|---|---|---|
| **Tw** | **10.98** | **4.67** | **Periodic** | **2** | **92.0** |
| DO | 2.427 | 4.67 | Non Periodic | 0 | 0 |
| pH | 2.216 | 4.67 | Non Periodic | 0 | 0 |
| S | 2.759 | 4.67 | Non Periodic | 0 | 0 |
| C | 2.985 | 4.67 | Non Periodic | 0 | 0 |
| **ORP** | **4.841** | **4.67** | **Periodic** | **4** | **81.9** |
| **R** | **11.70** | **4.67** | **Periodic** | **2** | **96.9** |
| **Ta** | **11.62** | **4.67** | **Periodic** | **2** | **99.2** |
| **Vw** | **5.092** | **4.67** | **Periodic** | **3** | **84.2** |

### 4.2.4 Multiple Linear Regression Model

The general form of the multiple linear regression model used to investigate the inter-relationships between the hydrometeorological variables is shown in Equation 4.18.

$$\hat{y}(t) = \beta_0 + \beta_1 x_1(t) + \beta_2 x_2(t) + \ldots\ldots\ldots\ldots + \beta_n x_n(t) \tag{4.18}$$

Where

$\beta_0$ = Constant coefficient

$\beta_i$ = Coefficients of the variables $x_i$ , $i = 1,2,\ldots..n$

$x_i(t)$ = Independent variables of parameters under investigation

$\hat{y}(t)$ = Dependent variable

Multiple linear regression analyses were performed for the following dependent variables:

(1) water temperature, Tw

(2) dissolved oxygen, DO

(3) pH

(4) salinity, S

(5) oxidation reduction potential, ORP

The multiple linear regressions for the five dependent variables were performed by assuming the dependence of each dependent variable on the time series of the sets of independent variables as shown in Table 3.2. It was observed from the initial correlation matrix of the hydrometeorological parameters under investigation that the product of solar radiation R and air temperature Ta denoted as R*Ta gave a higher correlation for water temperature Tw as compared to either the individual correlations of R and Ta or the summed correlation of R and Ta for Tw. The variable R*Ta was included as an independent variable while performing the multiple regression analyses. The following variable selection procedures were used to evaluate the inter-relationships between the variables under investigation:

(1) Backward elimination (2) Best subset regression

### 4.2.5 Model Identification for Multiple Regression

The Model identification stage of multiple regression equations comprised of calibrating the following parameters for the predictors which exhibited statistical significance.

(1) $\beta_o$ (2) $\beta_i$

$\beta_o$ is the constant term and $\beta_i$ are the coefficients of variables $x_{i,}$ where i varied from 1 to 9. It was attempted to identify the predictive expressions for all the dependent variables investigated. Predictive models for the dependent variables under investigation were identified using the statistical package 'Minitab' while applying the afore-mentioned variable selection techniques described below.

### 4.2.6 Backward Elimination

Backward elimination procedure for each dependent variable was started with its associated nine independent variables. Backward elimination proceeded iteratively, by dropping the independent variable with the least partial sum of squares. The stopping point for a predictive model was identified when all the dependent variables had statistically significant t-values for a significance level of 0.95. Predictive models only of those dependent variables were selected which gave a high correlation coefficient and a high adjusted correlation coefficient for the independent variables regressed. Models for those dependent variables which did not give statistically significant predictors were discarded as potential predictors of the hydrometeorological and water quality variables investigated in this research.

### 4.2.7 Best Subset Regression

Best subset regression for the independent variables yielded 5 subsets of the predictive models from a combination of possible models for up to N-1 predictors. The five best subset regression models were suggested for cases with one independent variable and also for cases with up to eight independent variables. The instance involving the maximum number of independent variables, 9 in this regression, yielded only one best subset regression model. The best subset regression models provided useful information about the following statistical parameters.

(1) Correlation coefficient, $r^2$

(2) Adjusted correlation coefficient, $r^2$(adj.)

(3) Mallow's statistic, C-p

A predictive model was selected by retaining those variables which had a high correlation coefficient and at the same time they also gave a lower value of Mallow's statistic. Statistically significant predictive expressions were obtained for the following dependent variables by using multiple linear regression procedures.

### 4.2.8 Water Temperature, Tw

The water temperature could be predicted with an $r^2$ of 92.0% as a function of

ORP and R*Ta while independently using both variable selection criteria. Figure 4.10 shows the independent variables retained in the Tw predictive model.

#### 4.2.8.1 Backward Elimination Procedure

The backward elimination procedure yielded the following predictive equation for water temperature.

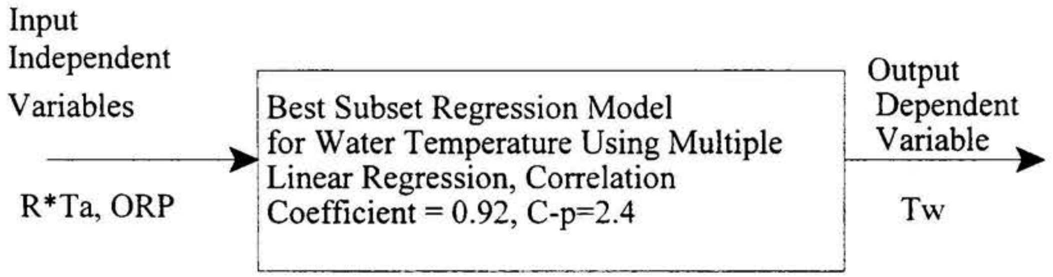

Figure 4.10 Multiple Linear Regression Model of Tw

$$\hat{T}w(t) = 6.944 + 0.035258\,R*Ta(t) - 0.007769\,ORP(t) \tag{4.19}$$

The plot of the multiple regression predictor for water temperature is shown in Figure 4.11.

#### 4.2.8.2 Best Subset Regression

Best subset regression gave results similar to those obtained by backward elimination.

$$\hat{T}w(t) = 6.944 + 0.035258\,R*Ta(t) - 0.007769\,ORP(t) \tag{4.20}$$

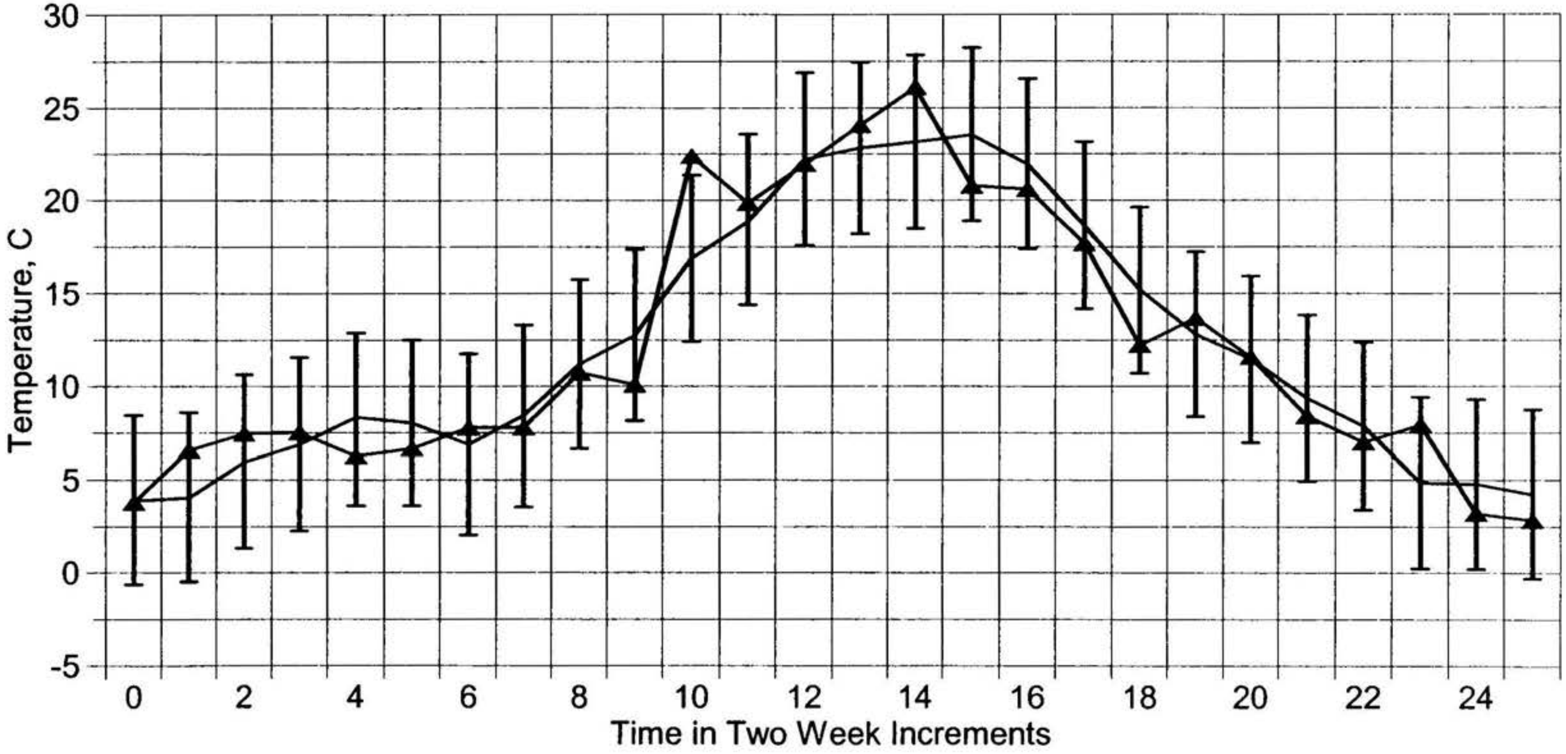

Figure 4.11 Multiple Linear Regression
95% CL, Water Temperature

### 4.2.9 Salinity, S

The following predictive expressions for salinity were obtained by applying the procedures of best subset regression and backward elimination respectively.

#### 4.2.9.1 Predictive Expression of Salinity by Best Subset Regression

Best subset regression provided the following predictive equation to estimate salinity in the surface waters of Pond No. 3.

$$S(t) = 0.077 - 0.005287R(t) + 0.00019195R*Ta(t) + 0.52683C(t) \quad (4.21)$$

The correlation coefficient for the predictive equation of salinity was 96.9%. Mallow's statistic had a value of 8.5 for the above stated predictive expression of Salinity.

#### 4.2.9.2 Predictive Expression of Salinity by Backward Elimination

Application of backward elimination procedure yielded the following predictive expression for salinity.

$$\mathrm{S(t)} = 0.15954 + 0.52196C(t) - 0.019538pH(t) + 0.0019260Ta(t) \quad (4.22)$$

The predictive equation had a correlation coefficient of 96.6% and a Mallow's statistic of 11.0. The relationship between the dependent and independent variables of the S model is shown in Figure 4.12. Figure 4.13 displays the Salinity predictor and its 95% confidence limits.

### 4.2.10 Error Analysis of Multiple Linear Regression Models

The residuals obtained from the difference between the significant multiple linear regression estimators and the corresponding original data series were tested for normality and randomness by constructing their normal score plots by plotting the ordered-observed

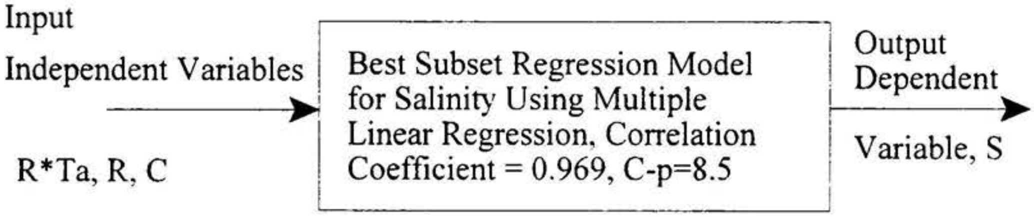

Figure 4.12 Multiple Linear Regression Model of Salinity

residuals against their normal ordered statistics. A straight line was fit through the data points of the normal order plots, both for water temperature and for salinity. The plots of the residuals of the regression models of Tw and S are shown in Figures A-10 and A-11 of Appendix A. The normal order plots of Tw and S are shown in Figures A-12 and A-13 of Appendix A.

### 4.2.11 Correlation Analysis of Multiple Linear Regression Models

Correlations between the original and the modeled data series of water temperature and salinity were evaluated as 95.88% and 98.69% respectively. Two sided 95% confidence limits were placed about the estimated data series of water temperature and salinity.

Multiple linear regression did not yield statistically significant predictors for the following variables:

(1) Dissolved Oxygen DO (2) pH (3) Oxidation Reduction Potential ORP

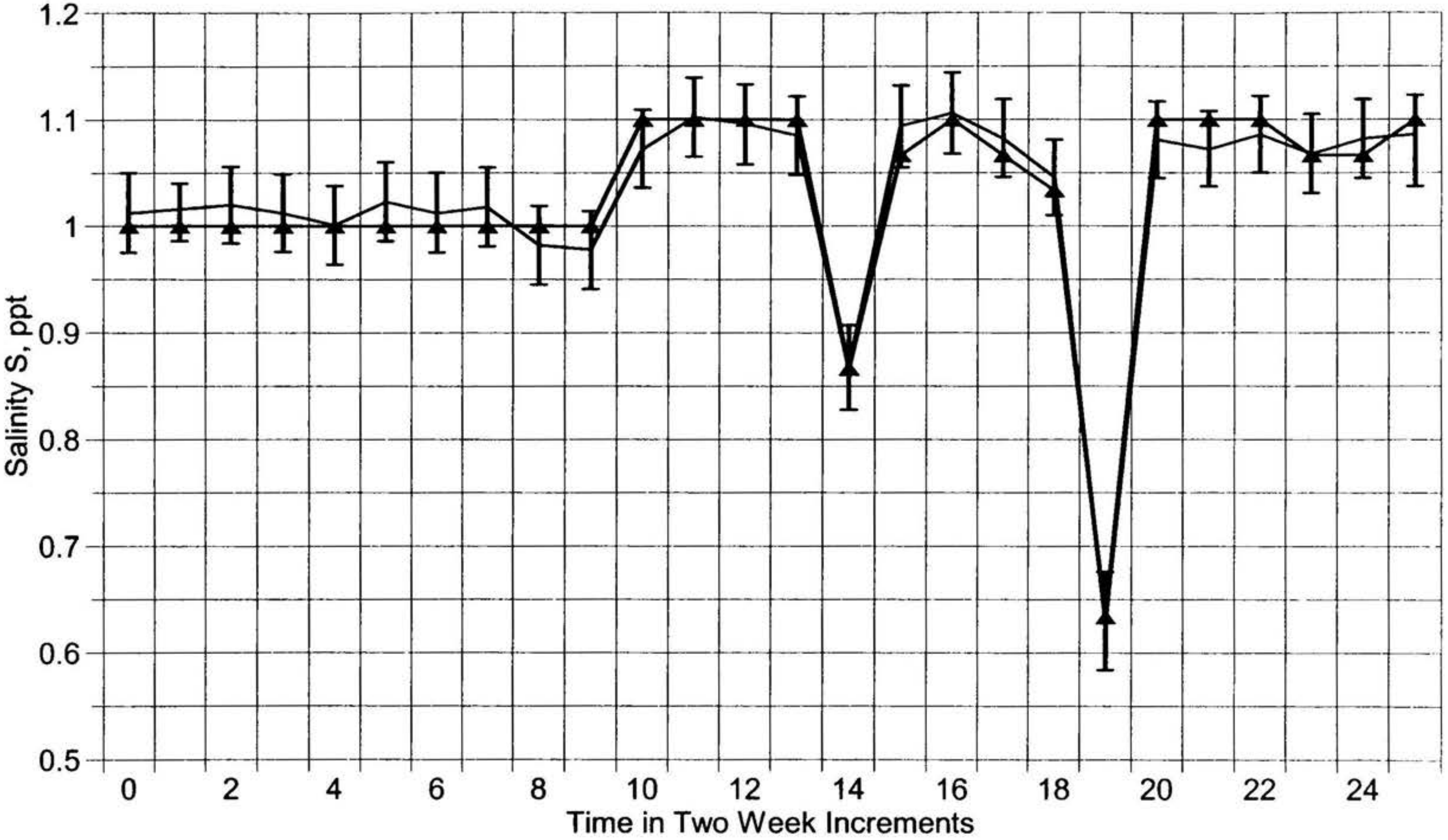

Figure 4.13 Multiple Linear Regression

95% Confidence Limits for Salinity

## 4.3 Summary

In this chapter, the statistical and mathematical models used to predict the hydrometeorological variables have been described. Information describing the model errors and correlations is also presented here. In the next chapter, the results of modeling presented in this chapter are analyzed for any significance. The spatial profiles are also analyzed in search of the important process-altering limnological phenomena.

# CHAPTER 5

# ANALYSIS OF MODELING RESULTS AND DEPTH PROFILES

The modeling results presented in the last chapter are analyzed for their significance on the limnological behavior of Pond No. 3. The input-output model formulation techniques employed in this study are also examined in the sections which follow later in this chapter. The depth profiles of the water quality variables are examined in an attempt to identify the important periodically occurring limnological phenomena which significantly impact the behavior of the 10 ft. deep wastewater treatment Pond No. 3 at Boxelder Sanitation District.

## 5.1 Discrete Fourier Models

The variables investigated in this research exhibited the following temporal behavior: (1) Periodic over the annual cycle, (2) Periodic with seasonal cycles, and (3) Non Periodic over the annual cycle, see Tables 4.4 and 4.5. Table 5.1 classifies the hydrometeorological and the water quality variables based upon their behavior over the annual and seasonal cycles.

The classification of the variables according to Fisher's test of periodicity, shown in Table 4.4, did not consider intra-annual seasonality in the variables investigated. It became apparent that higher classes of mathematical models are needed to develop

Table 5.1 Temporal Classification of Hydrometeorological Variables

| Variable Classification | Variable Name |
|---|---|
| Periodic over the Annual Cycle | Tw, R, Ta |
| Periodic with Seasonal Cycles | ORP, Vw |
| Non Periodic Throughout the Year | C, S, pH, DO |

reliable predictors of those hydrometeorolgical and biochemical variables which exhibited intra-annual seasonality.

The data sets of Tw; R; and Ta exhibited distinct periodic behavior and were rightly classified as periodic by Fisher's criteria of periodicity, see Table 4.4. The discrete Fourier models of the periodic data series, with one year as their fundamental period, gave satisfactory fits as seen by the application of the chi-squared $\chi^2$ goodness of fit test, see Table 4.3. The F-test harmonic selection criteria provided over-fits of the discrete Fourier series of these periodic data sets, see Figures 4.1; 4.7; 4.8; and Tables 4.4 and 4.5. Very high correlations were still obtained between the original and the generated data series by simply using less number of significant terms than those suggested by the F-test criteria, as shown in Table 4.5.

The F-test harmonic selection criteria, failed to accurately predict the right number of harmonics needed to generate the discrete Fourier series of the data sets which showed within-the-year seasonality, see Figure 4.2. The annual data series of Vw; ORP; and DO exhibited multiple peaks and were classified either as periodic or as nonperiodic when tested under Fisher's criteria of periodicity, see Figures 4.2; 4.6; and 4.7. The failure of the F-test harmonic selection criteria in the accurate prediction of the multi-periodic data series leaves room for the inclusion of additional harmonics to better simulate their discrete Fourier series. The Fourier series of the periodic data sets with distinct elements of seasonality call for the inclusion of higher sampling frequencies in order to better simulate the Fourier series of the multi periodic data sets.

According to Fisher's test of periodicity, the non periodic data series of pH; DO; C; and S were either too erratic or showed very little variance over the annual cycle, see Figures 4.2; 4.3; 4.4; and 4.5. Thus, the F-test harmonic selection criteria could not adequately and consistently model the above-mentioned multi-periodic and non-periodic data series. The poor fits of the non periodic data sets, which utilized only one significant harmonic for C and S, rendered their Fourier predictors unreliable, see Figures 4.4 and 4.5. As a consequence, only the average term was used to generate the Fourier series of all the non periodic data sets. Use of the average term in the simulated discrete Fourier series of these non periodic data sets, pointed toward the pertinence of the various regression techniques in order to examine the interrelationships among the various hydrometeorological variables as described below.

### 5.2 Multiple Linear Regression Models

It is notable that out of the five dependent variables examined, multiple linear regression yielded significant predictive expressions only for the following two variables, see Figures 4.11 and 4.13:

(1) Water Temperature, Tw (2) Salinity, S

Predictors of these dependent variables contained: (a) explanatory independent variables, and (b) a high correlation existed between the dependent variable and its corresponding group of independent variables. Inconsistencies among the predictive expressions obtained by multiple linear regression were ruled out by using the two variable selection schemes. Results of the statistically significant predictors obtained by multiple linear regression are summarized in Table 5.2. The remaining three dependent variables did not yield significant predictors when multiple linear regression was used.

