THESIS

First-Year Performance Evaluation of a Cold Climate Constructed Wetland for Wastewater Treatment

Submitted by

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In partial fulfillment of the requirements

for the Degree of Master of Science

Colorado State University

Fort Collins, Colorado

Fall 1999

COLORADO STATE UNIVERSITY

July 21, 1999

WE HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER OUR SUPERVISION BY MARY DEMARTINI ANDRE ENTITLED **FIRST-YEAR PERFORMANCE EVALUATION OF A COLD CLIMATE CONSTRUCTED WETLAND FOR WASTEWATER TREATMENT** BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE.

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ABSTRACT OF THESIS

FIRST-YEAR PERFORMANCE EVALUATION OF A COLD CLIMATE CONSTRUCTED WETLAND FOR WASTEWATER TREATMENT

A unique, subsurface flow (SF), constructed wetland pilot study was carried out at Highlands Presbyterian Camp located near Allenspark, Colorado. This site is located in a cold climate region at an elevation of 2530 m (8300 ft). The Highlands treatment system, designed for enhanced removal of suspended solids, biochemical oxygen demand, nutrients, and fecal coliforms, was constructed in the late summer of 1996 and monitored from October 1996 through September 1997.

The Highlands treatment system is a multiple-unit, passive treatment train with a 1.9 m^3/d (500 gpd) capacity located in between a standard septic tank and leachfield. The septic tank effluent flows sequentially through an upflow anaerobic filter with a dosing siphon, a vertical flow aerobic filter, a constructed SF wetland, and another automatic siphon dosing chamber to dose a subsurface disposal field.

Water quality monitoring of the system involved measuring physical, chemical, and biological variables at four sampling ports, which isolated each treatment unit. These variables included flow, water temperature, pH, total dissolved solids (TDS), specific conductance, dissolved oxygen (DO), oxidation-reduction potential (ORP), 5-day biochemical oxygen demand (BOD_5), total suspended solids (TSS), total organic carbon (TOC), ammonia/ammonium (NH_3/NH_4^+), nitrites/nitrates (NO_2^-/NO_3^-), total phosphorus (TP), and fecal coliforms (FC). Water quality monitoring was performed approximately biweekly for one year.

Monitoring results for the system's first year of operation showed a reduction in BOD_5, TSS, TP, and FC. However, the removal efficiencies are generally less than those presented in the literature for more established systems. As the literature indicates, the consistency and magnitude of removal efficiencies are expected to improve with maturation of the wetland plants and establishment of microbial communities.

Seasonally, the removal efficiencies for TSS, TP, and FC were more consistent and of higher magnitude in the warmer months than in the colder months. The removal efficiency for

NH_3/NH_4^+-N was negative in the colder months (indicating an increase through the system) and positive in the warmer months. The lower hydraulic wastewater loading during the winter months due to lower attendance levels at the camp provided a longer hydraulic residence time and compensated for the reduced treatment capability of the wetland at colder temperatures.

The effluent from the system did not meet secondary treatment standards for BOD_5 and TSS consistently. In addition, the observed removal efficiencies of BOD_5 and TSS for the SF wetland were significantly lower than those predicted by first-order kinetic models and regression models from the literature. However, the influent wastewater was consistently at least twice typical domestic wastewater strength.

The development of full wetland treatment potential is expected to take several growing seasons. Further monitoring is necessary to document nitrogen reduction and pollutant removal trends with respect to seasonal variation and system maturation.

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ACKNOWLEDGMENTS

This project represents a cooperative effort and would not have been possible without the dedicated involvement of many contributors. I gratefully acknowledge the following individuals and organizations for their important contributions to this research.

The Highlands treatment system was designed by John Grove (a constructed wetlands consultant in Buena Vista, CO), John Aldrich (a constructed wetlands consultant in Timnath, CO), and John Heidmiller and Brian Zick of The Engineering Co. (Fort Collins, CO). Grove Constructed Wetlands served as the primary contractor for construction of the system. Dave Strom, the Highlands Presbyterian Camp Facilities Superintendent, operated the treatment system, recorded flow measurements, and provided observations which were helpful in interpreting monitoring results and evaluating the system's performance.

The United States Environmental Protection Agency (USEPA) Region VIII provided sampling supplies and laboratory analysis. Terry Griffith served as the USEPA Project Manager and coordinated the USEPA involvement. Michael Bade and Vince Marti, USEPA inorganic chemists, analyzed the laboratory samples. The Colorado State University Environmental Quality Laboratory provided additional analysis of fecal coliforms with funding provided by USEPA Region VIII. Gene Gilbert of Agro-Enviro Consultants (Littleton, CO) provided sampling equipment that prevented cross-contamination and minimized sample disturbance, and analyzed fecal coliforms for three sampling events. The Colorado State University Department of Civil Engineering provided the use of its Hydrolab H20 probe for field measurements.

Finally, I give special thanks to Kelli O'Connor for assisting with the monitoring efforts, and to both Kelli and Laurel Saito for critiquing this thesis and providing encouragement. I thank my graduate committee: Dr. Maurice Albertson (Civil Engineering), Dr. Robert Ward (Chemical and Bioresource Engineering), and Dr. Donald Klein (Microbiology) for their assistance and for challenging me toward excellence. Most of all, I thank my friends and family for their support and encouragement.