Table 5.2, Multiple Linear Regression Results of Water Temperature and Salinity

| Dependent Variable | Regression Technique | Independent Variables | $r^2$ % | Mallows' Statistic, C-p |
|---|---|---|---|---|
| Tw | Backward Elimination | R*Ta, ORP | 92 | 2.4 |
| **Tw** | **Best Subset Regression** | **R*Ta, ORP** | **92** | **2.4** |
| S | Backward Elimination | C, pH, Ta | 96.6 | 11 |
| **S** | **Best Subset Regression** | **R, R*Ta, C** | **96.9** | **8.5** |

The predictive expressions for water temperature gave the same results using the two variable selection procedures, see Equations 4.20 and 4.21. It was observed during both the variable selection schemes that the combined variable R*Ta, the product of solar radiation and air temperature, was retained while independent variables such as solar radiation and air temperature were eliminated. Figure 5.1 displays the time series of

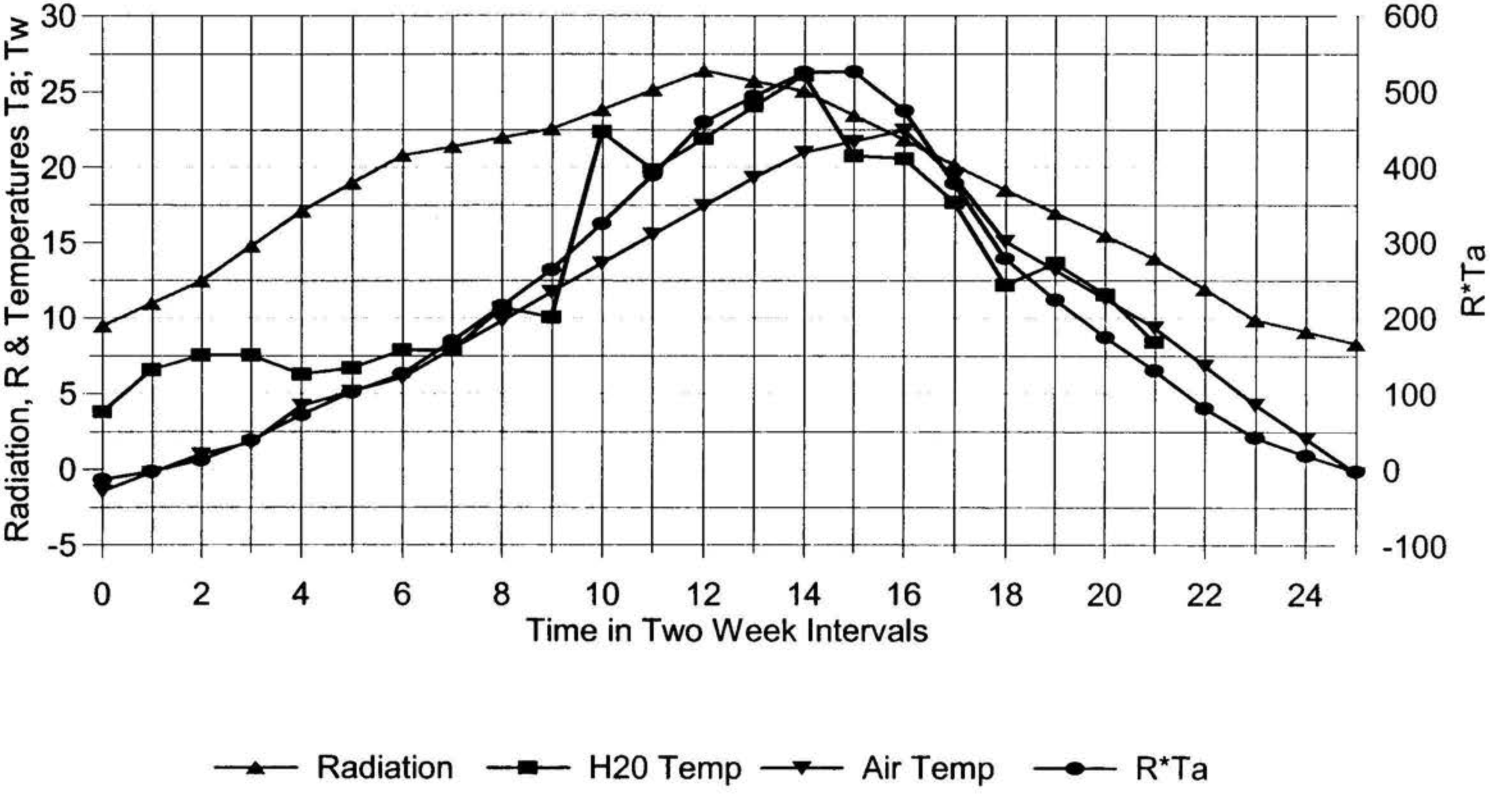

Fig 5.1 Max. Monthly Solar Radiation,
R*Ta, Max Air and Water Temperatures

Tw; Ta; R; and R*Ta. It was noted that the time series of the transformed variable, R*Ta, was more in-phase with the Tw time series. The time series of R and Ta showed greater lags with the Tw time series. R*Ta gave a higher correlation, than the first degree terms such as R and Ta, against Tw as seen in the correlation matrix in Table 5.3. R*Ta had the equivalent affect of a second order polynomial used to predict water temperatures. It seemed that the combined term R*Ta was a better representative of the over all affects of energy transfers which took place at the pond surface. This may very well be a reason for R*Ta to show a higher correlation than Ta and R considered either individually or additively. Other combinations of the transformed causal variables such as: $R^2$, $Ta^2$, $R + Ta^2$, $R^2 + Ta$, $R^2 + Ta^2$, logarithmic transformations, higher order polynomials, and other higher order transformations need to be investigated when correlating hydrometeorolgical and water quality data in future investigations.

For the salinity model, best subset regression yielded a predictive expression with a higher correlation coefficient and a lower Mallow's statistic than the predictive equation obtained by employing backward elimination procedure, see Sections 4.2.9.1 and 4.2.9.2. The independent variables of the salinity predictor obtained by best subset regression included two meteorological variables R and Ta, and one chemical variable C. Independent variables retained in the backward elimination predictor of S comprised of one meteorological variable Ta, and two chemical variables C and pH. The input-data requirements for backward elimination predictor of S involved higher costs than the costs associated with the input-data requirements of the best subset regression predictor of S, which involved only one chemical parameter C. Meteorological input-data such

Table 5.3, Correlation Matrix of The Hydrometeorological Variables Analyzed:

| | **Tw** | Ta | R | Vw | DO | ORP | C | S | pH | R*Ta | R+T |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Tw | 1 | | | | | | | | | | |
| Ta | 0.9115 | 1 | | | | | | | | | |
| R | 0.8189 | 0.8132 | 1 | | | | | | | | |
| Vw | -0.3396 | -0.3863 | 0.0054 | 1 | | | | | | | |
| DO | -0.1860 | -0.1562 | 0.0503 | 0.1947 | 1 | | | | | | |
| ORP | -0.4187 | -0.3258 | -0.1286 | 0.1577 | 0.4065 | 1 | | | | | |
| C | -0.1340 | -0.1700 | -0.0942 | 0.1057 | 0.0369 | -0.0360 | 1 | | | | |
| S | -0.0337 | -0.0690 | -0.0960 | -0.0007 | -0.0574 | -0.1196 | 0.9699 | 1 | | | |
| pH | 0.2814 | 0.3463 | 0.4818 | 0.2504 | 0.2634 | 0.1627 | -0.1548 | -0.2346 | 1 | | |
| **R*Ta** | **0.9505** | 0.9747 | 0.8680 | -0.3752 | -0.1698 | -0.3131 | -0.1140 | -0.0238 | 0.3059 | 1 | |
| R+T | 0.9140 | 0.9635 | 0.9393 | -0.2253 | -0.0690 | -0.2512 | -0.1436 | -0.0848 | 0.4257 | 0.9738 | 1 |

as solar radiation R and air temperature Ta can be easily obtained from the nearest weather station. In fact, optimization techniques can also be employed in such scenarios to minimize the costs of data collection and model formulation. Keeping in view the above-mentioned factors, the best subset regression predictor was chosen as the estimator of salinity. The random nature of the errors of the two predictive expressions was checked by plotting the normal order statistic graphs of their respective residuals.

### 5.3 Variable Contribution in Predictive Expressions

In this section, the significant contributing variables in the regression-based predictors of both water temperature and salinity have been identified.

#### 5.3.1 Water Temperature Contributors

The predictive expression of water temperature Tw was dependent upon R*Ta and ORP with a correlation coefficient of 92%. The x-y plot of the contributors of Tw showed that the constant term K and the product of solar radiation and air temperature R*Ta were the major contributors in the predictive equation of water temperature at the surface of Pond No. 3 of Boxelder Sanitation District. ORP had very little contribution in the predictive expression of surface water temperature in Pond No. 3, see Equations 4.20 and 4.21.

### 5.3.2 Salinity Predictor Contributors

The contributors to the predictive expression of salinity included a constant term K; conductivity C; solar radiation R; and the combined variable R*Ta. It was noted that if any variable was excluded from the salinity predictor then the predictive expression of salinity was significantly affected. The temporal and spatial profiles of the six hydrometeorological variables are examined in the following sections.

## 5.4 Temporal and Spatial Profiles of Hydrometeorological Variables

Out of the nine hydrometeorological variables investigated, Tw; R; and Ta exhibited very strong periodicity in their annual time series, see Figures 4.1; 4.7; and 4.8. The Tw depth-profiles began to stratify from early spring till late summer, as will be shown in Figures 5.4 and 5.5. The DO and ORP data sets showed multiple peaks over the annual hydrological cycle, see Figures 4.2 and 4.6. The erratic behavior of DO and ORP time series was signified by: (a) stratification, (b) accompanied by sudden surges or dips in their temporal and spatial profiles, see Figures 4.2 and 4.6. The pH time series showed very gentle variation over the year, see Figure 4.2. The only exception was a set of highly acidic readings, ranging from 4.37 to 4.38, recorded under the ice cover on December 24, see Figure 4.3. Very little temporal variations in the S and C readings indicated a lack of periodic behavior, see Figures 4.4 and 4.5. The spatial chemoclines of C and S coincided with the occurrence of the steepest thermocline recorded on July 26 and will be shown in Figures 5.10; 5.14; and 5.15. The formation of chemoclines is a well documented seasonal phenomenon observed in lakes and reservoirs during the periods of thermal stratification. The numbers adjacent to the plots of the various depth profiles are representative of the month in which the readings were taken.

### 5.4.1 Water Temperature Model, Tw

As noted in Pond No. 3 of Boxelder Sanitation District, the surface water temperatures varied from 2.8° C on December 24, to 26.11° C on July 26. Water temperatures at the pond bottom varied about 18° C. Very little variance was noted in the surface and bottom values of Tw from September through March. There was a critical period of about 20 weeks, which extended from around May 02 till September 24, during which distinct thermal stratifications were observed in the pond, as seen in Figure 5.2.

In January, there lay a thick sheet of ice on the pond surface. Although January had the lowest averaged monthly air temperatures in Fort Collins, the pond water temperatures kept on increasing over the entire depth profile. Increases in the pond water temperatures were primarily due to the increase in the incoming solar radiation since the Winter solstice. This led to the increased penetration of sun light, which in turn caused increased photosynthetic activity and hence higher DO values were observed during the day time. The increased light penetration under ice-covered acidic lakes was the most likely controlling factor which may have resulted in the reduced concentrations of dissolved organic carbon (DOC) and dissolved inorganic carbon (DIC). The increased

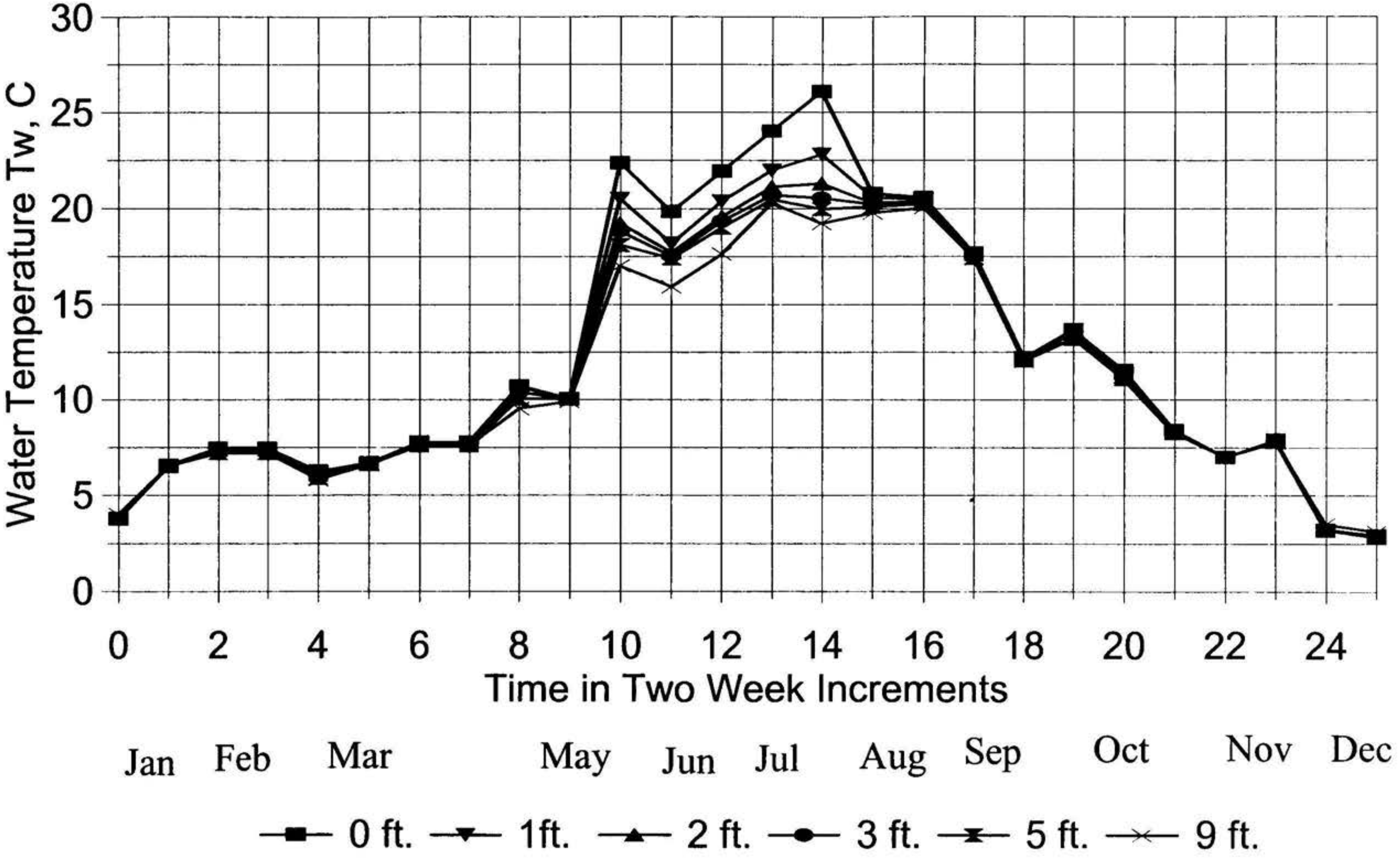

Figure 5.2, Site Averaged Water

Temperatures, Pond 3, 1995

light penetration under the ice cover provided larger depth for photosynthetic activity to take place. Figure 5.3 displays the important Tw depth profiles recorded in Pond No. 3 in 1995.

The ice cover melted by the end of February. Rapid warmup of the pond waters was observed in March with the approaching spring equinox, see Figures 5.3 and 5.4. The corresponding Tw depth profiles remained isothermal. The Tw depth profiles oscillated back and forth from the early part of spring till the early part of summer 1995, after the seasonal episodes of snowfall and precipitation, see Figures 5.4 to 5.6. The surface and bottom Tw readings in the pond ranged from 7.47° C to 7.22° C on February 23, 1995 respectively. Fort Collins received 5.1 inches of snow during the first week of March. As a result of the cold spell experienced on March 09, 1995, the pond's surface and bottom Tw readings decreased to 5.7° C and 6.1° C respectively. The next two weeks witnessed nice warm weather, as a consequence of which, on March 28 the respective Tw readings at the surface and bottom of Pond No. 3 ranged from 6.6° C to 6.7° C.

On April 13, the surface and bottom Tw readings varied from 7.79° C to 7.90° C. It took seven weeks for the Tw values to exceed the Tw reading of 7.47° C, which was recorded on February 23. The first signs of significant thermal stratification became apparent on May 02, 1995 when the respective surface and bottom Tw readings ranged between 10.71° C and 9.56° C. Once again, the surface Tw values decreased on May 22 to 10.07° C. This decrease in Tw readings most probably occurred due to the cooling effect caused by 5.69 inches of rainfall recorded from May 02 to May 22 in Fort Collins.

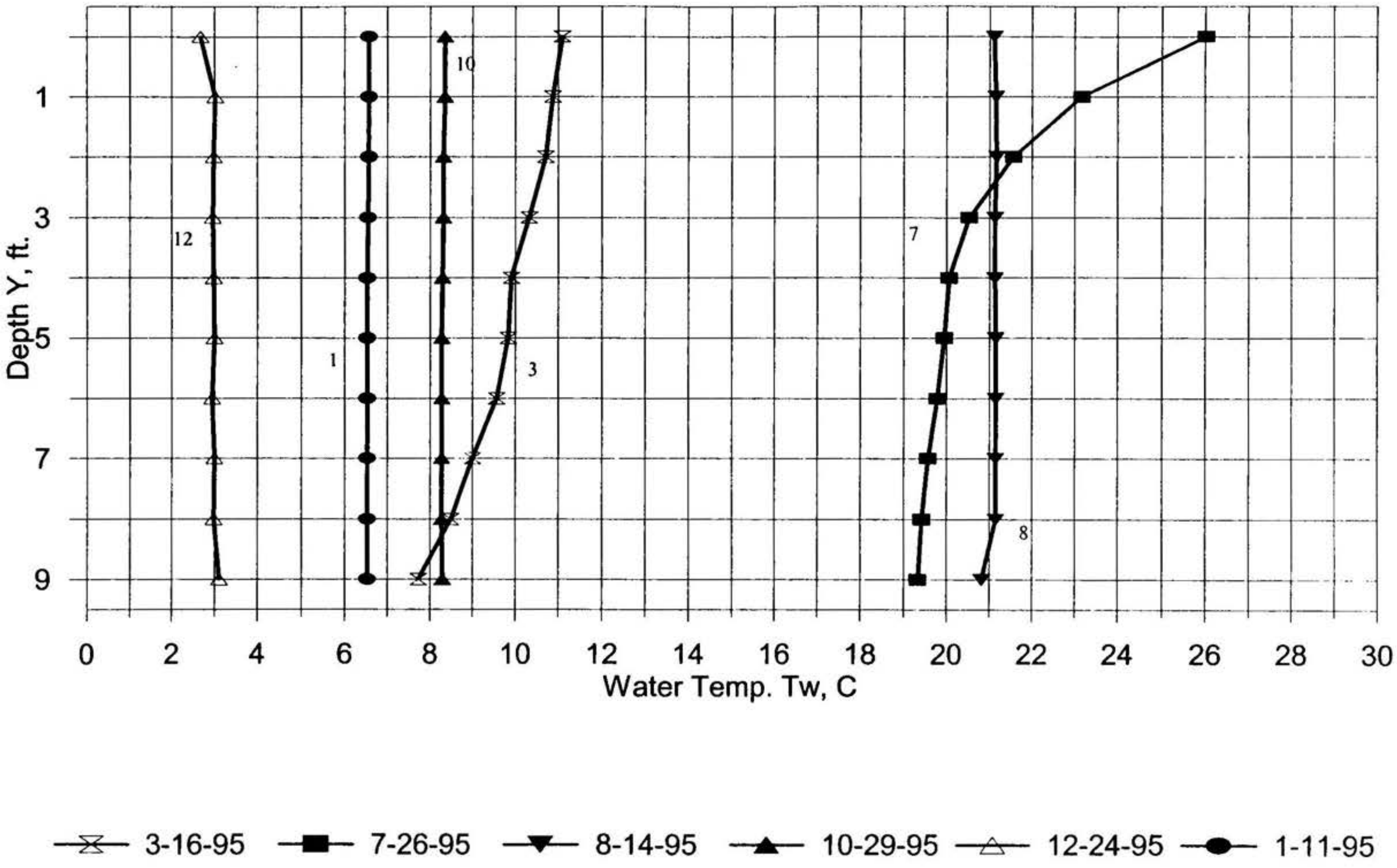

Figure 5.3, Water Temperature Depth
Profiles of Pond Number 3

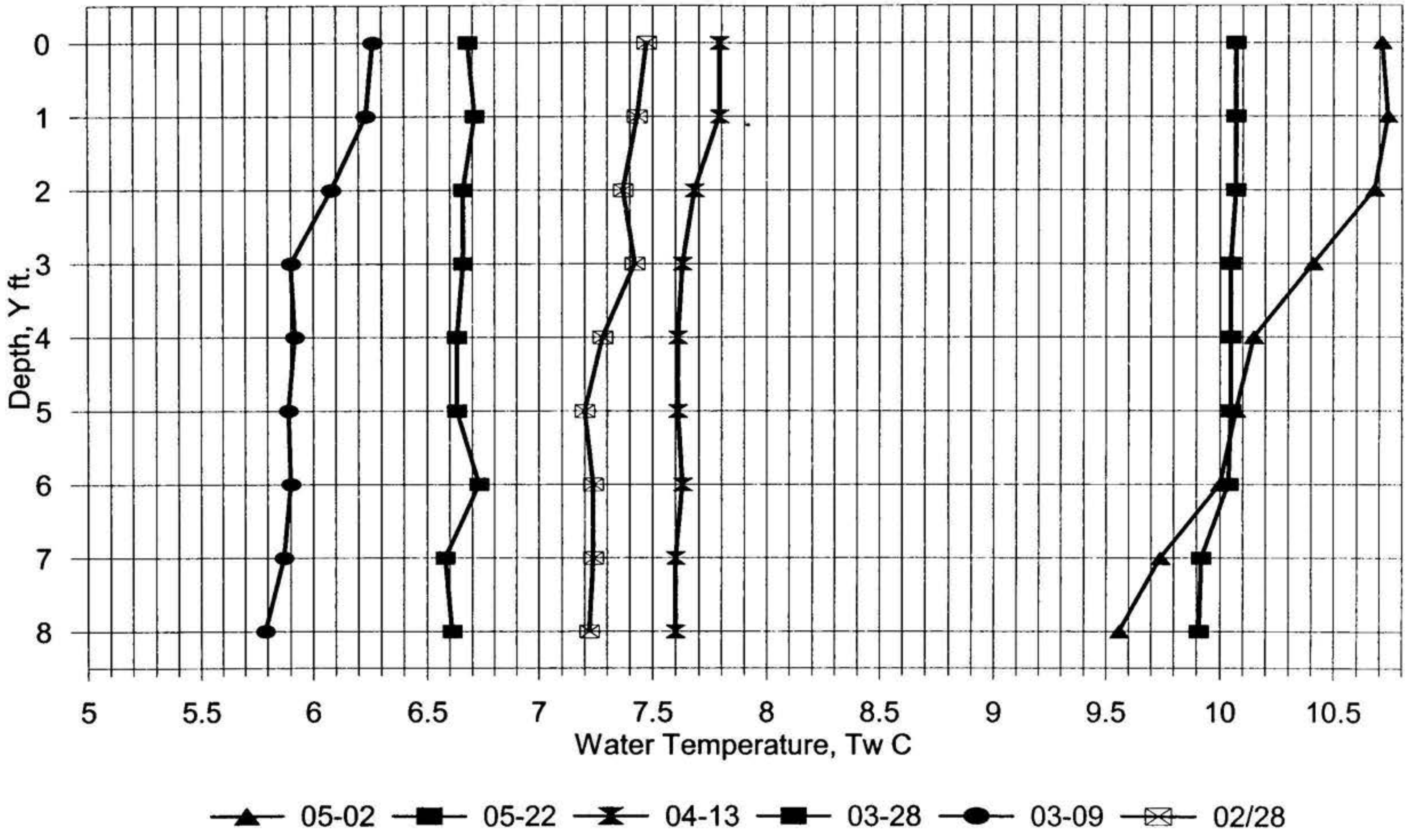

Figure 5.4, Thermoclines in Pond 3

Spring 1995

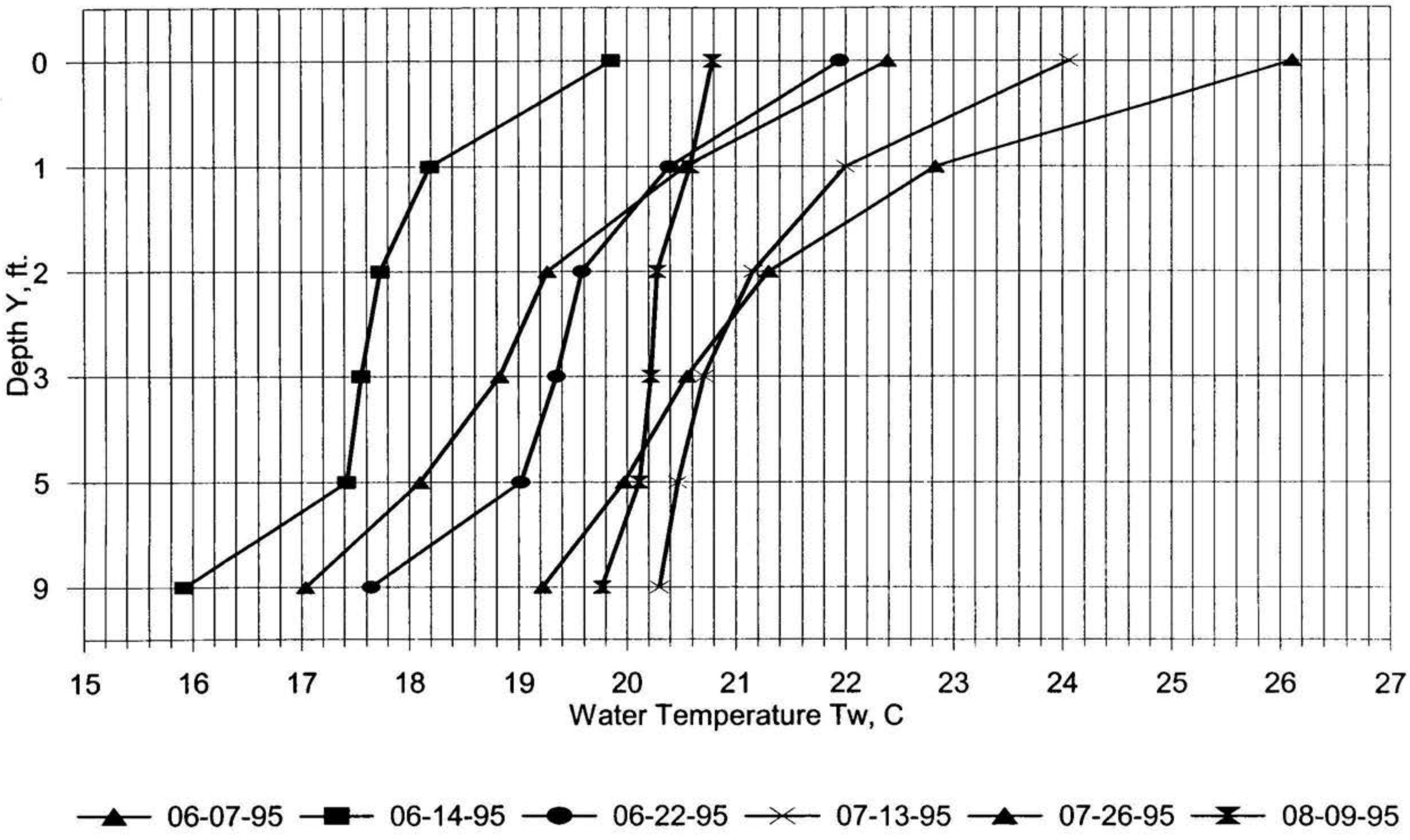

Figure 5.5 Thermoclines in Pond 3
Summer 1995

Oscillations of the unstable thermoclines continued in the early part of the summer. The surface and bottom Tw readings recorded on June 07 varied from 22.38° C to 17.15° C. These Tw readings were higher than the corresponding Tw readings observed on June 14, which ranged from 19.85° C to 16.78° C. 0.90 inches of rainfall, recorded in the first week of June, was the most probable cause of this cooling cycle of the pond water temperatures.

Thermoclines formed in the summer season are shown in Figure 5.5. A distinct and stable thermocline was formed on July 26, 1995. The Tw readings of July 26, were the warmest pond water temperatures with the largest spread between surface and bottom readings over the entire year. A 7° C temperature difference existed between the surface and bottom pond waters, shown in Figure 5.3. The top 2 feet accounted for about 5° C of the temperature difference, whereas the remaining 7 feet showed a water temperature difference of about 2° C. Around the 2 feet depth, there was a marked change in the slope of the temperature gradient, shown in Figure 5.3. After the stable thermocline formation on July 26, the pond stayed stably stratified with the top 2 feet of the pond containing the least dense waters. Due to a high level transfer from Pond No. 2, the underlying denser waters in Pond No. 3 prevented mixing at greater depths.

Sinking of the organic matter was mostly restricted to the top 2 feet of the pond depth. The decomposition of organic matter in the upper density stratum was accompanied by a sharp decrease in DO at the 2 feet depth in the corresponding DO profile. Along with reduced DO solubility, strength of the wastewater, and density of the partially treated wastewater entering Pond No. 3 were the contributing factors for the sharp reduction in DO between the interface of the two density strata. Concentrations of the different biological life forms in the various zones of the water column were the most likely contributing factors in the occurrence of the DO minima at 2 feet depth. The entire pond turned anoxic for about three to four weeks after the formation of the thermocline on July 26.

On August 15, the Tw readings in the entire depth profile ranged around 20.5° C, which indicated significant erosion of the stable thermocline formed on July 26. The falling values of both R and Ta appeared to be the causal factors which led to the decreasing trend in the Tw readings observed in the pond. The Fall cooling-effects became more pronounced and heat was mostly transferred from the pond waters into the surrounding air. The proximity of the restoration of the isothermal conditions over the entire depth profile and the Fall equinox were notable, see Figures 5.2 and 5.6.

Figure 5.6 displays the cooling phenomena observed in Pond No. 3 in Fall 1995. On September 24, near the Fall equinox, the water temperatures decreased rapidly and the isothermal depth profiles exhibited Tw values which ranged around 12.20° C. In Fort Collins, 6.1 inches of snowfall was recorded on September 23 and 24. From September 18 to 24, 2.98 inches of precipitation was also recorded. Maximum air temperatures of 50° F, 36° F, and 57° F were recorded on September 20, 21, and 24 respectively. September 22 was the first night of the Fall 1995 season when the minimum air temperature fell below the freezing point to 24° F. October 29, witnessed more cooler water temperatures around 8.40° C. The corresponding DO depth profile exhibited a positive heterograde. The pond water temperatures kept on decreasing till December 24.

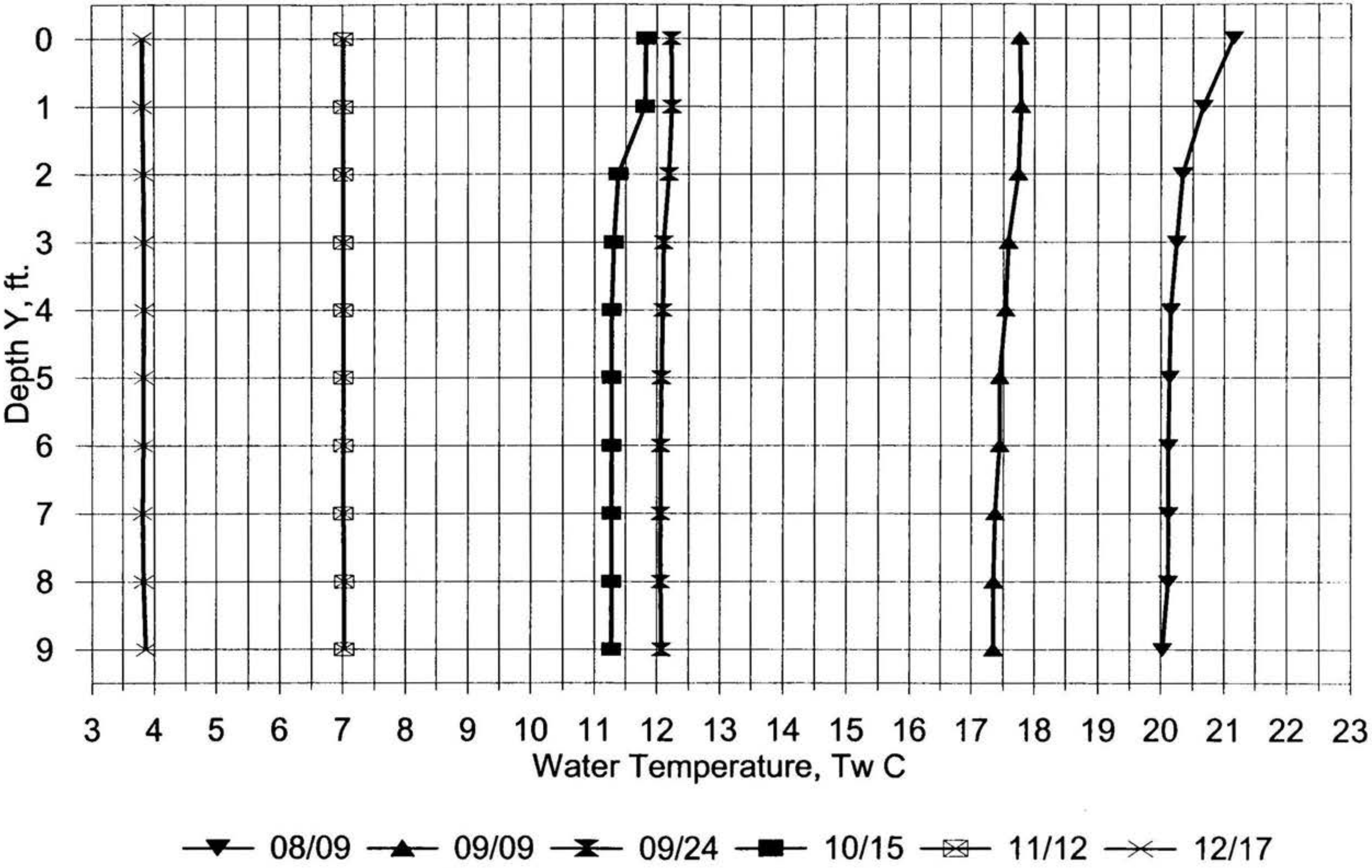

Figure 5.6, Thermoclines in Pond No. 3
Fall 1995

An ice cover had formed on the pond surface between December 17 and December 24. Inverse stratification occurred in Pond No. 3 around December 17 when the surface Tw readings went to 3.81° C and Tw values at the pond bottom stood at 3.86° C. As noticed earlier in the year, the water temperatures rose to around 6° C on January 11. Thus, in a period of about three to four weeks, the water temperatures twice crossed the 4° C mark. This fluctuation of Tw about the point of maximum density, most likely, caused at least two episodes of densimetric mixings, one in December and one in January, as shown in Figure 5.7. Other notable phenomena included the persistent lags in the occurrence of the minima and maxima of solar radiation R; air temperature Ta; water temperature Tw; and dissolved oxygen DO over the annual hydrological cycle.

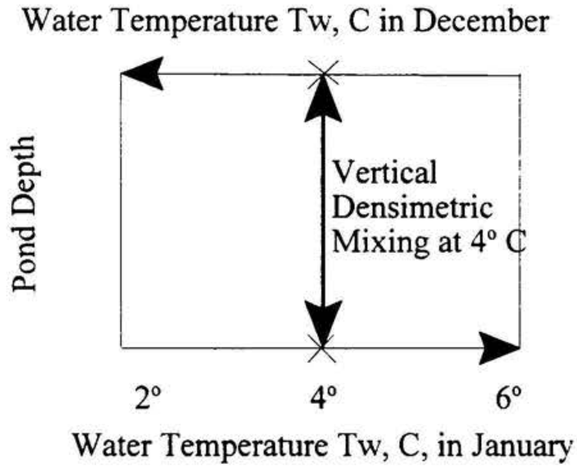

Figure 5.7 Water Temperature Variations and Vertical Mixings

In accordance with the rule of 10 ($Q_{10}$) the reaction rates varied widely in Pond No. 3, which exhibited a surface water temperature variance of about 25° C. The Tw values varied around 18° C at the pond bottom, see Figure 5.2. It is notable that application of the same reaction rate constants around the year to determine the important biochemical reactions in the pond will lead to misleading results.

### 5.4.2 Dissolved Oxygen Readings, DO

Dissolved oxygen concentrations of the surface waters showed three significant peaks. There were five instances when the dissolved oxygen concentration went to zero. The entire pond turned anoxic at the peak of the summer season, lasting from the fourth week of July till the third week of August. The time series of DO over six depths in Pond No. 3 are displayed in Figure 5.8. Examination of the site averaged DO profiles revealed that for most of the time, DO near the pond surface stayed the highest. The DO concentrations at the pond bottom kept going to zero more frequently than at the surface. This repeated anoxia indicated that anoxic conditions prevailed at the sludge water interface. Below the sludge layer, existence of anaerobic conditions was highly probable. Oxygen solubility in water, both theoretical and measured, was plotted as a function of temperature for an atmospheric pressure of 635 mm of Hg and is shown in Figure A-14 of Appendix A. Examination of the theoretical and measured DO values indicated that super saturation of the surface DO readings occurred on four occasions due to intense photosynthesis caused by algae blooms in the pond. The DO readings were indicative of a very strong tendency for the settling Pond No. 3 to function: (a) aerobically; (b) facultatively; (c) anoxically; and (d) anaerobically, at different depths

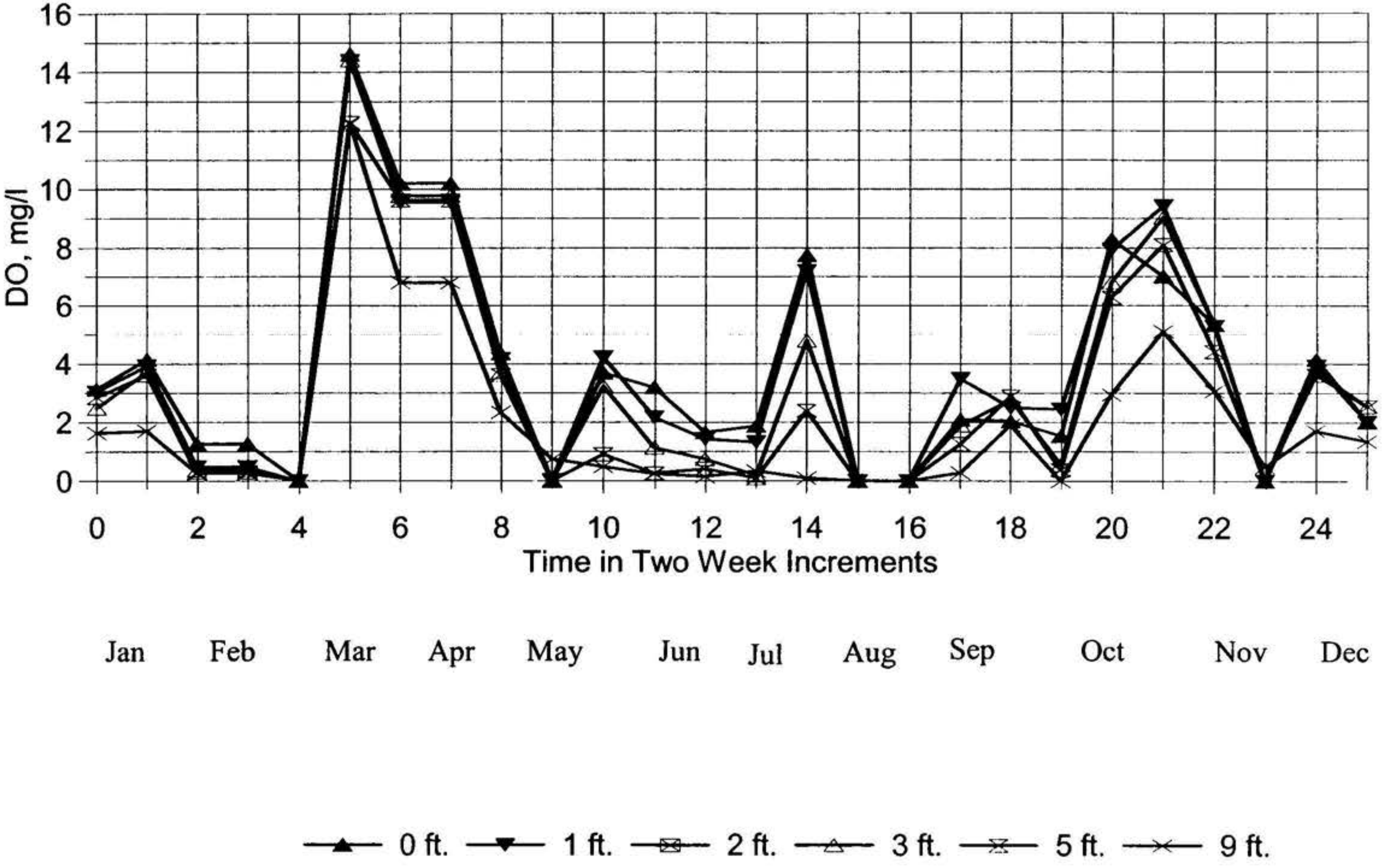

Figure 5.8 Depth Averaged DO, Pond 3

at various times of the year, even under the widely varying climatic conditions experienced in Northern Colorado. The significant DO depth profiles observed under these widely varying climatic conditions, for the one year period, are presented in Figure 5.9.

On January 11, the DO concentration in the surface waters was around 4.27 mg/l and at a depth of 8 feet, the DO gradually decreased to about 3.6 mg/l. One foot below at the pond bottom, the DO concentration sharply reduced to 1.97 mg/l. This sudden reduction in the DO concentrations was most likely due to the very slow reaction rates which led to the accumulation of undigested sludge at the pond bottom. It is well established that reaction rates greatly slow down at and near freezing temperatures. The layer of anaerobic bacteria critical for sludge digestion was either destroyed or was greatly reduced due to the sinking of denser and highly oxygenated waters to the pond bottom caused by inverse stratifications that occurred after ice formation as shown in Figure 5.7. For the pond water temperatures observed in January, the DO readings should have been much higher than those actually recorded because of increased DO solubility. The ice sheet overlying the pond surface had effectively cut off surface reaeration toward the end of the preceding December, reducing the surface DO to zero.

With the spring thaw of March and the approaching spring equinox, the surface water layers of Pond No. 3 became richly oxygenated. It is notable that inspite of decreased DO solubility, an increase in the pond water temperatures was accompanied with further increase in the DO values. Some of the reasons for such behavior included: the water entering Pond No. 3 was rich in dissolved oxygen due to the continuous

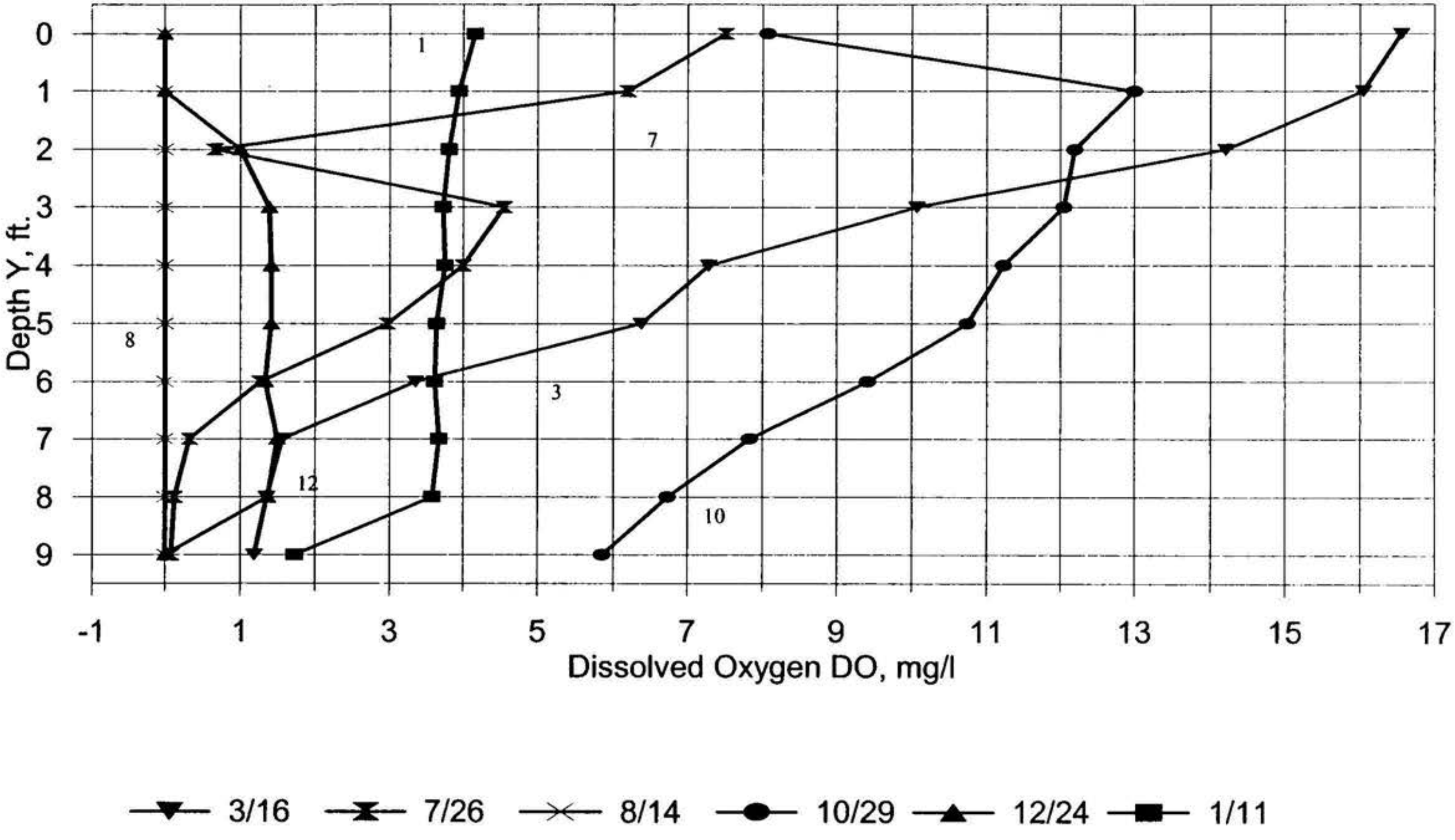

Figure 5.9, Dissolved Oxygen Depth
Profiles of Pond 3

aeration in Ponds Nos. 1 and 2. With the ice cover melted, there was also free exchange of oxygen between the surface pond waters and the surrounding air. Oxygen demand at the pond bottom was still high due to the undigested sludge that accumulated during the ice cover period, which most likely led to the reduced DO concentrations observed at the pond bottom. Effluent transfer near the surface, from Pond Nos. 2 to 3, resulted in the spreading of warmer and lighter waters in the upper layers of Pond No. 3. The nice warming trend experienced from mid March raised the pond water temperatures. The higher Tw values provided an environment conducive for intense algal activity. As a consequence of photosynthesis, the following higher surface DO readings were recorded on March 16, March 28, and April 13 respectively: 16.56 mg/l, 14.62 mg/l, and 10.21 mg/l. The corresponding elevated surface pH values were also recorded: 7.8, 8.06, and 8.2.

It is notable that the DO concentrations decreased at the bottom of Pond No. 3 from 1.97 mg/l on January 11 to about 1.18 mg/l on March 16. On the same dates, the surface DO concentrations increased from 4.27 mg/l to 16.56 mg/l, see Figures 5.8 and 5.9. The DO depth profiles of Pond No. 3 in March and clinogrades observed in the deep and shallow lakes were found to have great similarity, see Figures 2.4 and 5.9. The clinograde in the pond was formed due to the oxidative processes which occurred in the hypolimnion. The intensity of the clinograde reflected the amount of organic matter that reached the hypolimnion from the productive zones of the pond.

As a consequence of which, the DO concentration of the hypolimnion was reduced and stayed under saturated. Oxygen consumption was most intense at the sediment water interface due to the bacterial respiration and also due to the accumulation of the undigested organic matter in the hypolimnion. The increase in the surface DO concentrations in the upper stratum indicated the occurrence of very intense photosynthesis in the upper layers of the pond after the spring thaw and the subsequent warmup. Thus the upper layers of the water column experienced renewal mechanisms of oxygen production mostly due to photosynthesis.

The highly aerobic conditions experienced from March 09 till April 13, most likely facilitated for oxidative processes such as nitrification to occur in the pond. Very strong wind gusts experienced in March were found to be insignificant to influence the DO readings at the surface of the pond.