To my friends and family

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. INTRODUCTION

1.1 BACKGROUND

In isolated rural and mountainous areas, connection to centralized sewage treatment facilities frequently is infeasible or cost-prohibitive due to steep rocky terrain or distance. In such areas, resorts and individual cabins plan and construct their own on-site wastewater treatment facilities, typically referred to as individual sewage disposal systems (ISDSs). Traditionally, ISDSs have consisted of septic tank treatment followed by some method of subsurface disposal (*i.e.,* leachfields or infiltrators). However, widespread use of this traditional technology in densely populated areas has led to some long-term water quality and health problems due to poorly constructed or maintained systems, overloading, and/or inadequate soils (Otis *et al.*, 1975). To avoid these problems, the use of alternative technologies may be required to supplement the treatment provided by a traditional septic tank and leachfield system (Metcalf & Eddy, 1991). Alternative technologies for on-site wastewater treatment systems include constructed wetlands, intermittent sand filters, ponds, aquatic treatment systems, land-based treatment systems, and mechanical package plants (Reed *et al.*, 1995).

Highlands Presbyterian Camp, typical of many isolated mountain communities, faces a challenge regarding the selection of a feasible, cost-effective wastewater treatment technology capable of adapting to variable flow and loading, and cold winter temperatures while providing treatment that will consistently meet state and county regulations. The camp is located in the cold temperate climate of the Colorado Rockies, near Allenspark, Colorado at an elevation of 2530 m (8300 ft). The camp is planning an expansion of its facilities, which would result in projected summer wastewater flows exceeding 38 m^3/d (10,000 gpd) for full capacity. Highlands Presbyterian Camp's consulting engineers [The Engineering Co. (TEC), Fort Collins, CO] examined several alternatives for wastewater treatment including on-site systems (trench and bed, or an intermittent sand filter), a centralized mechanical treatment facility, and an off-site regional treatment facility (TEC, 1991). A constructed subsurface flow wetland treatment system was proposed to provide a cost-effective, natural, and passive treatment technology that would meet or exceed the state of Colorado's regulatory requirements (TEC, 1996).

Subsurface Flow (SF) wetland treatment systems have been designed to provide advanced biological treatment for septic tank effluent (Reed *et al.*, 1995). SF wetlands offer several advantages including passive treatment, minimal operational requirements and training, minimal vector nuisance (mosquitos), and aesthetics (Kadlec and Knight, 1996). Many regulatory personnel are aware of the existence of wetland technologies but consider them unproven experimental technologies and are hesitant to approve their use (Slayden and Schwartz, 1989; Otis, 1992). To address such uncertainties, the EPA is building its database on the performance of wetland systems (Kadlec and Knight, 1996). With a better understanding of the performance of SF wetland systems for wastewater treatment in cold climate conditions, it will be possible to demonstrate the technology's effectiveness, define the needs for further scientific research, and develop a sound methodology for the design and sizing of wetlands for optimal treatment performance and operational efficiency.

Since the performance and operational efficiency of SF wetland systems used at high altitude and cold climate regions are not well documented in the literature, a pilot wetland system of 1.9 m^3/d (500 gpd) capacity was built in the late summer of 1996 at Highlands Camp. The pilot wetland system was intended to extend the life of two existing leachfields by relieving their loading while simultaneously providing data that would aid in the determination of whether a wetland system could be used to treat projected wastewater flows for the camp's expansion. If the pilot system were deemed successful (*i.e.*, capable of consistently meeting regulations regarding the reduction of pollutants from primary sewage effluent to standards suitable for ground water recharge or surface water reintroduction), the data gained could also be used to aid in the subsequent design of a full-scale wetland system. The treatment train consists of a three-compartment septic tank with an effluent filter, an upflow anaerobic filter, a vertical flow aerobic filter, a constructed wetland, and an automatic dosing siphon tank that doses the infiltrators. A year-long, intensive, cooperative study of the system performance began in October of 1996. This thesis presents and discusses the results of the first year of the pilot study.

1.2 Purpose and Objectives

The purpose of this study is to document and evaluate the first-year performance of a cold climate, domestic wastewater treatment train utilizing a SF constructed wetland to reduce pollutants from primary sewage effluent to standards suitable for ground water recharge or surface water reintroduction. The study also will assess the scientific understanding of design methodologies for SF constructed wetlands within cold climate regions. To help accomplish this purpose, a year-long study of the pilot constructed wetland system was conducted with the following four objectives to evaluate the system's treatment performance and design:

1) Describe the contribution of each unit to the overall wastewater treatment provided by the system,
2) Quantify the seasonal variation of pollutant removal efficiencies through the system,
3) Compare the system's treatment performance to secondary treatment standards, and
4) Compare the observed results to those predicted by existing design models.

The basis of the objectives is derived from the need by regulators, designers, and researchers to determine the effectiveness of constructed wetlands for wastewater treatment in cold climate regions. There is a need to demonstrate, document, and evaluate the methods by which constructed wetlands for wastewater treatment, operating under various conditions, contribute to meeting the Clean Water Act's objective to "restore and maintain the physical, chemical and biological integrity of the Nation's waters." Constructed wetland technology may offer a viable wastewater treatment alternative for many isolated mountain communities. The information obtained by carrying out these objectives is intended to result in recommendations regarding the suitability of constructed wetland systems for wastewater treatment in high altitude and cold climate applications.

1.3 Scope and Constraints

The scope of the study involves monitoring and evaluating the first-year operation of a SF constructed wetland for domestic wastewater treatment conducted in a cold climate and high altitude region. The climate is seasonal with large temperature ranges, large snowfall accumulations, and annual precipitation between 25 to 76 cm (10 to 30 in.). The site is located at an elevation of 2530 m (8300 ft) and latitude/longitude coordinates of approximately 40°11'N and 105°31'W. The conclusions reached in the course of this study may not apply outside this scope. Constraints on this study include funding for time, equipment, and laboratory support. Extreme weather conditions interrupted regularly scheduled fieldwork on two occasions.

1.4 Overview

This thesis is divided into seven chapters and four Appendices. CHAPTER 1: INTRODUCTION presents an introduction to subsurface flow wetlands and includes the study's objectives and scope. CHAPTER 2: SUBSURFACE FLOW CONSTRUCTED WETLANDS presents a literature review of the general background, functioning, design, operation, and evaluation of subsurface flow constructed wetland systems for wastewater treatment. CHAPTER 3: WETLAND SITE AND DESIGN details the site location and pilot system design. CHAPTER 4: MONITORING AND ASSESSMENT METHODS presents the monitoring program and data analysis protocol. CHAPTER 5: MONITORING RESULTS presents results of each monitored variable for first-year operation of the Highlands treatment system. CHAPTER 6: DISCUSSION AND ANALYSIS discusses and analyzes the results with respect to each of the thesis objectives. CHAPTER 7: SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS presents a summary of the study, conclusions for each of the thesis objectives, and recommendations regarding scientific research, design, monitoring, and operation of SF constructed wetland systems for wastewater treatment. Appendix A contains a list of abbreviations and definitions for terms used commonly within this thesis. Appendices B through D contain data for climatic variables, field variables, and lab variables, respectively.

2. SUBSURFACE FLOW CONSTRUCTED WETLANDS

This section presents a literature review of the general background, functioning, design, operation, and evaluation of subsurface flow constructed wetland systems for wastewater treatment.

2.1 GENERAL BACKGROUND

2.1.1 Value of Wetlands

Wetlands have been described as "the kidneys of the landscape" in recognition of their ability to improve water quality. Wetlands have a high rate of biological activity and can transform many of the common pollutants that occur in conventional wastewater into harmless byproducts or essential nutrients that can be used for additional biological productivity. These transformations result in water quality improvement and the beneficial recycling of wastewater constituents in biological food chains. Wetlands provide a natural environmental treatment technology that harnesses the energies of the sun, wind, soil, plants, and animals, eliminating the need for fossil-fuel energy and chemicals (Kadlec and Knight, 1996).

The value of wetlands for water quality improvement was "rediscovered" during the last two decades of heightened environmental awareness, and wetlands have become a rallying point for restoration, conservation, and preservation (Kadlec and Knight, 1996). The Max Planck Institute for Limnology in Plön, Germany initiated wetland treatment research in 1952. Similar research in the Western Hemisphere started during the 1970's. Confidence generated from research on wetlands for water quality control has acted to accelerate the implementation of this technology around the world since 1985 (Kadlec and Knight, 1996). There are estimated to be more than 1000 managed wetland systems currently in operation world-wide (Reed *et al.*, 1995). Constructed wetlands have been employed to treat a wide spectrum of flows ranging from ~400 gpd for a single residence to three million gallons per day (MGD) for a small wastewater treatment facility (Hilton, 1993). Cooper (1993) reports that constructed wetlands are providing treatment for small flows, which were previously untreated.

The concept behind constructed wetlands for water quality improvement is becoming popularized. An article in Smithsonian discussed the attractions (economics, aesthetics, effectiveness, and simplicity) of utilizing plants to do the "dirty work" and "turning a messy problem into a garden" (Wiley, 1997). Popularity is due in part to lower costs and minimum requirements for operation and maintenance (O&M) compared to conventional technology (Smith, 1989; Freeman, 1993; Kadlec and Knight, 1996). Constructed wetlands are low-cost, simple, and effective systems for wastewater treatment in small communities where land is available (Hammer and Bastian, 1989; Vymazal, 1993). However, wetlands are land intensive, subject to weather/environmental conditions, dependent on flow patterns and loading rates, and affected by gradual development and continually changing components and processes (Bastian and Hammer, 1993). Table 2-1 provides a list of generally recognized advantages and disadvantages of constructed wetlands for wastewater treatment.

Table 2-1: Advantages and Disadvantages of Constructed Wetlands for Wastewater Treatment ***(from Brix, 1993b)***

Advantages	Disadvantages
low cost of construction and maintenance	more land required
low energy requirements	subject to environmental influences
low tech – operators don't require extensive training	

Driving forces behind the need for low-cost, low maintenance, reliable wastewater treatment alternatives include: 1) stricter water quality stream standards by the Clean Water Act, 2) discontinuation of the EPA's Construction Grants program and Innovative and Alternative funding Program, and 3) downturn in some regional economies (Cueto, 1993). Steiner and Combs (1993) discuss the affordability of small constructed wetland systems for single residences. Cueto (1993), in a preliminary cost comparison for conventional vs. wetland treatment systems, indicated that wetlands are more cost-effective for wastewater flow rates of up to five MGD. Vymazal (1996), in a survey of full-scale constructed wetlands in the Czech Republic, found that while construction costs were similar to conventional systems, the O&M costs were 20 to 50 times lower for constructed wetlands.