As the summer heating progressed, solubility of oxygen in water decreased and the pond started to turn anoxic around May 22. The DO-depth profile of 07-26-95 showed a DO concentration of 7.51 mg/l at the pond's surface. At the 2 feet depth, the DO concentration was only 0.66 mg/l. The DO concentration rose to 4.56 mg/l at the 3 feet depth. The DO concentration profile decreased gradually below the three feet depth to 0.08 mg/l at the pond bottom. This type of DO profile known as: "negative heterograde" in the limnological literature and is identified by a negative peak signifying metalimnetic oxygen minimum, with an inflection point. Formation of the negative heterograde took place when there was a greater uptake of oxygen in the metalimnion than in the upper hypolimnion. Concentrations of aquatic life in the nutrient rich zone were the most likely cause for the formation of the negative heterograde. The most plausible reason for such behavior was that the migration of aquatic life forms to the nutrient rich zones caused a sharp decrease in the DO concentrations due to increased respiration, see Figure 2.2. Pond No. 3 witnessed the formation of the negative heterograde on the same day as the formation of the steepest thermocline as shown in Figure 5.10. Location of the negative heterograde appeared to mark the lower boundary of the less denser overlying water stratum. Decay of the suspended organic matter along with increased respiration of aquatic life forms led to the formation of the negative heterograde in Pond No. 3.

As a consequence of the stable density stratification, the organic matter settling in the pond took longer to reach to the pond bottom due to greater resistance experienced from the larger buoyant forces of the underlying denser layer of wastewater. Stable density stratification caused the overlying lighter stratum of wastewater to become rich in nutrients due to the decomposition of the incoming organic matter. This led to the migration of aquatic life forms to the zone rich in nutrients. Hence the combination of the accumulated oxidizable organic matter and the increased respiration of aquatic life in the nutrient rich zone led to the formation of the negative heterograde. It is worth noticing that solar radiation had been decreasing since the summer solstice but the water temperatures kept on rising till July 26. To the contrary, the DO concentrations kept on decreasing till the middle of August. From a causal point of view, the lags in the occurrence of maxima and minima of Tw; Ta; R; and DO signified the signal response time $\tau$ in the occurrence of physically realizable phenomena.

The decreasing trend of the DO concentrations did not reverse in August. The negative heterograde profile formed on July 26, turned totally anoxic over the entire depth

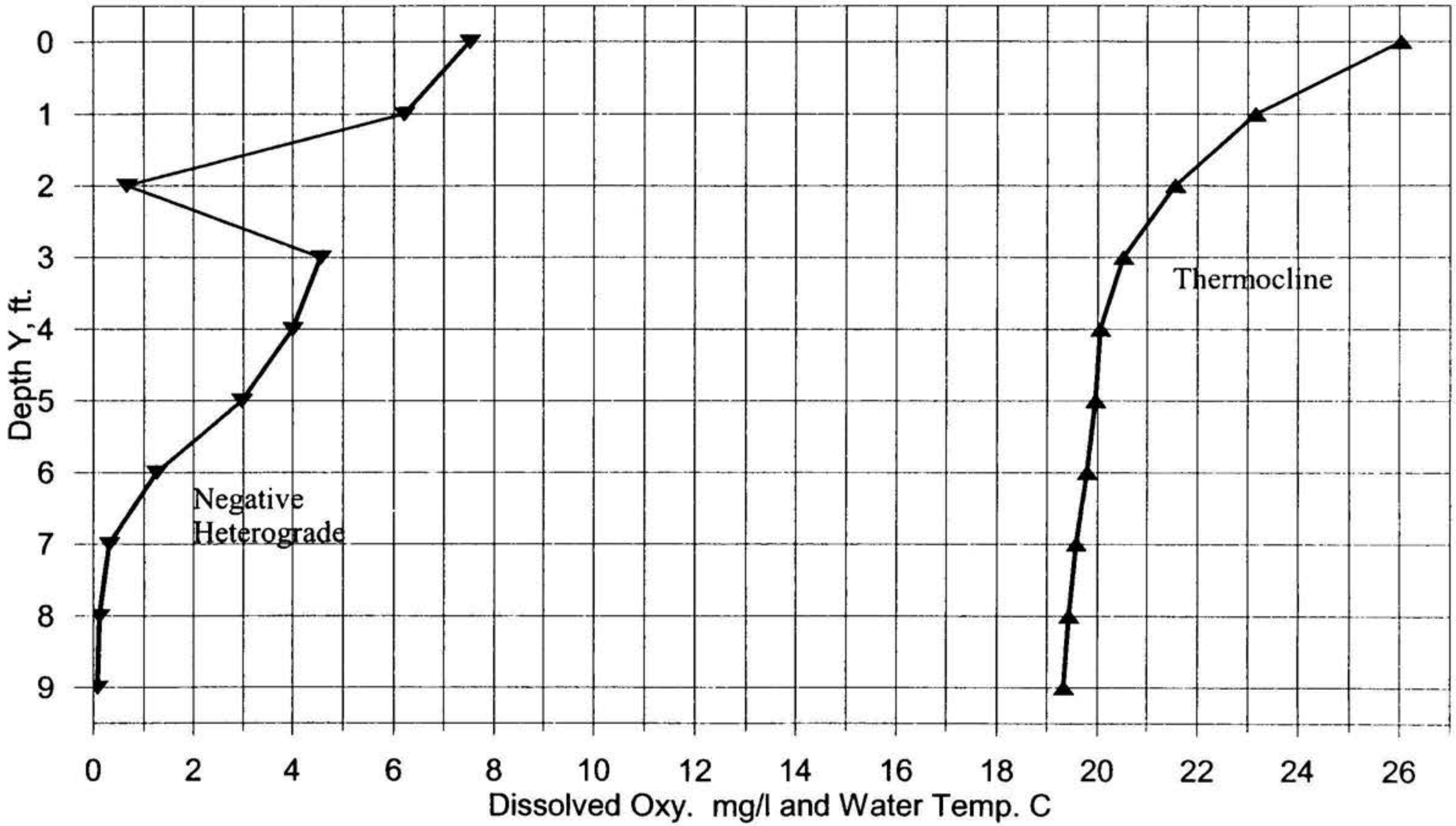

Figure 5.10 Negative Heterograde
and Thermocline on July 26 in Pond 3

of the pond. Very strong anoxic conditions existed over the entire depth from July 28 till August 15. These anoxic conditions created an environment, in the entire pond, suitable for denitrification and phosphorus release.

Wind induced reaeration coupled with falling temperatures, caused the pond to once again become aerobic. The mixing of DO in the surface waters intensified around the fall equinox. By 10-29-95, the entire water column became highly aerobic. October 29, showed a marked decrease in the Tw depth profile. The corresponding DO profile was signified by the formation of a positive heterograde near the pond surface as shown in Figure 5.11. Excessive oxygen production due to increased algal photosynthesis and increased phytoplanktonic activity were the most probable causes for the formation of the positive heterograde. The surface layer had lower DO concentrations than its underlying layer of water.

The positive heterograde was formed due to a decrease in the DO solubility, especially in the upper layers of the epilimnion because of the very high summer temperatures. The oxygen consumption in the hypolimnion resulted in the formation of a typical clinograde profile. The result was an absolute oxygen maximum in the metalimnion which was above saturation. Due to increased oxygen production, algal photosynthesis was the most likely contributor in the formation of the positive heterograde. As photosynthesis varied with the time of the day, positive heterogrades were very sensitive to the time at which readings were taken. The entire depth profile remained aerobic till the end of December.

An ice sheet formed over the entire pond during the last two weeks of December.

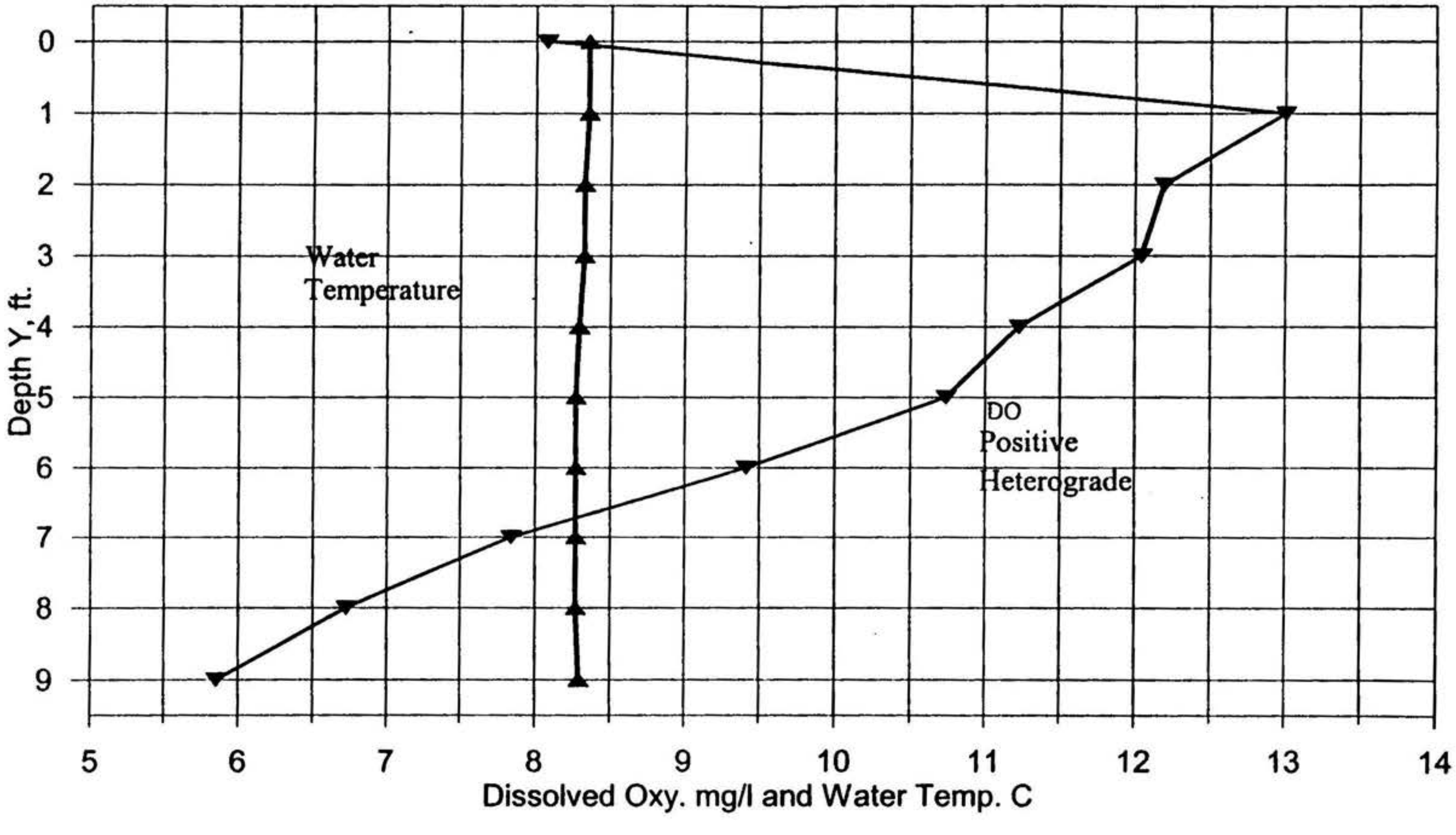

Figure 5.11 Positive Heterograde and WaterTemperature Profile. October 29

The Tw readings indicated that colder water lay on top of warmer water. This led to the plummeting of oxygen rich surface waters to the pond bottom. The affect of densimetric mixing was seen in the DO profile recorded on December 24. In the top one foot from the surface, the DO went to zero due to lack of surface reaeration and also due to the high oxygen demand of the partially treated influent. The DO rose to 1 mg/l at the 2 ft. depth. From 3 ft. to 8 ft. depths, the DO values stayed around 1.6 mg/l.

On October 29, throughout the entire depth profile, both the Tw and the DO readings were higher than the corresponding readings of Tw and DO observed on December 24. This contrast in the behavior of the Tw and DO values indicated that the water temperature was not the only factor which significantly influenced DO concentrations in Pond No. 3. Once again, the lags in the trend reversals of R; Tw; Ta; and DO concentrations were notable and warrant further detailed investigations.

### 5.4.3 Elevated and Acidic pH Readings, pH

For most of the year, the pH readings at the surface of the pond ranged from 7.2 to 7.6, see Figure 5.12. The pH values at the pond bottom varied between 6.7 to 7.2. On four occasions during the year, the pH observations exceeded 8.0. The most important exception in the pH readings occurred on December 24, soon after the ice cover formation. The entire pond turned acidic for a brief period. Very low pH values of 4.38 were recorded just below the ice sheet. The pH remained at 4.38 till the 4 feet depth, see Figure 5.13. From the 5 feet depth till the bottom of the pond, pH values of 4.37 were recorded. The more acidic pH readings in the lower depths of the pond indicated that the undigested carbon had most likely accumulated in the lower half of the

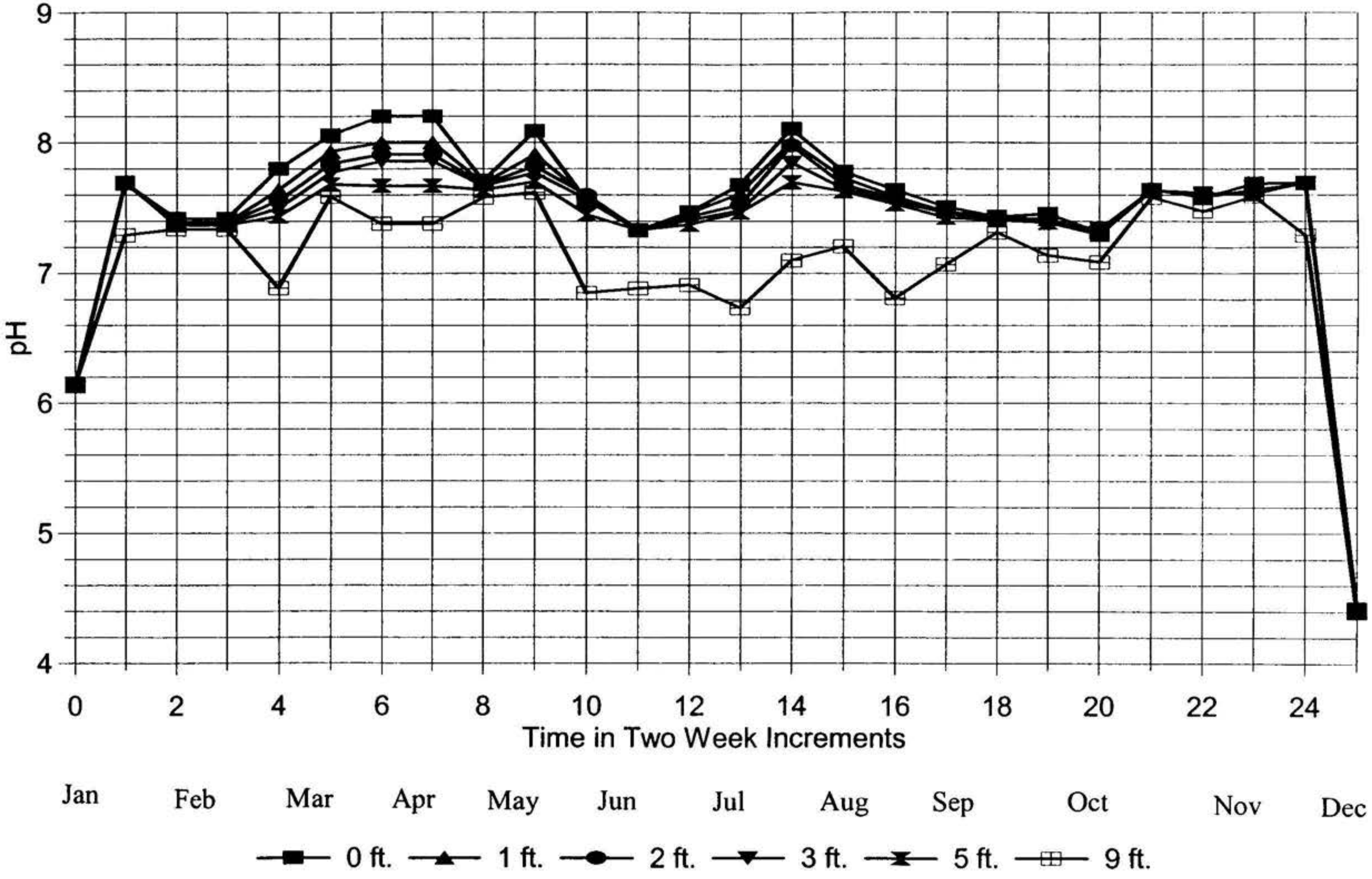

Figure 5.12, Site Averaged Time Series
of pH at 6 Depths, Pond 3

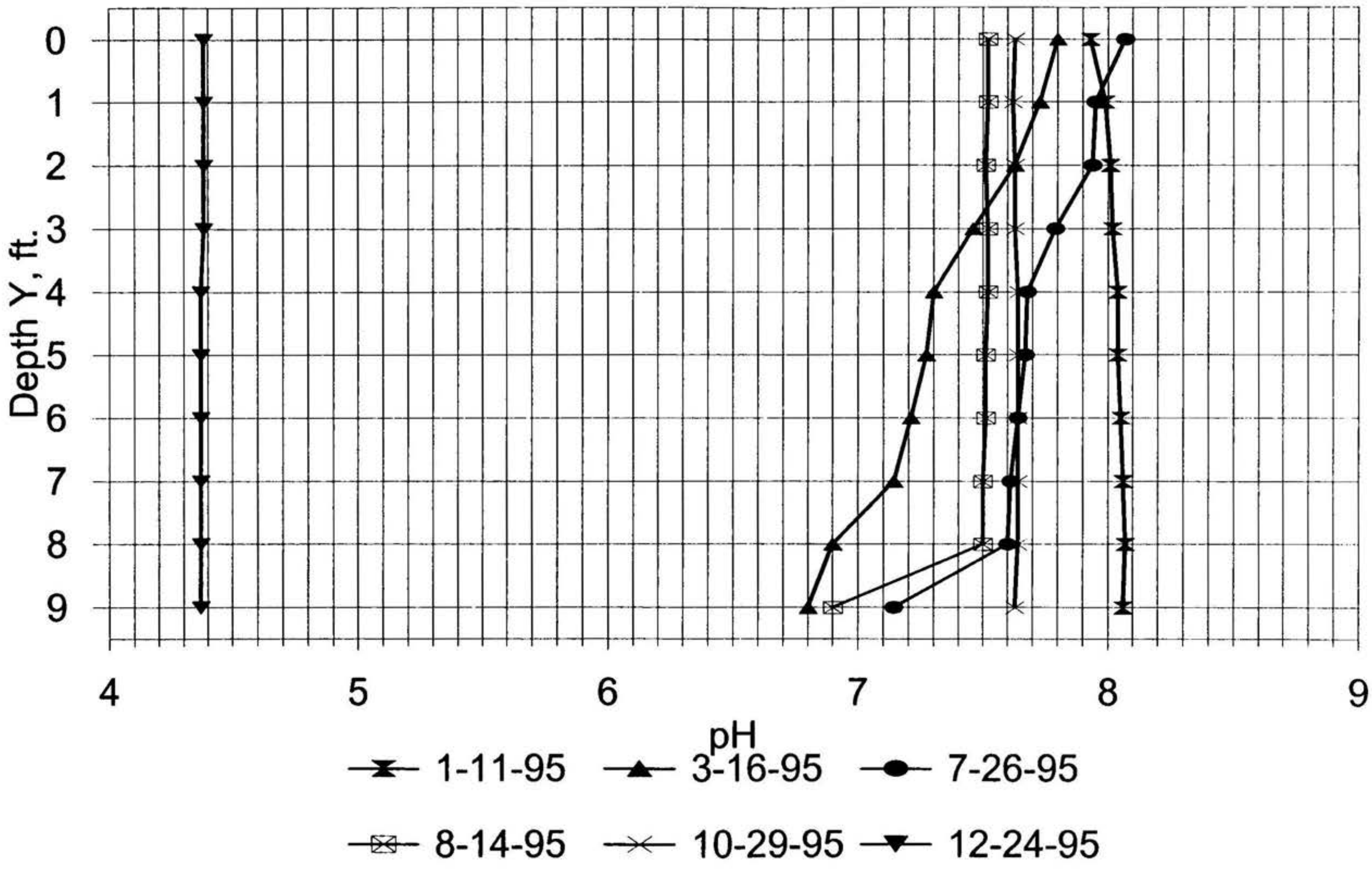

Figure 5.13, pH Depth Profiles Pond 3

pond, – especially at the sludge water interface. After experiencing strongly reducing conditions, the carbon dioxide gas released at the pond bottom could not escape into the atmosphere due to the overlying ice barrier. The entrapped $CO_2$ gas at and near freezing temperatures, with a very high solubility, most likely reacted with water to form carbonic acid. Hence the entire Pond No. 3 became acidified after the formation of the ice cover. The acidified pond was most likely to exhibit reduced DOC and DIC concentrations. The reduction in DOC and DIC would have allowed for increased light penetration under the solid ice cover. Even under the solid sheet of ice, the increased light penetration would have most probably facilitated for photosynthesis to occur over deeper depths. Thus, resulting in increased DO production and the DO values began to recover by the end of the first week of January.

It took till mid January for the pond to return to normal operating pH values. Earlier in the year on January 02, pH readings of 6.13 were recorded, see Figure 5.12. This three to four week period, from the third week of December till mid January, may very well be the period when either some reaeration, primarily from increased photosynthesis, became possible or the genera of bacteria in the pond were able to adapt and to recover from the drastic change in pH experienced soon after ice formation. Elevated surface pH readings were recorded on March 16, March 28, April 13, May 22, July 26, and October 29, see Figure 5.12. Except for May 22, the elevated surface pH readings coincided with very high DO observations in the surface waters. The elevated values of pH and DO pointed to the occurrence of intense photosynthesis in the upper layers of the pond, where light penetration was greater than in the deeper zones of the pond. The glass pH probe was also found broken after data was collected under the ice cover over lying Pond No. 3 on December 24.

### 5.4.4 Salinity Model, S

Salinity depth profiles for most of the year, shown in Figure 5.14, stayed vertical and oscillated between 1.0 and 1.1 ppt. An exception to the vertical S profiles occurred by the end of July when the salinity profiles stratified. Salinity stratification was recorded with the same observation which showed formations of a distinct thermocline and a negative heterograde on July 26, see Figure 5.10.

Chemoclines of salinity in lakes were identified with the existence of a density gradient. Examination of the depth profiles of water temperature, dissolved oxygen, and salinity for 07-26-95 indicated that the salinity gradient increased from 0.85 to 1 ppt at 1 ft. below the surface. The stable thermocline indicated that density stratification occurred around the 2 to 3 feet depth from the pond's surface. The negative heterograde was formed about two feet below the pond's surface, which indicated higher concentrations of dissolved and suspended matter. In effect, there was accumulation of suspended organic matter in a layer of wastewater extending from 1 foot below the pond surface and about 2 feet below the pond surface.