Although the beneficial use of constructed wetlands for wastewater treatment is well-established, the dynamics and long-term operation of constructed wetlands are still in a developing state of knowledge (Tchobanoglous, 1993). There are still many questions concerning optimization of wetland treatment that must be answered through research and analysis of accumulated wetland operational data, and conservative design approaches are advised (Kadlec and Knight, 1996). "As the uncertainties now associated with the use of constructed wetlands are resolved, this technology will assume its rightful place alongside more conventional technologies for the treatment of wastewater" (Tchobanoglous, 1993).

2.1.2 Types of Wetlands

There are three primary types of wetlands used for treatment: free-water-surface (FWS) constructed wetlands, subsurface flow (SF) constructed wetlands, and natural wetlands. Each of these share common characteristics which allow them to be classified broadly as wetlands. Wetlands are land areas that are wet during part or all of the year. "Wetlands are wet long enough to alter soil properties because of the chemical, physical, and biological changes that occur during flooding, and to exclude plant species that cannot grow in wet soils" (Kadlec and Knight, 1996).

First, it is important to understand the distinction between natural and constructed wetlands. Natural wetlands and constructed wetlands are both highly productive systems, which possess the capability to remove pollutants. Natural wetlands commonly are used as receiving waters for permitted discharges of treated wastewaters. However, "any use of natural wetlands for treatment purposes requires extensive pre-project review to ensure the wetland ecosystem is not unacceptably altered" (Bastian *et al.*, 1989). The exploitation of natural wetlands for wastewater treatment could damage ecosystems, which would subsequently require long-term recovery (Hammer and Bastian, 1989; Brix, 1993b). Whereas constructed wetlands are designed, built, and operated as wastewater treatment systems and, in general, are excluded from the definition of "water of the United States" (40 CFR Part 122.2). Therefore, constructed wetlands are not subject to the same protection and restrictions as natural wetlands (Bastian *et al.*, 1989). As Brix discusses (1993b), constructed wetlands are better suited for wastewater treatment, and natural wetlands should be preserved for environmental conservation. Wetzel (1993) agrees that constructed wetlands can provide greater treatment efficiency since certain wetland characteristics can be enhanced and managed, although he adds that natural wetlands offer greater diversity and their integrated operation may not be fully appreciated or understood.

A constructed wetland, also referred to as an engineered or artificial wetland, is defined by Hammer and Bastian (1989) as a "designed and man-made complex of saturated substrates, emergent and submergent vegetation, animal life and water that simulates natural wetlands for human use and benefits." Constructed wetlands offer the opportunity to control the substrate composition, vegetation type, flow pattern, site selection, sizing, hydraulic pathways and retention time. In contrast, natural wetlands are extremely variable, may have channelized flow patterns, and have an unpredictable treatment capacity (Brix, 1993b).

Constructed wetlands consist of several basic components which are critical to their functioning to improve water quality; these include: plants, soils/media, microbes, inflow and outflow structures, and usually a liner. Plants remove pollutants directly by assimilation into plant tissue and indirectly by providing surfaces and suitable environment for microbes (Brix, 1993b). The soils/media support vegetation, provide surfaces for microbial attachment, and are associated with physical and chemical treatment mechanisms (Steiner and Freeman, 1989). The microbes aid in biotransformation and degradation of entering nutrients and organics. The inflow and outflow structures maintain a water level and encourage a flow regime with minimal hydraulic short-circuiting. A liner, if used, contains the water within the reactive zone.

There are two main types of constructed wetlands: free-water-surface (FWS) constructed wetlands and subsurface flow (SF) constructed wetlands. Free-water-surface wetlands are more typically what one may imagine when the word "wetlands" is mentioned. A FWS constructed wetland consists of a bed of emergent aquatic vegetation in shallow water (~0.4 m) exposed to the atmosphere, a layer of soil for rooting media, a liner to protect the groundwater, and appropriate inlet and outlet structures (Reed *et al.*, 1995). Open water areas may be incorporated to enhance wildlife habitat (Kadlec and Knight, 1996).

In contrast to FWS constructed wetlands, subsurface flow (SF) constructed wetlands maintain the water level below the bed surface. A SF wetland consists of a lined basin of up to 0.75 m (2 ½ ft) depth, filled with a permeable packing medium (*e.g*, soil, sand, or gravel), and planted with emergent plants (*e.g.*, catails, bulrushes, sedges, and other species) (Weider *et al.*, 1989). A diagram of a SF constructed wetland is provided by Figure 2-1. Table 2-2 details a comparison of FWS and SF constructed wetlands. Subsurface flow wetlands have been described as vegetated submerged beds (VSB), microbial rock reed filters, gravel marsh, root-zone, reed bed, rock/plant filter, and gravel-based emergent macrophyte systems. There is some confusion in the literature when subsurface flow wetlands are abbreviated as SSF wetlands, and free-water-surface wetlands are designated as surface flow (SF) wetlands. In this thesis, SF wetlands refer to subsurface flow wetlands exclusively.