### 5.4.5 Conductivity Readings, C

Conductivity readings gave almost vertical profiles throughout the year as shown in Figure 5.15. Conductivity readings ranged from 1.8 to 2.1 mS/cm over the year. July 26 also experienced stratification of the conductivity profile which coincided with the stratified salinity profile. July 26 and August 14, exhibited increased conductivity in the

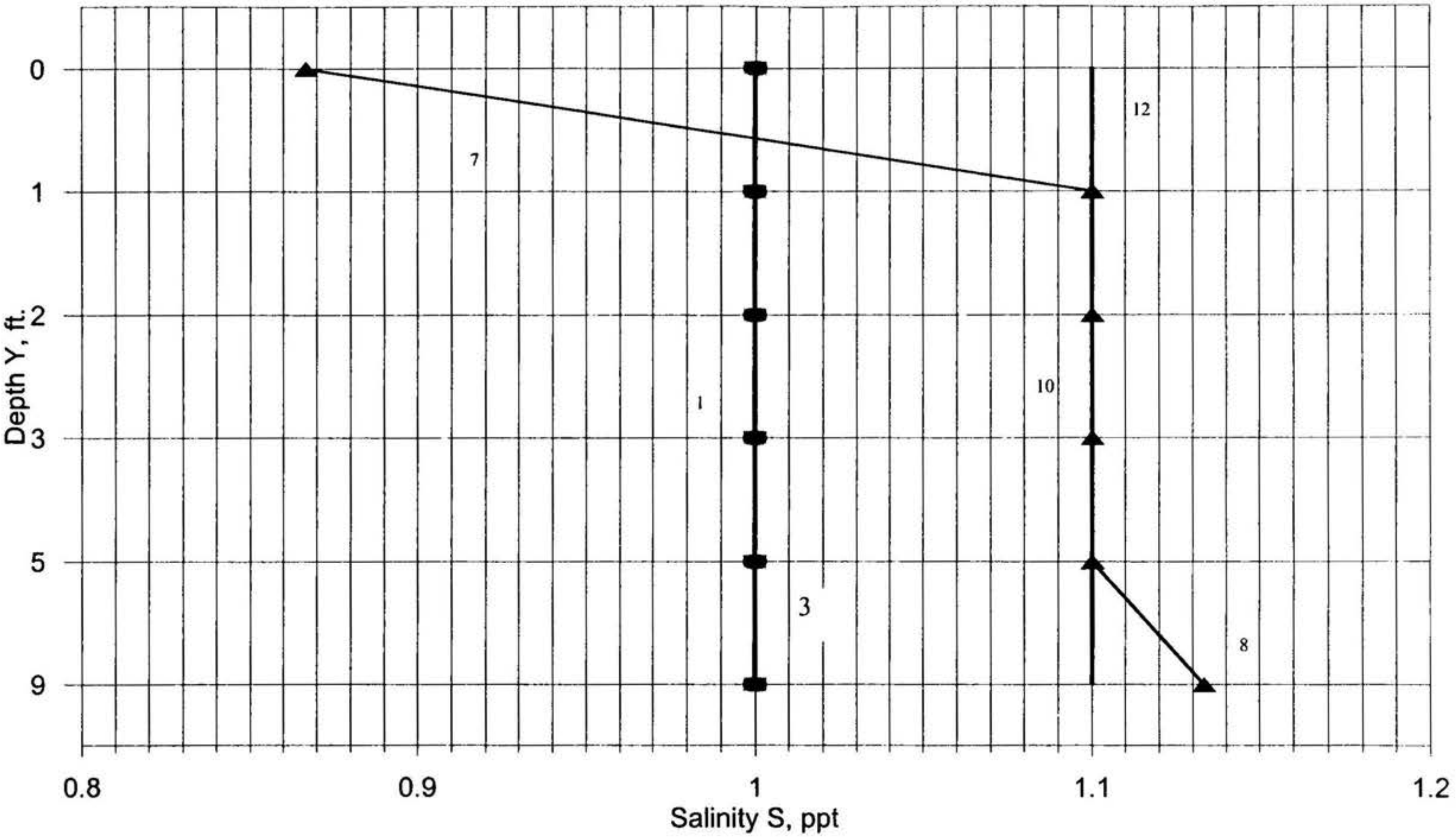

Figure 5.14, Salinity Depth Profiles
Pond 3

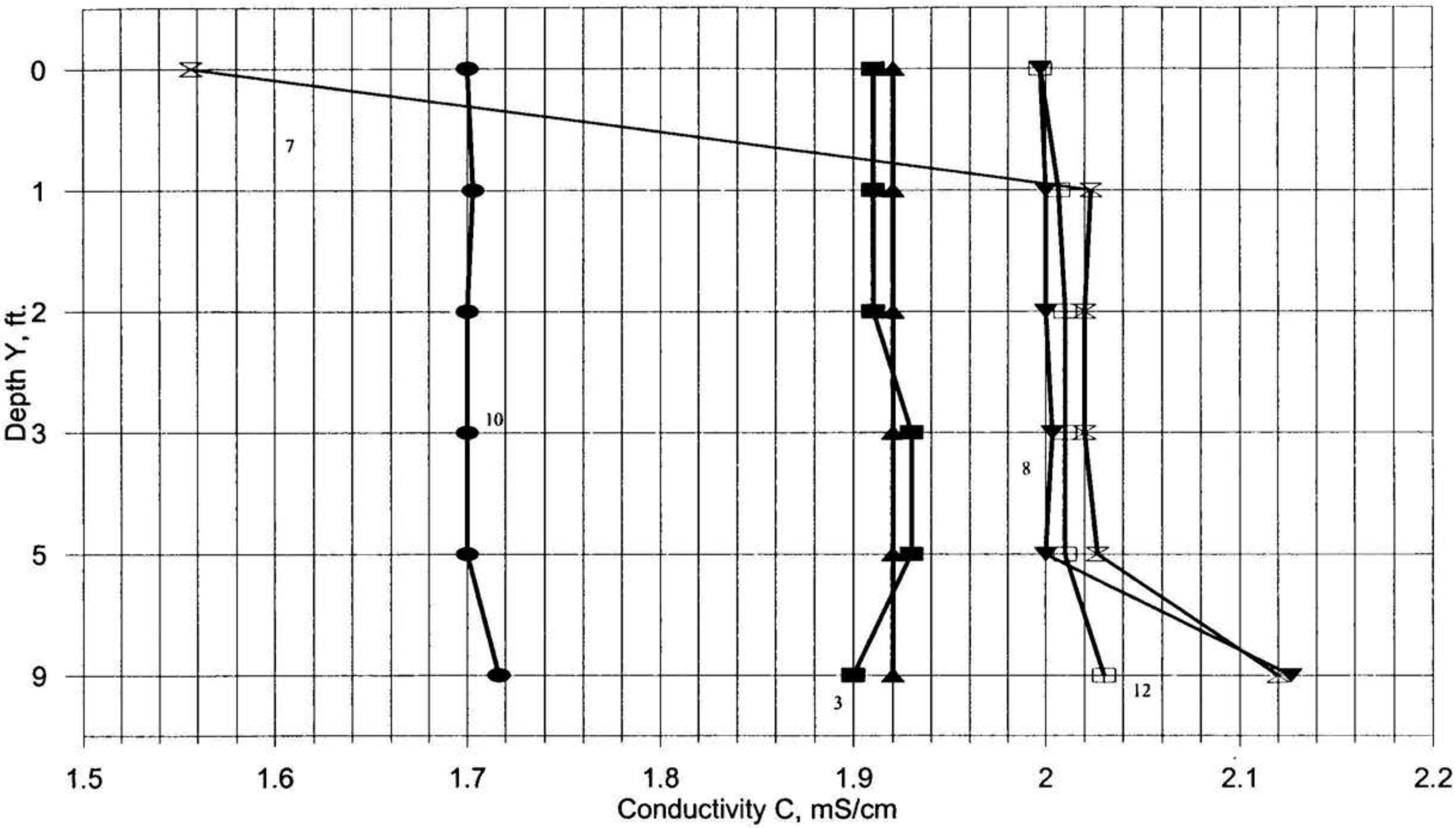

Figure 5.15 Conductivity Depth Profile
Pond 3 1995

lower depths of each water density stratum. Increases in the conductivity and salinity profiles signaled increased concentrations of suspended and dissolved solids in the pond waters. Which in turn indicated that the suspended and dissolved materials were in suspension in the water column. Settling of the suspended particles indicated either: (a) the digestion rate of organic matter was slower than the rate of replenishment of suspended particles in the pond, or (b) the suspended particles took longer to reach to the pond bottom when the pond was stratified.

### 5.4.6 Oxidation Reduction Potential Readings, ORP

Oxidation reduction potential ORP was the only parameter which showed stratification throughout the year at various depths of the pond. Figure 5.16 shows oxidation reduction potential data for six depths in Pond No. 3. The ORP depth profiles in Figure 5.17 showed that for most of the year ORP readings at the pond bottom stayed in the anaerobic range. Very low sludge accumulations at the sludge water interface indicated that organic material was being consumed by sludge digesting bacteria. Surface waters mostly exhibited ORP readings which were in the aerobic range for most of the year. In late spring, the ORP values rose significantly to the positive side of the ORP scale. Very high ORP readings, varying from 497 mv to 372 mv, were observed at the pond's surface from April 13 till May 22. These highly aerobic ORP readings provided an environment conducive for the occurrence of oxidative processes such as nitrification and photosynthesis. Other important process-altering phenomena which could be identified with the help of the temporal and spatial ORP profiles include: denitrification, ammonification, heavy metal cycling, and phosphorus release.

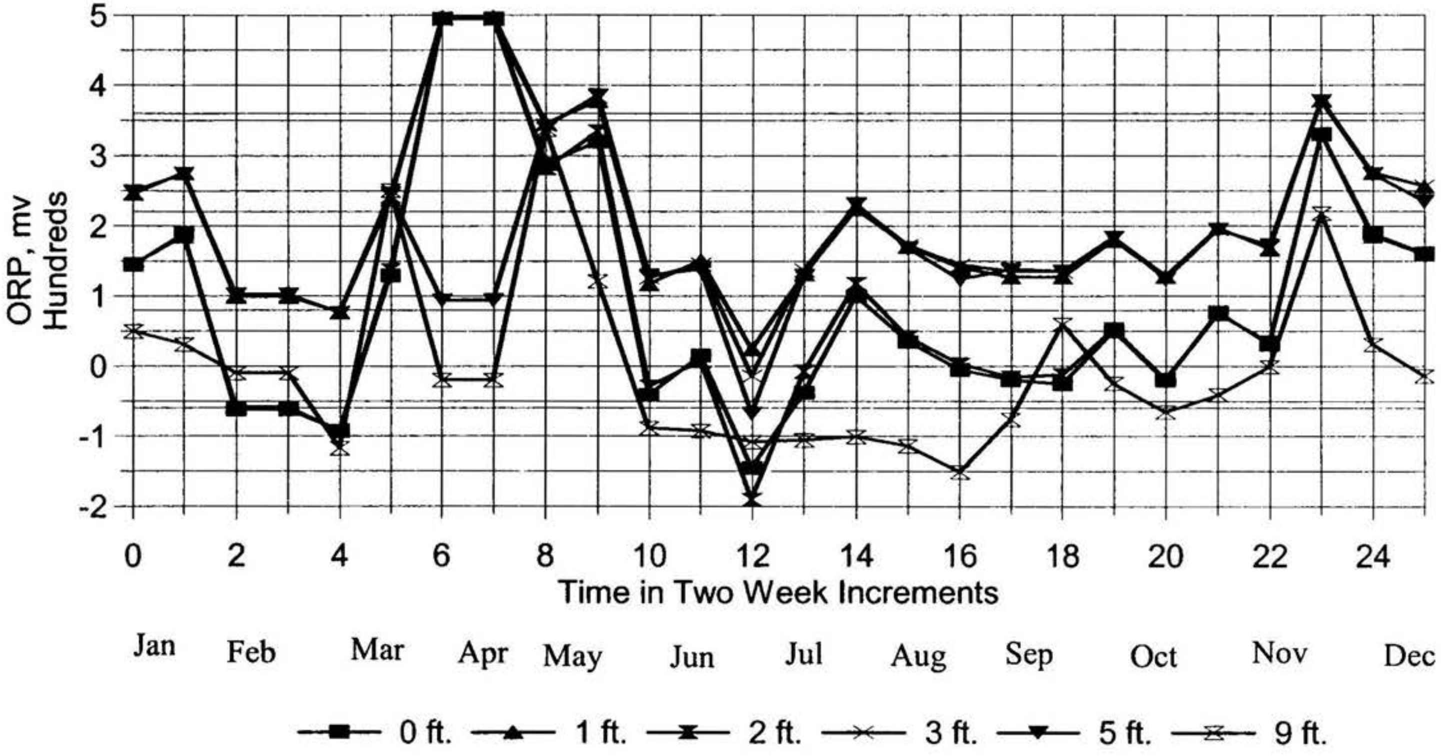

Figure 5.16, Depth Averaged Redox
Potentials Pond 3, 1995

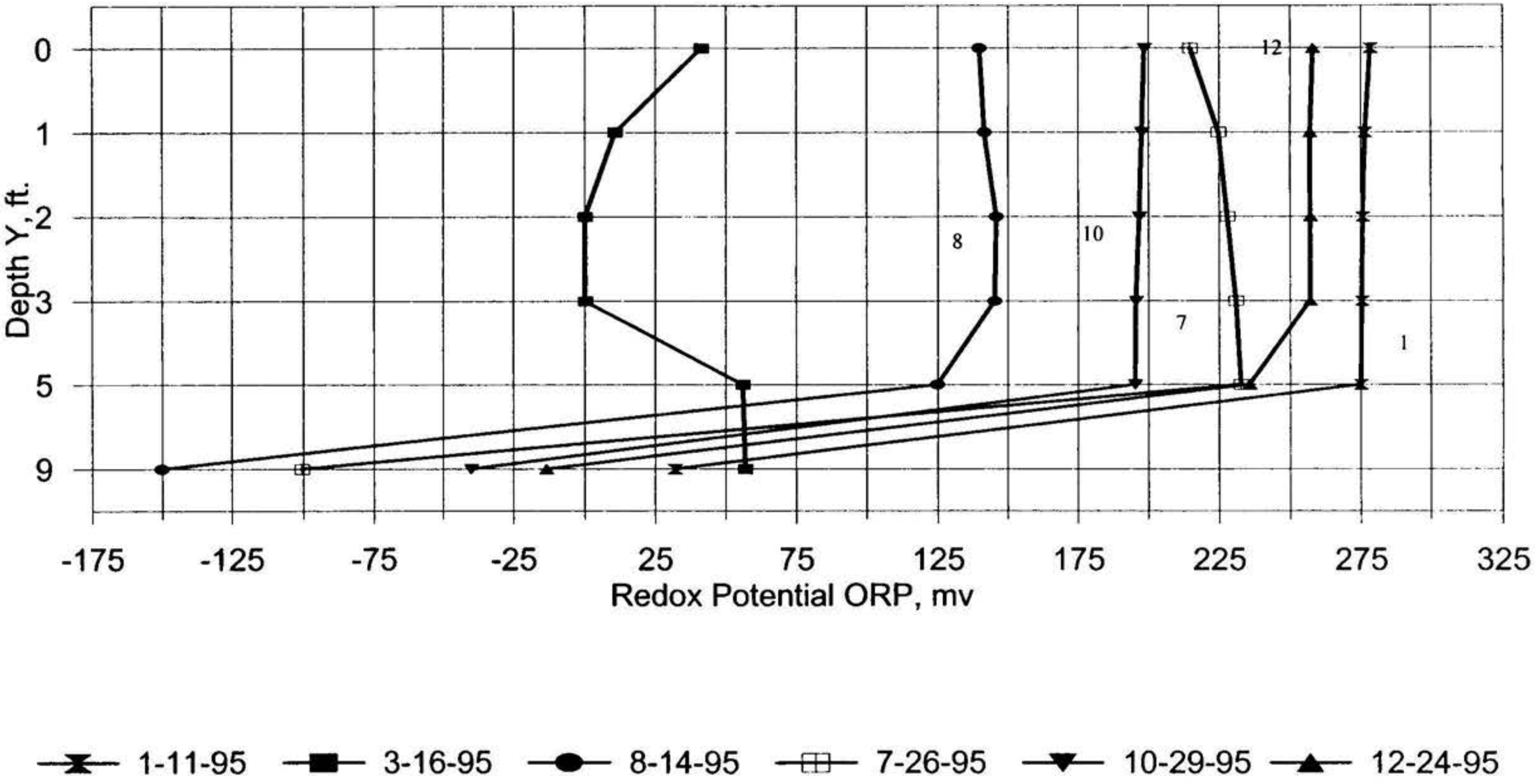

Figure 5.17, Redox Potential Depth
Profiles of Pond 3, 1995

The ORP readings in the top 5 feet of the pond were highly aerobic. While ORP values at the pond bottom ranged from -150.33 mv on August 14, to 57 mv on March 16, see Figures 5.16 and 5.17. The ORP values at the pond bottom indicated anoxic and anaerobic conditions prevailed at the pond bottom for most of the year. The behavior of the pond ranged from moderately eutrophic in the winter to highly eutrophic in the summer season. If the ORP readings were taken 1 foot to 2 feet below the sludge surface, the ORP values would have approached -200 mv to -250 mv. Effects of ORP on nitrification, denitrification and phosphorus releases in Pond No. 3 could provide very useful information for the periods which are critical for successful pond operation.

From a depth of about 5 feet to about 8 feet below the pond surface, the ORP readings mostly stayed in the anoxic range for most of the year. During the anoxia extending from July 28 till August 15, when the entire pond functioned anoxically, significant amounts of nitrogen, carbon dioxide, phosphorus, and methane were likely to be released from the pond. Recycling of metals such as iron, manganese, copper, chromium, nickel, mercury, and other heavy metals also took place due to the temporally and spatially varying ORP values recorded in Pond No. 3.

The ORP; DO; and Tw profiles indicated that Pond No. 3 functioned as a facultative pond, except for the critical summer period when the entire pond functioned anoxically. It is notable that over the entire year both ORP and DO values were in-phase and fluctuated with the same trends. The increased ORP; DO; and pH values most probably occurred due to the intense photosynthesis which occurred near the surface of the pond.

## 5.5 Summary

In this chapter, the input-output modeling technique is evaluated for time series generation of the hydrometeorological variables which exhib different periodic behavior at the surface Pond No. 3 of Boxelder Sanitation District. The important periodically recurring limnological phenomena such as: negative heterogrades, positive heterogrades, chemoclines, anoxia, thermoclines, density stratifications, photosyntheses, algae blooms, seasonal turn-overs, and acidification are identified after analyzing th time series and epth profiles of the water quality variables sampled. The probable causal factors which lead to the occurrence of these process-altering limnological phenomena are also outlined. The next chapter discusses the impact of these limnological phenomena on Pond No. 3.

# CHAPTER 6

# DISCUSSION OF RESULTS

This chapter is organized and based on the objectives outlined in Chapter 1. The information provided by the hydrometeorological and water quality variables, collected in Pond No. 3, is of direct relevance for the design and operation of deep wastewater treatment ponds. The following process-altering variables directly influenced the year-round temporal and spatial behavior of the various limnological phenomena that occurred in Pond No. 3 of Boxelder Sanitation District.

(1) Water Temperature, Tw (2) Solar Radiation, R (3) Salinity, S
(4) Air Temperature, Ta (5) pH (6) Conductivity, C
(7) Oxidation Reduction Potential, ORP
(8) Product of Solar Radiation and Air Temperature, R*Ta

## 6.1 Introduction

Wastewater stabilization Pond No. 3 was chosen to study the response of the water quality variables to seasonal hydrological variation by considering it as a system receiving hydrometeorological input-signals and emitting biochemical output-signals, shown in Figures 3.1 and 3.2. The interaction among the various inputs to the pond system transformed the state variables into their output values. The input-output approach provided highly reliable predictors of Tw and S. The temporal and spatial behavior of the 10 ft. deep wastewater treatment pond indicated that the simultaneous interactions among the complex and distinct variables resulted in the occurrence of the various process-altering limnological phenomena. Due to the complexity of the interactions between the various hydrometeorological and biochemical variables and the limited number of variables sampled, it appeared difficult to obtain a comprehensive integrated model of the wastewater treatment pond system which would also offer meaningful physical explanations (Yan 1997). Instead, the significant process-altering variables were identified and their interrelationships were investigated.

Application of the discrete Fourier series input-output modeling technique furnished accurate predictors only of those variables which were strongly periodic over the annual cycle. The hydrometeorological variables which either exhibited seasonality or were nonperiodic, over the one year period, could not be modeled reliably and accurately by using the discrete Fourier series approach, see Table 4.4; Figures 4.1 to 4.9. Higher frequencies of data collection may furnish better predictors of these variable types.

By employing multiple linear regression, the most significant hydrometeorological factors were retained while the least important variables were dropped out. Still, an overall picture was obtained about the various important interactions among the significant hydrological, biological, chemical, and meteorological processes that occurred in the pond, see Figures 4.10 and 4.12. The physical phenomena came in strongly in the regression models and they accounted for the physical aspects of the factors which significantly influenced the process-altering limnological phenomena. The statistical models developed were not totally unrelated to the physical aspects of the pond behavior.

Multiple linear regression models furnished direct solutions. In fact, random arbitrary values, which were hard to measure, all contributed to an insolvable solution of the closed-form solution to the integrated system problem. The systemic approach helps to design a wastewater treatment pond by identifying those process-altering variables which significantly impact the limnological behavior of the 10 ft. deep wastewater treatment pond. Among the variables investigated, Tw stood out as the key process-altering variable. Thus, reliable knowledge of Tw at the design-stage allows for the year-round accurate predictions of the various temperature dependent processes which exhibit wide temporal and spatial variations in deep wastewater treatment ponds.

Results of the modeling indicated that there is a very strong need to incorporate more process-altering variables, especially biochemical, in the future investigations of deep wastewater treatment ponds. This will allow a better understanding and accurate forecasts of the behavior of deep wastewater treatment ponds over the annual hydrological cycle. The investigation of a broader variety of process-altering variables will also help in the year-round smooth and reliable operation of deep wastewater treatment ponds.

The results of both the modeling techniques furnished highly accurate predictors of Tw. The advance and reliable knowledge of Tw values at the design stage would enable accurate spatial and temporal forecasts about the behavior of the various temperature dependent phenomena in deep wastewater treatment ponds. $BOD_5$ is monitored around the year at Boxelder Sanitation District. The development of accurate

Tw predictors can lead to the reliable estimates of year-round $BOD_5$ removal rates at the various depths of the pond, – especially during the periods of thermal stratification.

Thus, the periods critical to the temporal and spatial variation of the key hydrometeorological and biochemical variables could then be recognized and effective operational policies can be devised accordingly. Eventually, the hydraulic retention time can be adjusted by modifying the operational policies for deep wastewater treatment ponds operating under widely varying climatic conditions (Soniassy and Lemon 1986).

## 6.2 Fourier Series Harmonic Selection Criteria

The F-test criterion for the significant harmonics selection proved accurate only to generate the discrete Fourier series of Tw; R; and Ta, which exhibited very strong periodicity over the annual cycle, see Table 4.4; Figures 4.1; 4.7; and 4.8. The data series of ORP and Vw were found to be periodic with seasonal cycles and could not be predicted adequately with the application of the F-test harmonic selection criterion, see Table 4.4; Figures 4.6 and 4.9. In fact, the harmonic selection criteria provided over-fits of the time series of the variables which either exhibited: (1) strong annual periodicity, or (2) strong elements of seasonality, see Tables 4.4 and 4.5; Figures 4.1; 4.2; 4.6; 4.7; 4.8; and 4.9. The data series of DO; pH; S; and C were inaccurately and inconsistently predicted and were found to be nonperiodic over the annual cycle, see Table 4.4; Figures 4.2; 4.3; 4.4; and 4.5. The DO time series exhibited strong elements of seasonality. The peaks of the DO time series identified periods of intense oxygen production. The time series of pH; C; and S were devoid of significant periodic behavior.

### 6.3 Regression Criteria

Multiple linear regression showed that the Tw predictor depended heavily on R*Ta and ORP, see Figures 4.10 and 4.11. Through out the year, the Tw values lagged the gradual seasonal variations in the values of R. The lag time was representative of the signal response time $\tau$, which in this case, accounted for the time needed for the heating and cooling of the pond waters, see Figure 5.2. These lag times can be utilized to formulate delay equations in order to identify the significant cause-effect relationships among the various process-altering variables. The salinity predictor was found to be a function of C; R*Ta; and R, see Figure 4.12. The salinity predictor relied heavily upon the variations in conductivity, see Figures 4.12 and 4.13. Both of these predictors indicated that the annual variations in the readings of solar radiation and air temperature caused the temporal and spatial variations in the water quality variables investigated in Pond No. 3.