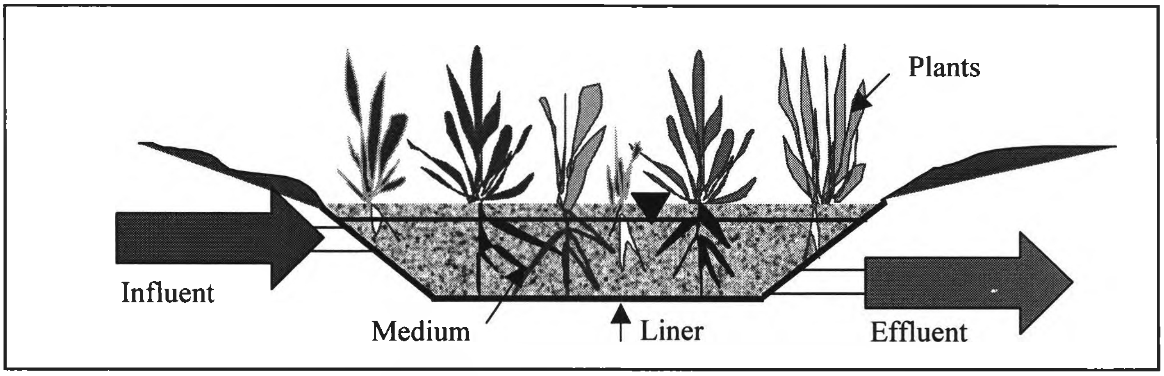


Figure 2-1: Subsurface Flow (SF) Constructed Wetland Diagram

Table 2-2: Comparison of Free-Water-Surface (FWS) and Subsurface Flow (SF) Constructed Wetlands *(from Freeman, 1993 and Reed et al., 1995)*

FWS wetlands	SF wetlands
lower installed cost ($/gal)	greater assimilation rate
simpler hydraulics	less land required
more natural wetland values (wildlife habitat)	no visible flow
	less nuisance (vector problems, odors)
	more cold tolerant

2.2 WASTEWATER TREATMENT ASPECTS

Subsurface flow (SF) constructed wetlands are constructed to treat domestic and municipal wastewater, commercial and industrial wastewater, stormwater runoff, combined sewer overflows, agricultural runoff, livestock wastewaters, landfill leachates or acid mine drainage (Reed *et al.*, 1995; Kadlec and Knight, 1996). This thesis focuses on the use of SF constructed wetlands to treat domestic wastewater. As general background, this section presents a description of domestic wastewater characteristics, treatment levels, historical progress, and an overview of on-site treatment technologies.

2.2.1 Progress in Wastewater Treatment

The modern era in sanitation began in the latter half of the nineteeth century with advances in the sciences of microbiology and epidemiology. These developments revolutionized the understanding of the relationship between pollution and disease, and served as an impetus for the construction of wastewater collection and treatment systems to improve public health conditions (Hendricks, 1997).

Early efforts in wastewater treatment included the use of land-based natural treatment systems. In the United States, the move toward adopting more intensive wastewater treatment processes began in the early twentieth century, lagging behind Europe due to the availability of large water bodies for untreated wastewater discharge and large areas for land disposal (Metcalf & Eddy, 1991). The passage of the Federal Water Pollution Control Act Amendments of 1972 (Public Law 92-500) set the stage for wastewater treatment innovations and efforts with an aggressive approach toward pollution control and grants for treatment facility construction. In 1988, over 15,000 treatment facilities were in operation within the United States, and trends indicated that both the total number of treatment plants and the level of treatment provided by these plants was increasing (Metcalf & Eddy, 1991).

For the past three decades, most wastewater treatment efforts have been focused on the design, construction, and operation of large regional wastewater treatment plants. Small systems were designed and constructed as small-scale models of large plants and consequently, their operation was often energy and resource intensive (Metcalf & Eddy, 1991). Small communities with populations of 1,000 or less are served by about 32% of the nation's treatment plants but account for only 0.7% of the nation's wastewater treatment capacity (Metcalf & Eddy, 1991). These small communities are challenged with a variety of problems when constructing and operating a community-wide managed wastewater treatment facility. The main problems relate to (1) stringent discharge requirements, (2) high per capita cost, (3) limited finances, and (4) limited operation and maintenance budgets (Metcalf & Eddy, 1991). The evolution of treatment systems has circled back on itself with the growing popularity of less energy-intensive and more cost efficient systems utilizing natural treatment technologies.

2.2.2 Wastewater Characteristics

Domestic wastewater is characterized by biological, physical and chemical variables. The typical measured variables include 5-day biochemical oxygen demand (BOD_5), total organic carbon (TOC), chemical oxygen demand (COD), total suspended solids (TSS), ammonia/ammonium (NH_3/NH_4^+), total kjeldahl nitrogen (TKN), nitrite/nitrate (NO_2^-/NO_3^-), total phosphorus (TP), and fecal coliforms (FC). These terms are defined in Appendix A.

2.2.3 Wastewater Treatment Levels

Wastewater treatment is categorized as primary, secondary, or tertiary (*i.e.*, advanced). In primary treatment, physical operations such as screening and sedimentation are used to remove the floating and settleable solids (SS) found in wastewater. In secondary treatment, biological and chemical processes are used to remove most of the organic matter. In tertiary treatment, additional treatment combinations of operations and processes are used to remove other constituents such as nitrogen and phosphorus that are not significantly reduced by primary and secondary treatment. Natural systems combine physical, chemical, and biological treatment mechanisms and are capable of producing effluent with similar or higher quality than that from advanced wastewater treatment (Metcalf & Eddy, 1991). Generally, constructed wetlands are used for secondary or advanced treatment and require pretreatment (Wieder *et al.*, 1989; Sauter and Leonard, 1997).

2.2.4 Applicable Laws and Regulations

The legal and regulatory basis for wastewater treatment is provided primarily by the federal Clean Water Act (PL 100-4, The Water Quality Act of 1987). The Code of Federal Regulations (CFR) defines the responsibilities of the U.S. Environmental Protection Agency (USEPA) in enforcing the provisions of this act. State and county health departments, with authority derived from this federal act, issue regulations and guidelines governing all aspects of the permits, performance, location, construction, alteration, and installation of wastewater storage, collection, and treatment systems.

On a broad basis, the goals of the Clean Water Act provide the legal foundation for wastewater treatment. Section 101 (a) notes that "the objective of this act is to restore and maintain the chemical, physical, and biological integrity of the Nation's waters." This act calls for zero discharge by 1985, fishable and swimmable waters by 1983, prohibition of toxic pollutants, federal assistance for the construction of publicly owned wastewater treatment works, area-wide waste treatment management planning processes, national development of technology to eliminate pollutant discharge through research and demonstration effort, and the control of nonpoint pollution sources.

The CFR defines and details the responsibilities of the USEPA to enforce the provisions of the Clean Water Act and contains provisions specifically relating to wastewater treatment for small systems. The USEPA's mandate includes the comprehensive documentation and evaluation of innovative and improved methods of sewage reduction, collection, and treatment for rural and isolated areas (33 USC Sec. 1254).

The current minimum national standards for secondary treatment are defined in 40 CFR 133 pursuant to Section 304(d) of Public Law 92-500 (Metcalf & Eddy, 1991). The definition includes three major effluent parameters: pH, BOD_5, and TSS. The standard specifies that pH be maintained within the range of 6.0 to 9.0 at all times. The secondary treatment standard for BOD_5 and TSS specifies that the average 30-day concentration of either BOD_5 or TSS is not to exceed 30 mg/l, and the average 7-day concentration of BOD_5 or TSS is not to exceed 45 mg/l (this standard is commonly referred to in shorthand notation as 30/45 mg/l BOD_5/TSS). In addition, the average removal of BOD_5 and TSS shall not be less than 85%. Additional details and exceptions are presented in 40 CFR 133.

2.2.5 On-site Treatment Technologies

On-site treatment can be accomplished by traditional septic tank and leachfield systems, mechanical systems (*i.e.*, packaged mechanical treatment plants), or natural systems (*e.g.*, intermittent sand filters, ponds, aquatic treatment systems, land treatment systems, and wetlands). Many on-site treatment systems use a combination of the traditional, mechanical, and natural components. The unique characteristics and constraints of each site (*i.e.*, land availability, soil conditions, climate, wastewater flow and loading, permit standards, and available finances) should be considered when assessing the feasibility and appropriateness of various treatment technologies. Generally, natural treatment systems are land intensive, while conventional mechanical treatment systems are energy intensive (Kadlec and Knight, 1996). In cases with periodic high loads and strict discharge standards, the control enabled by a mechanical treatment system may be preferred over the large land requirement of a natural treatment system in order to meet permit standards consistently. However, where adequate land resources are available, natural treatment systems often provide the most cost effective and practicable alternative (Kadlec and Knight, 1996).

2.2.5.1 Traditional Septic Tank and Leachfield Systems

Septic tank and leachfield systems have been used traditionally for individual residences to provide primary wastewater treatment and disposal. Septic tanks are sized based on a recommended minimum detention time of 30 hours (Metcalf & Eddy, 1991) or up to 2-3 days (Reed *et al.*, 1995). Septic tanks are usually made of concrete, fiberglass, or polyethylene, and must be watertight and structurally sound. Interior baffles are sometimes used to divide the tank into two or three compartments. Access ports are provided for inspection and cleaning purposes.

Septic tanks provide an environment for sedimentation, flotation and anaerobic digestion. The settleable solids form a sludge layer in the bottom of the tank while the greases and other light material form a floating scum layer. The septic tank effluent flows from the area between these distinct layers. The accumulating sludge undergoes anaerobic digestion. Gases produced by this process may cause some of the settled solids to float up and subsequently adhere to the scum layer, increasing its thickness. Occasionally, septic tanks should be pumped when the sludge and scum layers become too deep and lead to decreased retention times as well as contributing undesirable material to the effluent. Table 2-3 describes the typical characteristics of septage, the sludge produced by septic tanks (Metcalf & Eddy, 1991).