### 6.4 Spatial and Temporal Behavior of The Variables Investigated

Consideration of the occurrence of the episodes of mixing along with the interruptions in the mixing phenomena, and the formations of: (1) thermocline; (2) negative heterograde; (3) chemocline; and (4) the seasonal formation and thawing of the ice cover; led to the classification of the 10 ft. deep Pond No. 3 as discontinuous cold polymictic, see Table 2.1. The temporal and spatial variations of the water quality variables in Pond No. 3 were found to be in agreement with the limnological assertions about the formations of: (1) thermoclines; (2) chemoclines; (3) summer anoxia; (4) densimetric mixings; (5) pond acidification under ice cover; (6) seasonal turn overs;

(7) algae blooms; (8) positive heterogrades; (9) negative heterogrades; (10) algae blooms; (11) intense photosyntheses; and (12) elevated pH and DO values, see Section 3.4.

All of the foregoing phenomena are well documented indicators of periodic limnological behavior, See Figures 2.1; 2.2; 2.3; 2.4; and 2.5. The periodic variations in the hydrometeorological and water quality variables, at the surface of Pond No. 3, were identified in Table 4.5. The depth profiles of the water quality variables, measured in Pond No. 3, provided very useful insight into the temporal and spatial dynamics of the various process-altering phenomena, especially biochemical, which occurred mostly in deep wastewater treatment ponds, see Figures 5.4; 5.5; 5.6; 5.7; 5.8; 5.9; 5.10; 5.11; 5.12; 5.13; 5.14; 5.15; 5.16; and 5.17.

The behavior of the deep wastewater treatment ponds, subject to widely varying climatic conditions, can be predicted with a higher degree of accuracy by taking into account the temporal and spatial variations of the various hydrometeorological and biochemical variables in smaller increments of depth and time than those used in this research. The various process-altering periodically recurring limnological phenomena identified in this research are discussed below.

### 6.5 Thermoclines

In January, an episode of seasonal turnover took place when the pond water temperatures under the winter ice cover exceeded the 4° C mark, see Figure 5.9. The ice cover melted by the end of February, and another circulation of the pond waters occurred when the surface waters crossed the freezing point of water, see Figures 5.6 and 5.9. The initial unstable formations of thermoclines were noticed in Pond No. 3 around the Spring equinox in March. These initial thermoclines oscillated back and forth due to the interruption in the heating process caused by the intermittent episodes of precipitation, see Figures 5.4 and 5.5. Under the highly aerobic conditions experienced after the Spring thaw, the warmer surface waters of the pond facilitated photosynthesis, see Figures 5.4; 5.8; and 5.9. The occurrence of intense photosynthesis in the pond surface waters resulted in supersaturated DO values and elevated pH readings at the pond's surface, see Figures 5.8 and 5.12. Thus, the pond environment became conducive for the oxidative processes to take place. The ORP readings, especially at the pond bottom, also substantiated the seasonal circulation of oxygen-rich waters to the pond bottom. In December the ORP reading at the pond bottom was -13.33 mv, see Figure 5.16. In January, after another probable circulation of oxygen-rich waters to the pond bottom, an ORP of 32 mv was recorded at the pond bottom, see Figure 5.17. The circulation after the Spring thaw in March witnessed a further aerobic ORP reading of 57 mv at the pond bottom.

By the third week of July, hot and clear weather prevailed in Fort Collins. This sustained hot and dry climatic spell led to the formation of a distinct and stable thermocline in the pond, see Figure 5.10. From the third week of July till the middle of August, the water column was stably stratified into two distinct layers, with the lighter water overlying the heavier water, see Figure 5.10. The stable density stratification of the water column led to the formations of: (1) negative DO heterograde, see Figure 5.10, and (2) chemoclines of C and S, see Figures 5.14 and 5.15. The stable thermocline started to erode after the Fall climatic conditions began to set in toward the second half of

August, see Figure 5.6.

Once the Fall cooling conditions were firmly established by the third week of September, then the isothermal conditions prevailed in the pond along with the occurrence of circulation throughout the pond depth. The ORP readings at the pond bottom increased from -150 mv, at the peak of the Summer anoxia, to -40 mv on October 29 1995 after the Fall circulation, see Figures 5.16 and 5.17. The isothermal conditions continued to dominate the entire pond depth until thermal stratification occurred due to the following spring warmup. Around the third week of December, the surface waters of the pond froze into solid ice. The ice cover formation caused inverse stratification of the pond waters which resulted in the circulation of the oxygen-rich waters to the pond bottom, see Figure 5.9. When compared with the ORP readings observed in October, once again, the ORP readings at the pond bottom moved further to the aerobic side to -13.33 mv on December 24 1995, see Figure 5.17. The availability of DO at the sludge-water interface most likely inhibited the sludge digestion by anaerobic bacteria at the pond bottom. However, a little distance below the sludge-water interface, the anaerobic bacteria would have, most likely, remained unaffected. The ORP readings below the sludge-water interface need to be investigated in order to confirm this assertion.

## 6.6 Oxyclines

The DO concentrations at different depths fluctuated with the seasonal variations in the various DO controlling phenomena that occurred in Pond No. 3. Under the ice cover in January, the DO values were highly aerobic because of the occurrence of increased photosynthesis in the immediately underlying pond waters, see Figure 5.9. The increase in photosynthetic activity was most probably caused by increased light penetration after the acidification of the pond resulted in reduced concentrations of dissolved organic carbon and dissolved inorganic carbon. The only exception occurred at the pond bottom, which exhibited lower DO values, than rest of the DO profile, because there was a high DO demand at the sludge-water interface, most probably, due to the accumulated undigested sludge, see Figure 5.9.

The ice cover melted by the end of February and the reaeration of the pond surface water resumed and eventually spread over the entire depth,-- especially after the Spring turnover, see Figure 5.9. In March, when heating of the pond waters proceeded at a much faster pace than that witnessed in the Winter months, the warmer and quiescent climatic conditions allowed for intense photosynthesis to take place in the upper layers of the pond, see Figure 5.9. The results of heating and increased oxygen production resulted in the formation of : (1) a weak clinograde profile which spread over the entire pond depth, see Figures 2.4 and 5.9; (2) supersaturated surface DO readings, see Figure 5.8; and (3) elevated pH readings at the pond's surface, see Figure 5.12. This highly aerobic environment was most likely to be ideal for nitrification to take place in the pond.

The stable stratification at the peak of the Summer season witnessed the formation of the negative heterograde profile, see Figure 5.10. The negative heterograde was signified by the formation of a metalimnetic DO minimum near the interface of the two density strata. The metalimnetic DO minimum indicated the accumulation of the suspended and dissolved solids near the water-density interface. At the same time intense photosynthetic activity in the surface waters of the pond, most likely, produced supersaturated DO concentrations.

The progression of the Summer season and the nutrient rich influent reaching the pond resulted in anoxia over the entire pond depth from the last week of July till the middle of August, see Figure 5.9. These anoxic conditions were indicative of hyper eutrophication of the pond waters. The combination of the warmer water temperatures and the Summer anoxia was conducive for the occurrence of: (1) denitrification; (2) phosphorus release; (3) cycling of important elements including heavy metals; (4) carbon dioxide production; and (5) methane production in the pond.

The isothermal conditions along with the Fall cooling conditions, once again, facilitated photosynthesis to occur in the upper layers of the pond, and supersaturated surface DO readings were noted in the positive heterograde recorded in October, see Figure 5.11. The Fall turnover and increased DO solubility were also plausible significant contributors to these increased DO readings over the entire water column. The formation of the positive heterograde was also accompanied with elevated pH readings at the pond's surface, see Figure 5.12.

After the ice cover formation in December, the surface reaeration into the pond was cutoff. The DO depth profile showed zero DO concentrations at the surface and at the 1 ft. depth, see Figure 5.9. The DO concentration at the pond bottom was greater than that in the top 1 ft. depth of the pond. This unique behavior of the DO profile in the ice-covered deep wastewater treatment pond, most likely, occurred because the Winter turnovers of the oxygen-rich surface waters met the high DO demand of the undigested sludge accumulated at the sludge-water interface, see Figure 5.9.

## 6.7 Chemoclines

The chemoclines of conductivity and salinity in Pond No. 3 exhibited periodic stratification along with the formations of: (1) stable thermal stratification; (2) stable density stratification; and (3) negative heterograde. The period of chemocline formation was critical to the settling of total suspended solids (TSS). The depth profiles of C and S at the time of the stable summer thermal stratification revealed the stratification of the suspended and dissolved solids over the pond depth, see Figures 5.14 and 5.15. The uneven concentrations of the conductivity and salinity depth profiles indicated that the suspended and dissolved solids accumulated at the lower ends of both the water density strata. In effect, the settling time of these suspended solids was increased. During the period of stable and prolonged thermal stratification, the increased settling time required by the suspended solids to settle to the pond bottom rendered the designed hydraulic retention time of Pond No. 3 as inadequate, see Figure 5.14 and 5.15.

It was observed in the pond compliance and performance data, presented in Tables 3.2 and 3.3, that for the part of the month of August, the Boxelder wastewater treatment pond system exceeded the 75 mg/l effluent TSS limit set forth by The Colorado Department of Public Health and Environment. Thus, the hydraulic retention time during the critical, stable, and prolonged Summer stratification period needs to be adjusted. The depth profiles of conductivity and salinity could be used to calibrate the predictors of total dissolved solids. The peaks in the time series of the original conductivity data series identified the occurrences of: (1) intense photosyntheses; (2) algae blooms; and (3) elevated DO and pH readings at the pond's surface, see Figures 4.4; 5.8 and 5.12.

### 6.8 Acidification

The solid ice cover formation in December led to the acidification of the entire Pond No. 3. These acidic conditions most likely resulted in reduced dissolved organic carbon and dissolved inorganic carbon. As a consequence of which, increased light penetration occurred in the ice covered pond -- especially after the Winter solstice, see Figure 5.13. The increased light penetration in January, most probably resulted in increased photosynthetic activity at greater depths which in turn raised the DO values throughout the water column than the DO concentrations observed in the colder waters of December, see Figure 5.9. Thus, acidification of the pond most likely altered the composition of the predators and prey communities in the pond. The crests in the time series of the surface pH readings, see Figure 5.12 also pointed to the occurrences of: (1) intense photosyntheses; (2) increased oxygen production; and (3) algae blooms.

### 6.9 Oxic States of the Pond

The stratified and widely varying ORP profiles pointed to the occurrences of: (1) nitrification; (2) dentrification; (3) phosphorus release; (4) recycling of metals including heavy metals; and (5) eutrophication over various times and depths in the pond, see Figure 5.16 and 5.17. The ORP depth profiles indicated that for most of the year the surface ORP readings were highly aerobic, see Figure 5.16. At the middle depths, the ORP readings were in the anoxic range, Figures 5.16 and 5.17. For most of the year the ORP values at the pond bottom were in the anaerobic range. The exceptions to the anaerobic conditions occurred with the seasonal circulations caused by the Spring, Fall, and Winter turnovers, when the oxygen-rich waters plummeted to the pond bottom. With the exception of the Summer anoxia and the seasonal turnovers, the 10 ft. deep wastewater treatment Pond No. 3 functioned as a facultative pond, see Figures 5.8; 5.9; and 5.17.

## 6.10 Performance of Pond No. 3 of Boxelder Sanitation District

The wastewater treatment Pond No. 3 of Boxelder Sanitation District functioned satisfactorily for most of the year in 1995. Except for a three week period from the third week of July to mid August, when Pond No. 3 showed the formation of a distinct and stable thermocline, see Figure 5.10. During the same period, the pond system exceeded the effluent limit set forth to remove suspended solids, see Table 3.3, primarily due to the larger buoyant forces exerted by the underlying denser waters. It is for this critical period of stable and distinct thermal stratification that the hydraulic retention time of the water under-going treatment may be adjusted in order to allow for the suspended solids to settle to the pond bottom by: (1) providing additional ponds in addition to the present settling ponds; (2) chemical coagulation is another alternative worth investigation in an attempt to improve the settling of solids in the pond; or (3) destratification of the stable thermocline by forced aeration may also be explored.

The thermocline formation and the accompanying anaerobic conditions in the pond water column were most likely followed by algae blooms due to nutrient enrichment, especially by high concentrations of P and N in the incoming pond waters, see Figure 5.10. Techniques such as food web manipulation should be employed to control eutrophication in the settling Pond No. 3. The use of stand by aerators during the critical summer period of thermal stratification should also be explored in detail.

Pond No. 3 functioned satisfactorily after the Fall turnover. Only one episode of super saturation was observed in October, most probably due to excess oxygen production due to the photosynthesis occurring in the surface waters of the pond, see Figures 5.8; 5.11; and A-14. By the end of December a thick ice cover had formed on the surface of Pond No. 3. The combination of the ice cover formation and the subsequent warming of pond waters after the Winter solstice, due to increased solar radiation and higher air temperatures, accounted for at least two episodes of inverse stratifications when the oxygen-rich waters plummeted to the pond bottom, see Figure 5.9. These episodes of density driven mixing call for exploring the usefulness of the provision of deep fermentation pits at the bottom of the pond so as to allow for uninterrupted sludge digestion to proceed around the year (Oswald 1996).

After a long period of operation, only one foot of sludge had accumulated over the bottom of Pond No. 3. Which indicated that there exist strains of bacteria which adapt very well to the widely varying climatic conditions experienced in Northern Colorado. These genera or species of the beneficial bacteria need to be identified so that wastewater treatment ponds can be designed on the similar scientific principles which are in use to design chemical reactors. By the third week of December, very low pH values were observed in the pond waters. A plausible explanation for this acidic behavior of Pond No. 3 could be that at very low pH values, lot of free $CO_2$ was produced in the carbon-rich pond wastewaters. The carbon dioxide gas could not escape to the atmosphere due to the overlying ice cover. This led to the formation of carbonic acid due the reaction between carbon dioxide and water. As a consequence of which, the entire pond turned acidic, see Figure 5.13.

The conductivity and salinity readings through out the pond stayed almost the same over the entire year. Significant variations were noticed in the depth profiles of C and S in July when the formation of the distinct-and-stable thermocline was accompanied by chemoclines of C and S, see Figures 5.14 and 5.15. One more instance of significant variation in C and S temporal readings from their average values occurred in October. The Tw predictors can be used to design and predict the performance of deep wastewater treatment ponds in similar geographical and physiographical settings. This will also enable designers to accurately predict the variations in other temperature dependent phenomena. Likewise, accurate predictions of S and C can help in the prediction of chemocline formation and TDS concentrations (Metcalf and Eddy 1991) due to the stratification of solids along the water column -- especially under widely varying climatic conditions.

### 6.11 Lessons Learned from Pond No. 3

The simultaneous collection of the six water quality variables significantly cut down the cost of data collection. The period of thermal stratification can be considered as a critical period with regard to the needs of aeration of the pond waters. If such critical periods are identified in the annual operation of deep wastewater treatment ponds, especially those receiving raw influent, then substantial savings can result in the form of reduced operation and maintenance costs. At present, Boxelder Sanitation District operates six aerators for 24 hours a day, 365 days a year. The high power consumption by electric aerators at Boxelder can be reduced by using them either as: (1) Standby aerators and to use them only in the critical periods; or (2) Adopt an on-off off-on policy to operate aerators. The on-off off-on approach will allow for the establishment of anoxic conditions in the pond even during adverse climatic conditions.

The EPA manual on wastewater treatment pond design considered four shallow ponds, 1.2m to 2m deep. Deep wastewater treatment ponds were not considered for obtaining pond performance data. Grab samples were taken from these shallow research ponds. Thus, the occurrences of process-altering limnological phenomena were missed. As identified in this research, most periodically occurring limnological phenomena did not adversely impact the deeper zones of Pond No. 3. The extra depth of the pond, more than 3 ft., played a crucial role in the year-round smooth and effective functioning of the 10 ft. deep wastewater treatment pond, see Figures 5.9; 5.10; 5.11; 5.14; 5.15; and 5.17. Thus, there is a very strong need for an in depth study of additional process-altering variables in deep wastewater treatment ponds in order to analyze their response to the various periodically occurring process-altering limnological phenomena by the investigation of a wider spectrum of: (1) pond depths; (2) pond locations; (3) influent types; and (4) climatic conditions. The afore-mentioned discussion led to the accomplishment of the following objectives.

### 6.12 Objectives Achieved

The following objectives were achieved, as stated in Section 1.5.

1. The key hydrometeorological variables which significantly impacted the performance of the 10 ft. deep wastewater treatment pond were identified.
2. Utilization of the Hydrolab H-20 multi-parameter water quality probe enabled the

simultaneous data collection of the key process-altering water quality variables in small temporal and spatial increments over the one year period. Data collection in small temporal and spatial increments led to the identification of the various process-altering limnological phenomena.

3. Discrete Fourier series were formulated to generalize the temporal behavior of the key hydrometeorological variables which influenced the year-round limnological behavior of Pond No. 3.

4. Statistical models were derived by using multiple linear regression to study the temporal response of the water quality variables to the hydrological variation at the Pond's surface.

5. The variable selection criteria used in multiple regression indicated that reliable predictors were obtained only for those dependent variables whose explanatory variables were also investigated in this research.

6. The Fourier series harmonic selection criteria generated highly accurate predictors of those data series which exhibited strong periodic behavior over the annual and seasonal cycles.

7. Solar radiation was found to be the main causal factor which affected the air and water temperatures. The combined effect of R; Ta; and Tw was noticed on the values of DO; pH; C; S; and ORP. Wind velocity was found to be an insignificant contributor to the surface DO and ORP values.

8. The limnological behavior of the 10 ft. deep wastewater treatment pond was found to be similar to that of shallow lakes over the annual and seasonal cycles. Over the course

of the year, the periodic occurrences of: (1) thermoclines; (2) chemoclines; (3) summer anoxia; (4) densimetric mixings; (5) pond acidification under ice cover; (6) seasonal turn overs; (7) algae blooms; (8) positive heterogrades; (9) negative heterogrades; (10) algae blooms; (11) intense photosyntheses; and (12) elevated pH and DO values, – all confirmed that the Pond No. 3 of Boxelder Sanitation District exhibited year-round limnological behavior.

9. The highly accurate Tw predictors developed in this research can aid in the development of year-round reliable predictors of the various temperature dependent phenomena which occur, – especially in deep wastewater treatment ponds.

### 6.13 Summary

In summary, the results of modeling and the identification of year-round limnological behavior of Pond No. 3 are discussed from the view point of significance and application to deep wastewater treatment ponds. In the next chapter, the conclusions ensuing from this research are stated.

# CHAPTER 7

# CONCLUSIONS

The modeling, analysis, and discussion of the impact of the causal hydrometeorological variables on the key process-altering water quality variables lead to the identification of year-round periodic limnological behavior observed in Pond No. 3. This research investigation arrives at the following conclusions:

1. The gradual variations in solar radiation R are the main causal-factors which directly impact the fluctuations in air temperature Ta. The combined effects of the variations in R and Ta are noted on the annual variations in the water temperature Tw throughout the pond depth. The complex interactions between R; Ta; and Tw result in the occurrence of periodic limnological behavior with the formations of thermoclines. The peak wind gusts Vw do not impact any of the meteorological and water quality variables investigated in this research.

2. Use of the multiparameter water quality probe has resulted in enormous savings of time and costs by the simultaneous collection of the valuable water quality data in small spatial and temporal increments. In fact, the database of the water quality variables investigated is available for utilization for the design and operation of deep wastewater treatment ponds in: (1) similar physiographic and geographical locations; and (2) similar

operating environments.

3. The temporal behavior of the variables under investigation is generalized by generating their discrete Fourier series at the pond surface. It is noticed that the strongly periodic variables over the annual cycle are modeled adequately. The discrete Fourier series approach cannot adequately-and-consistently generate the periodic data series which exhibit strong elements of seasonality. The nonperiodic data series are inadequately modeled by the discrete Fourier series approach.

4. Statistically significant predictors are obtained only for those dependent variables whose explanatory variables are also included in the data collection scheme.

5. The significant harmonic selection criterion satisfactorily generates the discrete Fourier series of the annually periodic data series. The harmonic selection criterion shows inconsistency to generate accurate discrete Fourier series of the seasonally periodic data series. The same significant harmonic selection criterion fails to generate highly accurate discrete Fourier series of the non periodic data sets.

6. The impact of the meteorological variables on the water quality variables in Pond No. 3 is identified throughout-the-year, at varying depths, in the form of periodically occurring limnological phenomena such as: (1) clinogrades; (2) negative heterogrades; (3) positive heterogrades; (4) summer anoxia; (5) thermal stratifications; (6) fall destratifications; (7) algae blooms; (8) super saturations; (9) winter acidifications; (10) elevated pH values; (11) density driven mixings; and (12) seasonal turn-overs.

7. The comparison of the year-round temporal and spatial profiles of the 10 ft. deep wastewater treatment pond and shallow lakes lead to the classification of the deep

wastewater treatment pond as discontinuous cold polymictic. Throughout the year, with the exception of the Summer-anoxia, the 10 ft. deep wastewater treatment functioned as a facultative pond.

8. The accurate and reliable information about the temporal and spatial variations of Tw can be used to predict: (1) periods of thermal stratifications; (2) anoxic conditions; and (3) inverse stratification of the pond waters. The temporal and spatial profiles of pH and Tw identify periods critical for acidification of the pond. The stable and distinct summer thermocline in conjunction with the C and S depth profiles can be used to identify periods of chemocline formation. The Summer-anoxia and the stable thermocline formation identify the probable periods of eutrophication. The DO depth profiles are indicative of the formations of clinogrades; negative heterogrades; and positive heterogrades. The C; pH; DO; and ORP time series -- all help to identify the periods of: (1) photosyntheses; (2) intense oxygen production; and (3) algae blooms at the pond's surface. The ORP temporal and spatial profiles also identify the periods of: (1) nitrification; (2) denitrification; and (3) the oxic state of the pond.

In summary, the impact of the environmental factors on the limnological behavior of deep wastewater treatment ponds is evaluated. The findings of this research establish that deep wastewater treatment ponds operating under widely varying climatic conditions, at mid latitudes and at higher elevations, exhibit year-round limnological behavior. In the next chapter, recommendations are made for the future applications of the findings of this investigation.

# CHAPTER 8

# RECOMMENDATIONS

The recommendations stated-below are aimed at providing low-cost, sustainable, and scientific bases for the design, construction, and operation of deep wastewater treatment ponds.

1. The impact of the meteorological variables on the behavior of additional variables – especially biochemical-needs to be explored in detail. The interactions among the various process-altering variables such as: Discharge Q; hydraulic retention time $\Theta$; BOD; CBOD; TOC; COD; TSS; TDS; P; N; $NH_3$; $NH_4$; fecal coliform; e-coli; carbonates; bicarbonates; sulfates; methane; and heavy metals – also require long-term in-depth investigations. Techniques of optimization should be used to minimize the cost of data collection.

2. Efficient multi-parameter variable collection technologies such as: (1) water quality probes and (2) floating robots, such as RUSS, should be used to develop data bases of the various process-altering variables in deep wastewater treatment ponds. These data bases should be developed over the entire pond depth in small temporal and spatial increments, for the various physiographic and geographic regions, for each step of the treatment process in deep wastewater treatment ponds.