Table 2-3: Typical Characterization of Septage ***(from Metcalf & Eddy, 1991)***

Constituent	Concentration (mg/l)	
	Range	**Typical**
Total Solids (TS)	5,000 - 100,000	40,000
Total Suspended Solids (TSS)	2,000 - 100,000	15,000
Volatile Suspended Solids (VSS)	1,200 - 14,000	7,000
5-day, 20°C Biochemical Oxygen Demand (BOD_5)	2,000 - 30,000	6,000
Chemical Oxygen Demand (COD)	5000 - 80,000	30,000
Total Kjeldahl Nitrogen (TKN as N)	100 - 1,600	700
Ammonia (NH_3 as N)	100 - 800	400
Total Phosphorus (TP as P)	50 - 800	250
Heavy metals	100 - 1,000	300

Septic tanks remove much of the suspended solids and a portion of the BOD (Reed *et al.*, 1995). An estimate of the average removal efficiencies through septic tanks can be obtained by referring to Table 2-4, which provides an average wastewater characterization of raw sewage and septic tank effluent. To improve performance of an existing septic tank, several modifications can be considered. An effluent filter may be added, effectively acting as an additional compartment within the septic tank. Aerators can be added to the third compartment to improve nitrification and aerobic decomposition.

Generally, the septic tank effluent is discharged to and treated by a soil absorption and infiltration system. The most common on-site disposal system is a gravity-flow leachfield or trench system. These work well for sites where the soils are deep and permeable, the groundwater level is deep, and the site is relatively level. Alternative infiltration systems have been developed for adverse site conditions and may incorporate pressure-dosed distribution, fill, mounding, or artificial drainage (Metcalf & Eddy, 1991; Reed *et al.*, 1995).

Table 2-4: Treatment Performance of Septic Tanks ***(from Metcalf & Eddy, 1991)***

Constituent	Raw Waste	Septic Tank Effluent
BOD_5 (mg/l)	210-530	140-200
TSS (mg/l)	237-600	50-90
Nitrogen (mg/l)		
Total N	35-80	25-90
NH_4^+	7-40	20-60
NO_3^-	<1	<1
Total Phosphorus (mg/l)	10-27	10-30
Fecal Coliforms (MPN/100 ml)	10^6 - 10^{10}	10^3-10^6
Viruses (PFU/ml)	Unknown	10^5-10^7

2.2.5.2 Mechanical Systems

Prefabricated treatment plants, small versions of conventional mechanical wastewater treatment systems known as package plants, are commercially available. These are most commonly used in the flow range of 0.01 to 0.25 million gallons per day (MGD). The most common types of package plants are: (1) extended aeration, (2) contact stabilization, (3) sequencing batch reactors, (4) rotating biological contactors, and (5) physical/chemical (Metcalf & Eddy, 1991). The key to consistent performance of package plants is operational attention and consistent removal of sludge. Package plants can be problematic during periods of low loading because a minimum level of organic loading is required to sustain the microbial treatment populations. The expense, operational requirements, and poor performance of package systems under low loading have led engineers to consider other treatment options (Slayden and Schwartz, 1989).

2.2.5.3 Natural Systems

Natural systems are passive systems that rely primarily on natural physical, chemical, and biological processes that occur in a soil-water-plant ecosystem rather than depending on chemical additions, energy inputs, and complex equipment that are used in a mechanical system to treat wastewater (Metcalf & Eddy, 1991). The use of natural systems can reduce costs, energy, and complexity of operation (Reed *et al.*, 1995). In addition to constructed wetlands, natural systems include: intermittent sand filters, stabilization ponds, aquatic treatment systems, and land treatment systems.

Intermittent sand filters are shallow beds of fine to medium sand with a surface distribution system and an underdrain system. Septic tank effluent is applied intermittently to the surface of the sand bed and subsequently, the treated effluent is collected through an underdrain system at the bottom of the filters. Treatment in intermittent sand filters is achieved by physical, chemical, and biological mechanisms. Buried and covered filters more effectively maintain temperatures for microbial activity in cold climates. Intermittent application and venting of the underdrains helps to maintain aerobic conditions within the filter to promote nitrification. Flooding the underdrain system can provide an anaerobic environment to enhance denitrification. The principal design criteria for intermittent sand filters are sand size, sand depth, hydraulic loading rate, and dosing frequency. Performance can be improved by recirculating a proportion of the effluent for reapplication. Recirculating fine gravel filters, similar to intermittent sand filters except for the larger media and higher hydraulic loading rate, have been successful in nitrifying over 90% of the total nitrogen flowing into the filter (Reed *et al.*, 1995).

Stabilization ponds (also called oxidation ponds) utilize biological treatment mechanisms. There are four major pond types (facultative, aerated, aerobic, and anaerobic) classified by the dominant biological reactions that occur. Pond design also should consider hydraulics, seasonal effects, sludge accumulation, and treatment by ponds in series. Hydraulic short-circuiting can be prevented by modification of the pond configuration length-to-width ratio, orientation with respect to prevailing wind direction, and/or use of inflow diffusers and baffles (Reed *et al.*, 1995).