3. The availability of credible and substantial process-altering data for the various steps involved in the treatment process will allow for the application of the mass balance approach. Hence, better control over the deep wastewater treatment pond processes may eventually become possible by applying principles similar to those used to design chemical reactors. Eventually, deep wastewater treatment pond design and operation will become more efficient, effective, and reliable.

4. The multi-year time series which emulate the temporal behavior of deep wastewater treatment ponds at various depths should be utilized to establish the recurrence of the process-altering limnological phenomena. Higher order models such as: (1) ARMA; (2) PARMA; (3) ARIMA; and (4) PARIMA need to be developed in order to make reliable predictions.

5. Site specific statistical models should be developed, as a first step, to identify the temporal and spatial behavior of the key water quality variables in deep wastewater treatment ponds.

6. Techniques of comparative limnology should be utilized to identify the annually and seasonally recurring limnological behavior of deep wastewater treatment ponds and shallow lakes.

7. The lake classification schemes, incorporating shallow lakes, need to be modified for application to deep wastewater treatment ponds in the various geographic and physiographic regions of the world.

8. Principles of shallow lake management should be explored for the effective and efficient operation of deep wastewater treatment ponds.

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# APPENDIX A

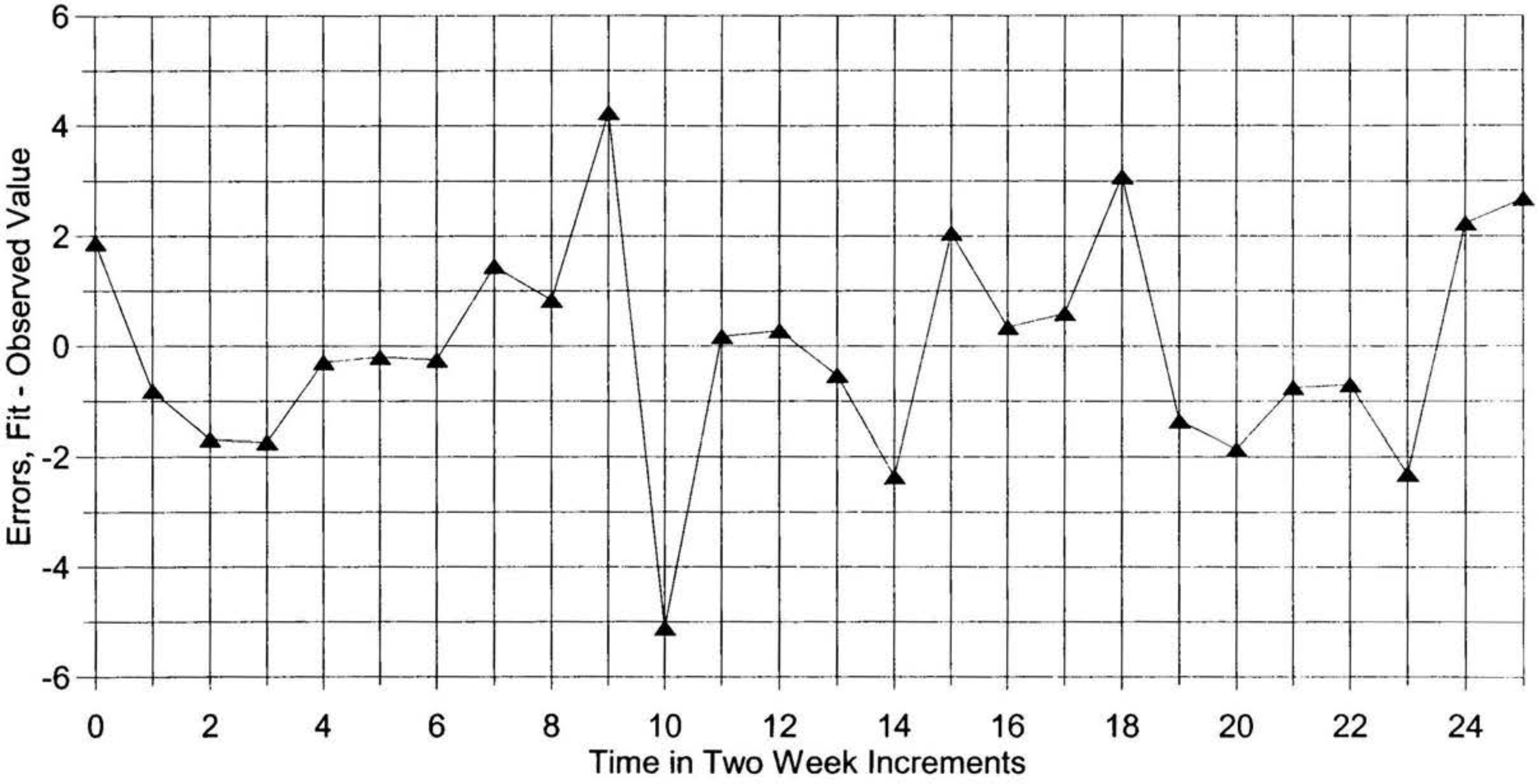

Figure A.1, Errors Water Temperature
Fourier Model

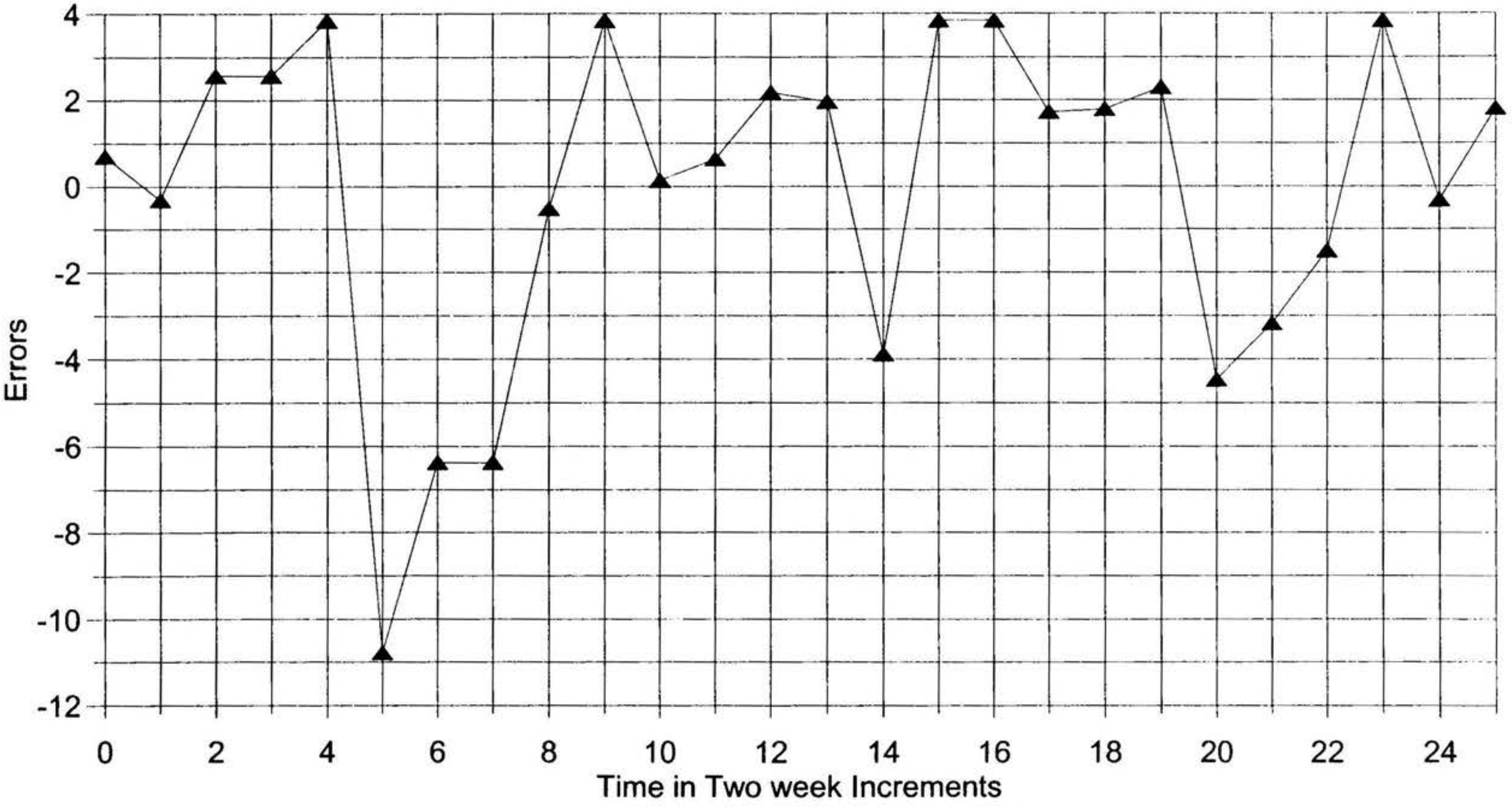

Figure A.2, Errors Dissolved Oxygen Fourier Model

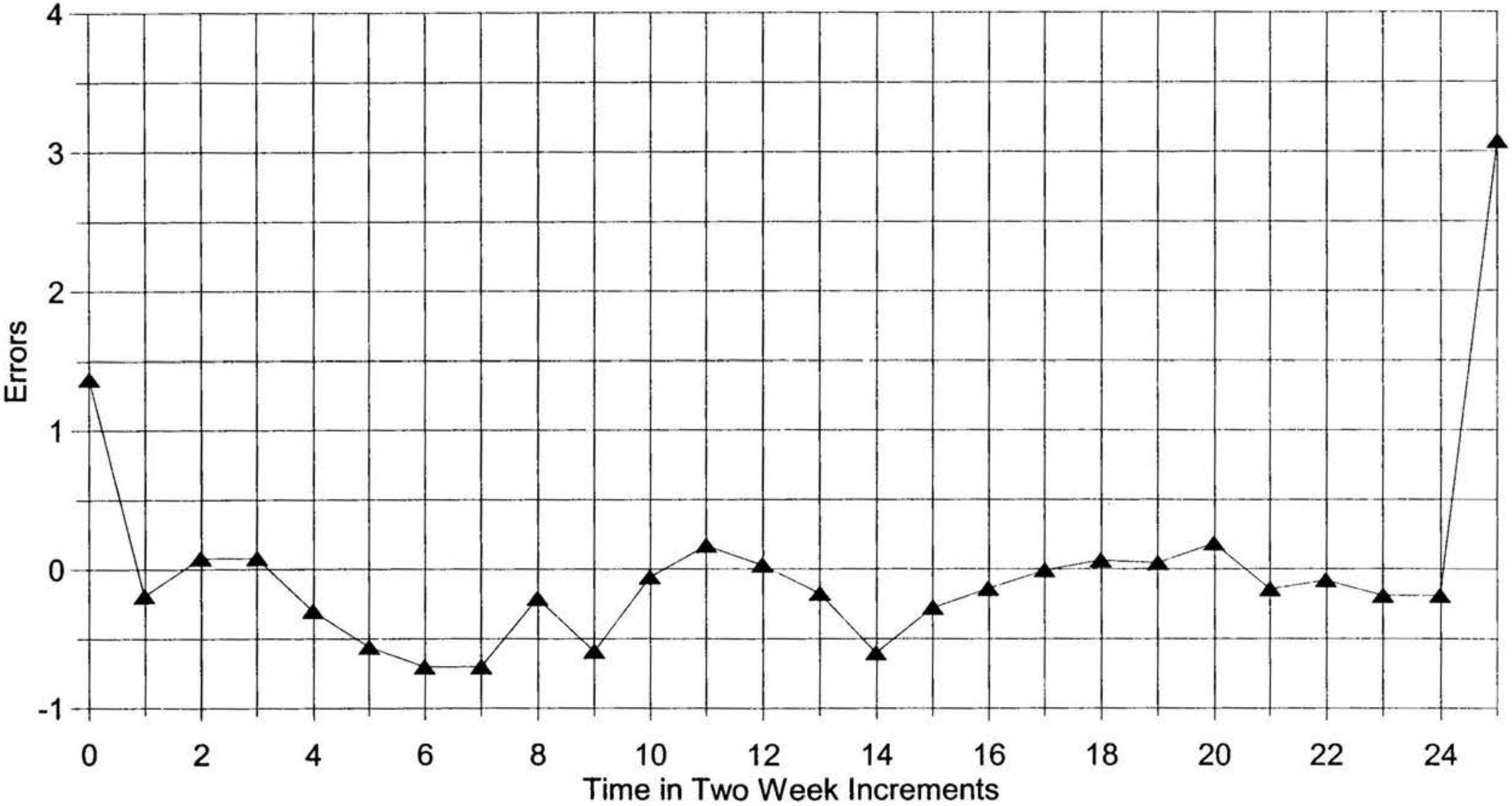

Figure A.3, Errors pH
Fourier Model, N=0

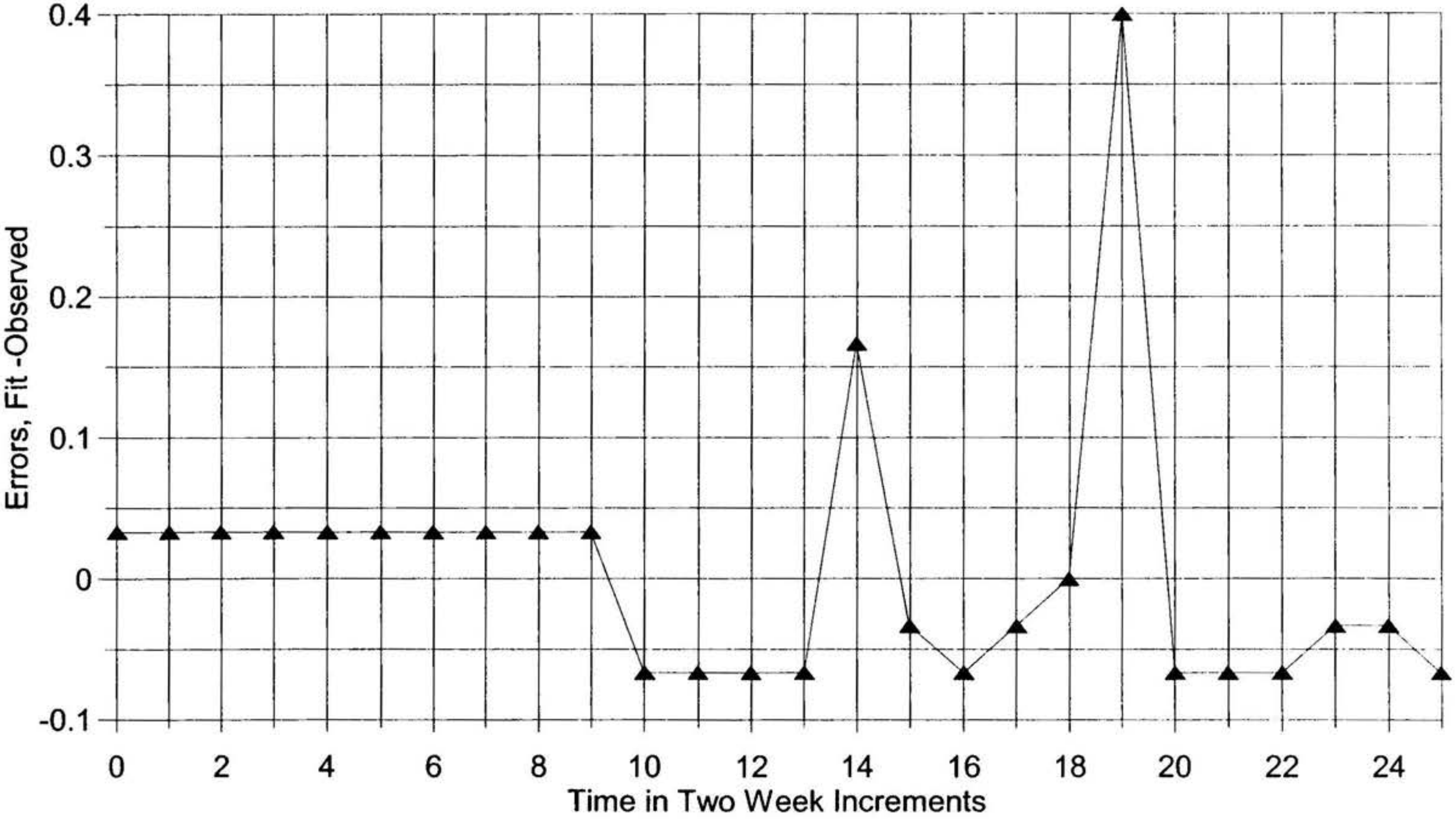

Figure A.4 Errors Salinity
Fourier Model, N=0

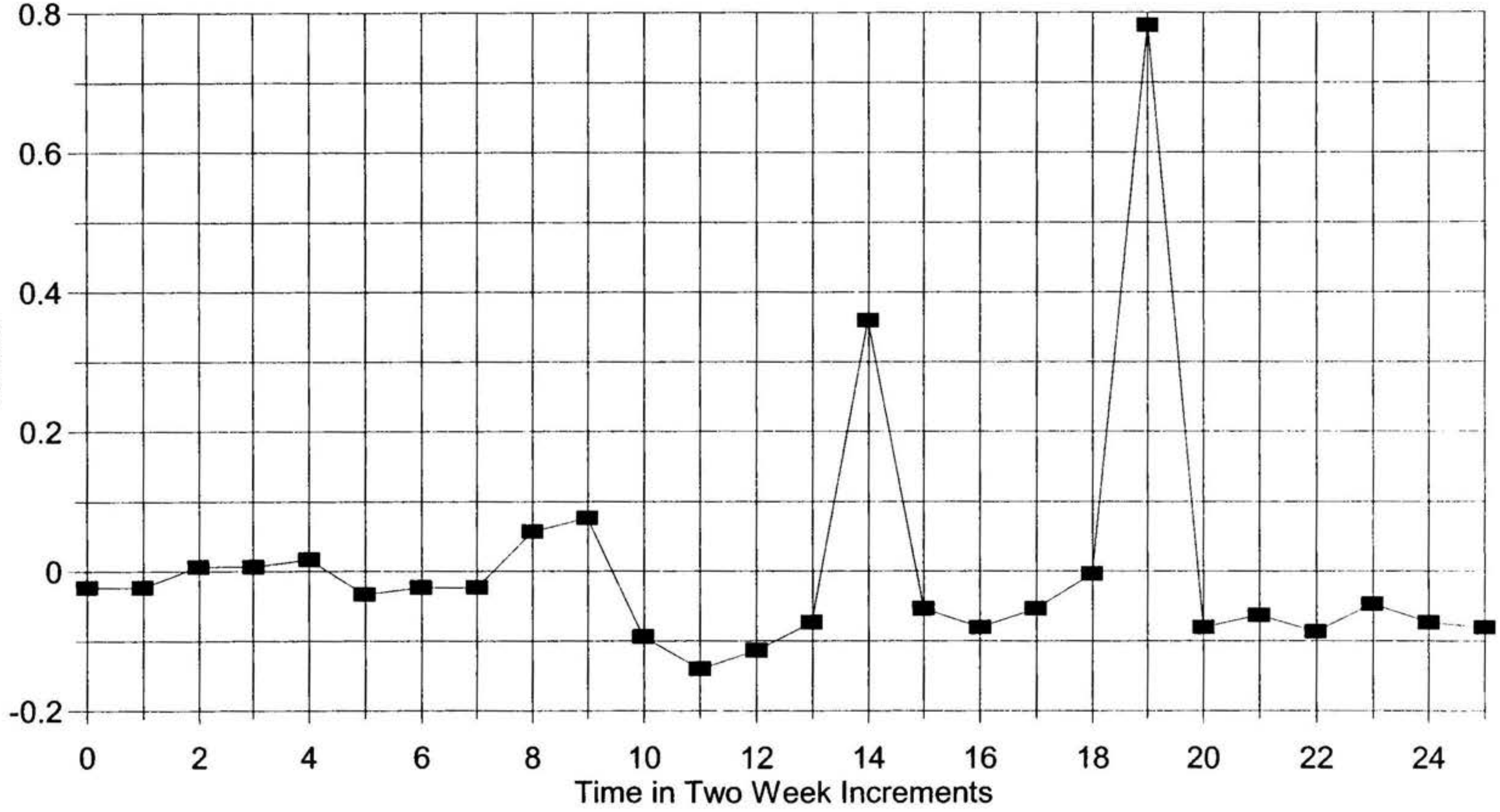

Figure A.5, Errors Conductivity
Fourier Model, N = 0

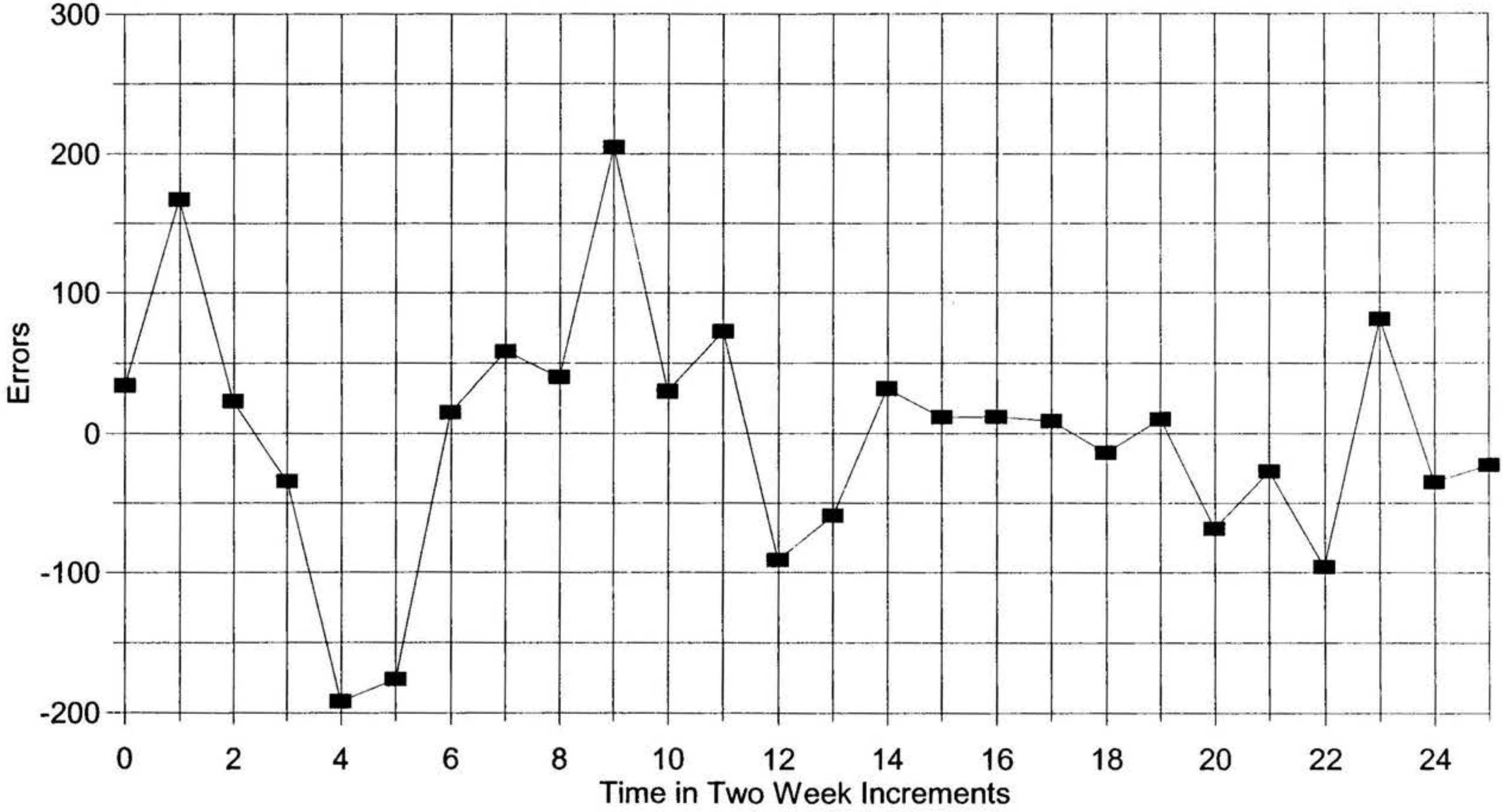

Figure A.6, Errors Redox Potential
Fouier Model, N = 4

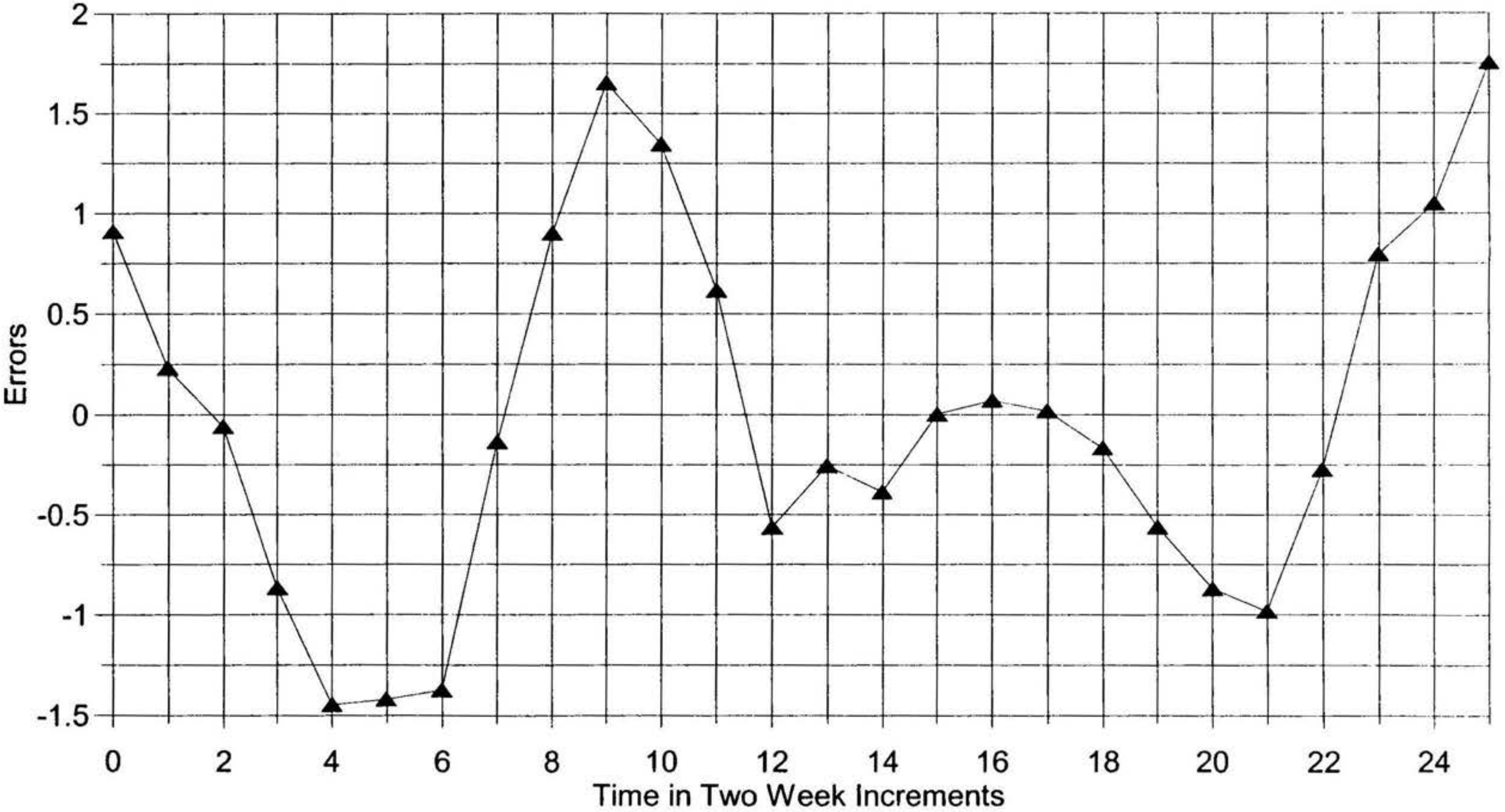

Figure A.7, Errors Solar Radiation
Fourier Model N= 2

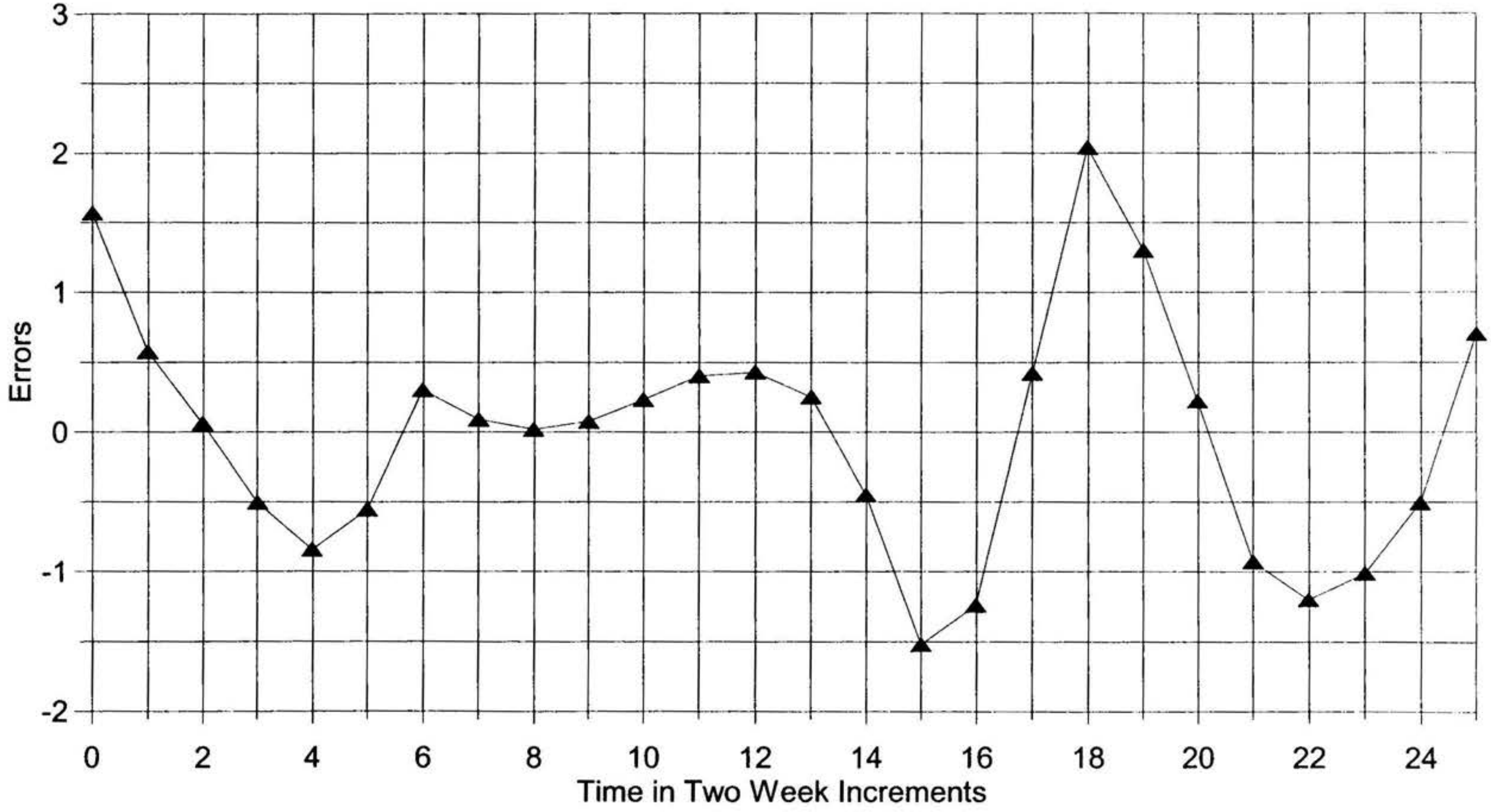

Figure A.8, Errors Air Temperature
Fourier Model

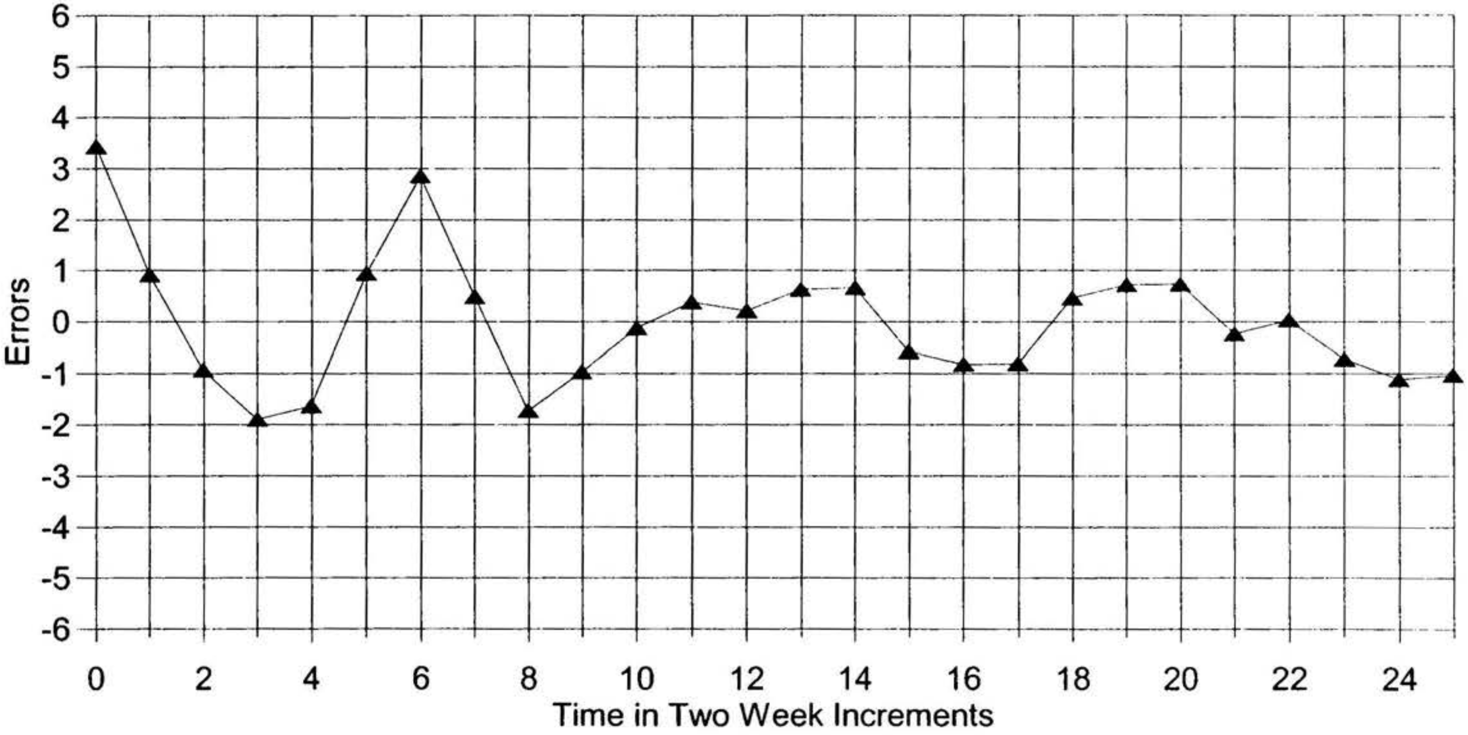

Figure A.9, Errors Peak Wind Gusts
Fourier Model, N=3

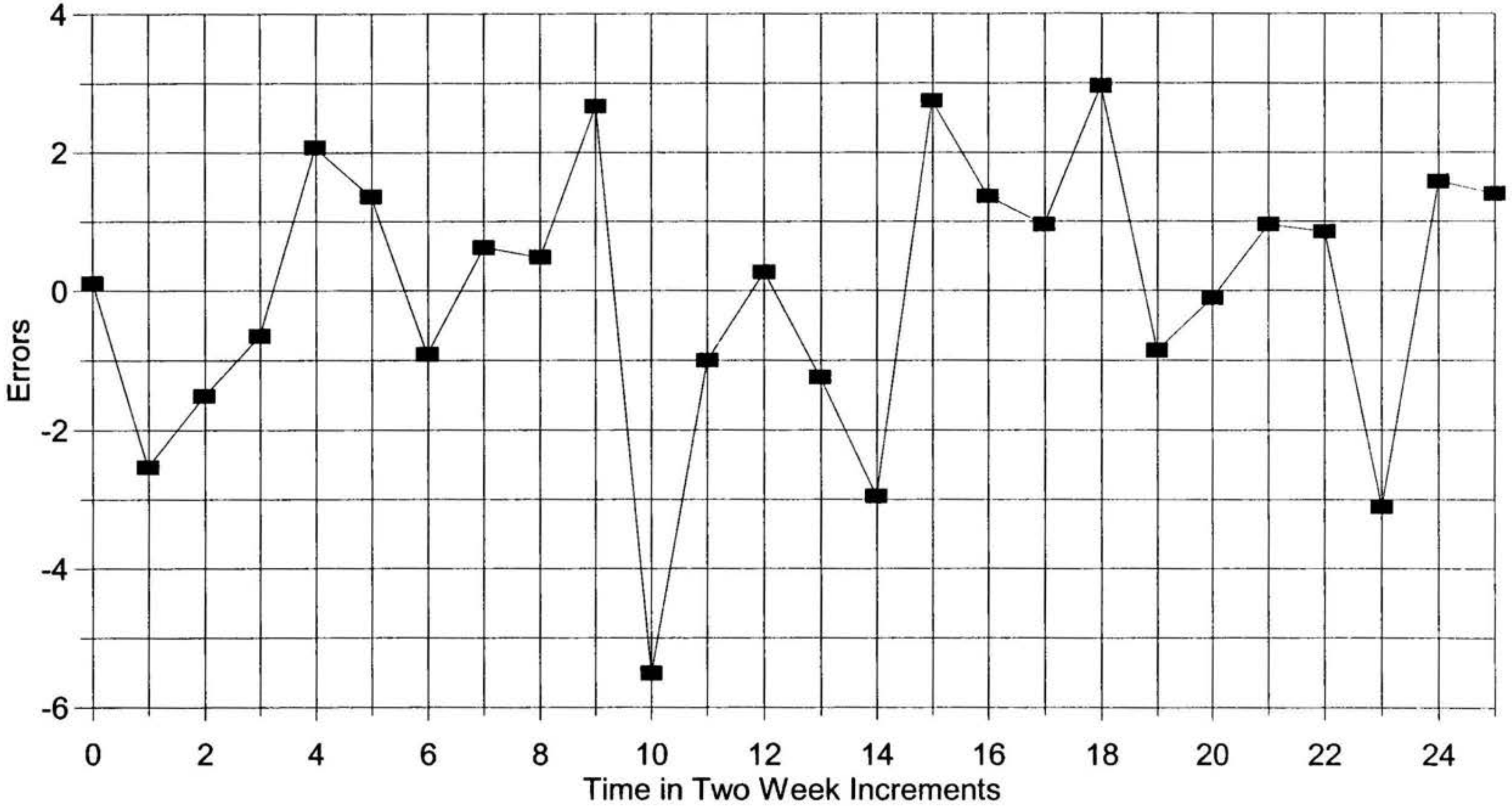

Figure A.10, Errors Water Temperature
Using Multiple Linear Regression

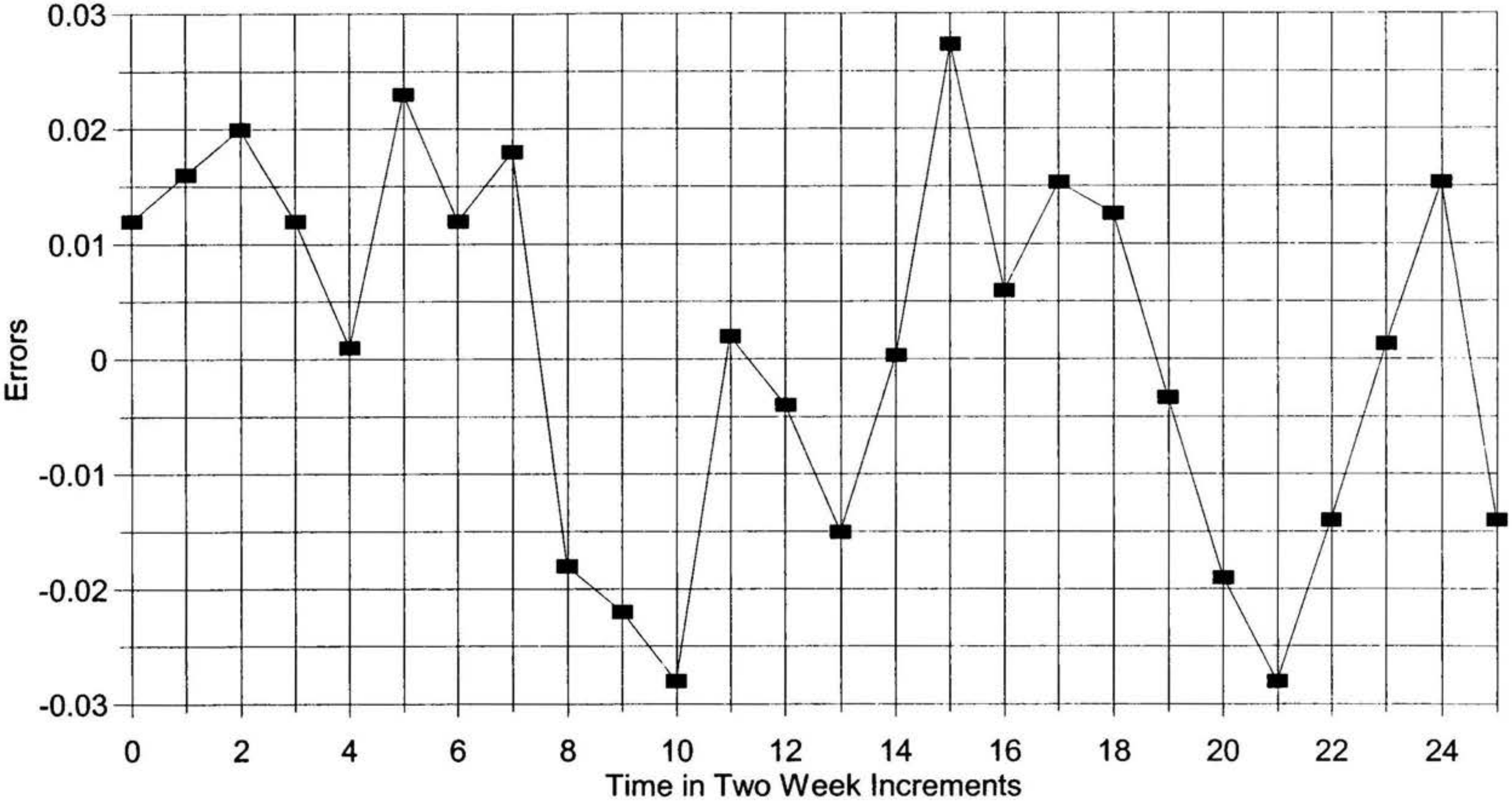

Figure A.11 Errors Salinity Estimate
Using Multiple Linear Regression Model

Figure A.12 Normal Score Plot
Water Temperature

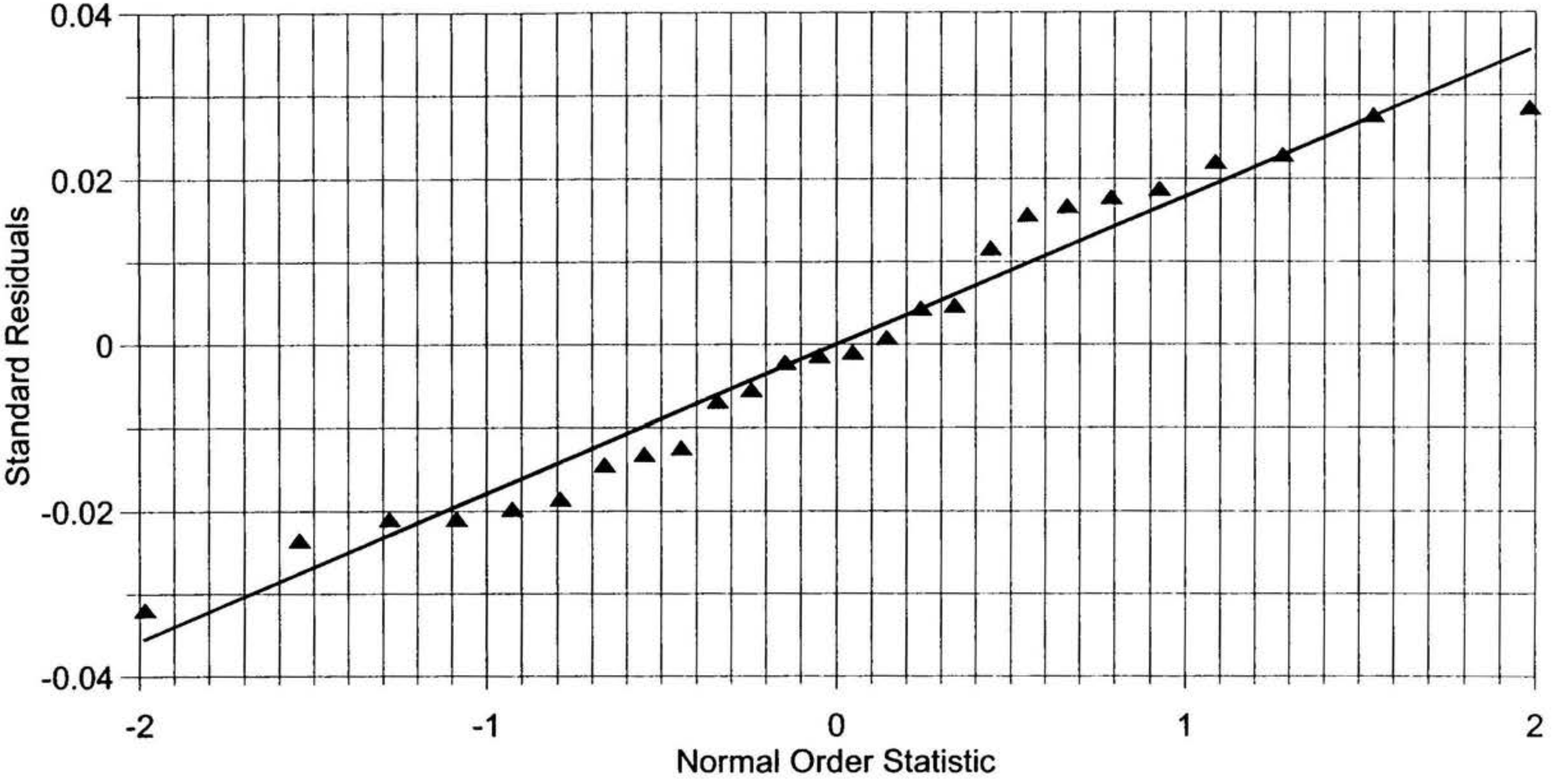

Figure A.13 Normal Score Plot Salinity