Aquatic treatment systems use aquatic plants (*e.g.,* water hyacinths and duckweed) or aquatic animals (*e.g., Daphnia*, shrimp, and fish) as a component in wastewater treatment. The presence of aquatic plants or animals can facilitate treatment directly (through uptake with subsequent harvesting) or indirectly (by altering the treatment environment or providing an environment for attached microbial activity). The plants and animals have specific environmental requirements (*e.g.,* temperature, dissolved oxygen, pH) that must be met to function successfully (Reed *et al.*, 1995).

Land treatment is the controlled application of wastewater to soil to achieve treatment of constituents in wastewater using physical, chemical and biological processes within the soil-plant-water matrix. Three common land treatment types include slow rate, overland flow and rapid infiltration. Slow rate is similar to conventional agricultural irrigation and has low loading rates and the widest range of acceptable soil types and permeabilities. Overland flow provides treatment to wastewater as it flows down grass-covered slopes; the treated effluent is collected at the bottom as surface runoff. Rapid infiltration provides treatment to wastewater as it percolates through a permeable soil with intermittent application (Reed *et al.*, 1995).

2.3 Treatment Mechanisms

Biogeochemical cycling in natural wetlands involves many interactive processes that collectively contribute to the purification of incoming waters. Constructed wetlands are designed to utilize the same processes and mechanisms in a more controlled environment to treat wastewater. The principal treatment mechanisms include sedimentation, filtration, adsorption, biochemical transformation and plant uptake. Sedimentation and filtration are effective in removing suspended solids and the particulate pollutants due to the very low water velocities and dense vegetation in the root matrix. Adsorption involves the pollutant sorption on plants, soil, and organic substrates. Biochemical transformation involves both aerobic and anaerobic degradation of nutrients and organic matter by microbes. Plant uptake involves incorporation of nutrients and some pollutants into plant biomass; harvesting is necessary to maintain plant nutrient uptake rates. These treatment mechanisms, summarized in Table 2-5, contribute to the removal of organic matter, removal of nutrients, and the removal of fecal coliforms.

Table 2-5: Pollutant Removal Mechanisms of Wetlands *(from Brix, 1993b)*

Constituent	Removal Mechanisms
SS	sedimentation/filtration
BOD	microbial degradation (aerobic and anaerobic)
	sedimentation
Nitrogen	ammonification followed by microbial nitrification and denitrification
	plant uptake
	ammonia volatilization
Phosphorus	soil sorption (adsorption – precipitation reaction w/ Al, Fe, Ca, and clay minerals in soil)
	plant uptake
	(phosphine production)
Pathogens	sedimentation/filtration
	natural die-off
	UV radiation (if open water)
	excretion of antibiotics from roots of macrophytes

The efficacy of constructed wetlands for wastewater treatment is dependent on developing and maintaining optimal environments for desirable microbial populations. Such microbes are ubiquitous and naturally occurring in most water with adequate nutrient and energy sources (Hammer and Bastian, 1989). "Microbial populations can be maintained in the logarithmic phase by continually providing new supplies of energy, nutrients, and other requirements. Generation time depends on the type of organism, concentration of available nutrients, temperature, pH, and oxygen. In general, species multiply rapidly when provided with favorable conditions" (Portier and Palmer, 1989). Portier and Palmer (1989) provide an overview of microbial processes of importance to constructed wetlands for wastewater treatment.

Macrophytes remove pollutants directly by assimilation into plant tissue and indirectly by providing surfaces and a suitable environment for microbes (Brix, 1993b). Breen (1990) states that plant uptake (absorption) is the main removal mechanism for nitrogen and phosphorus. Breen cites other studies in which it is concluded that plant nutrient uptake rates were inadequate as a removal mechanism for wastewater treatment but explains that these studies physically minimized the opportunity for plant-mediated processes. Guntenspergen *et al.* (1989) discuss major categories of wetland vegetation and morphological and physiological adaptations to environmental gradients and examine the abilities of plants to affect their environment and transform wastewaters. Vegetation interacts with wastewater in several ways, including: (1) assimilation of inorganic and organic constituents of wastewater, (2) storage of various mineral nutrients, (3) incorporation of mineral nutrients into biomass, (4) oxidation of substrate, (5) retardation of water flow, causing suspended solids reduction, and (6) lowering of water level due to transpiration rates (Guntenspergen *et al.,* 1989).

One physiological characteristic that permits wetland species to exist in flooded conditions is the ability to diffuse oxygen (O_2) to root tips. Butler *et al.*, 1993 describes this process for reeds as a "result of convective movement of air from the aerial shoots of the common reed, *Phragmites australis*, through its aerenchyma channels, to reach the root surface where it is released into the surrounding media." Diffused O_2 not only supplies the roots but can oxidize the surrounding soil, which is a process termed radial oxygen loss (ROL) (Michaud and Richardson, 1989). The ROL (on a per unit biomass basis) for five wetland species grown in shallow water is listed in descending order as: *Typha latifolia* (cattail), *Juncus effusus* (rush), *Sparganium americanum* (burreed), *Eleocharis quadrangulata* (spikerush), and *Scirpus cyperinus* (woolgrass) (Michaud and Richardson, 1989). Stengel (1993) found that the aeration of water flowing past the root horizons was highest with *Typha* (cattail), much lower with

Phragmites (reed), and lowest with *Iris*. Oxygen supplied by reeds is estimated to range from 0.02 g O_2 m^{-2} d^{-1} for soil-based reeds to as high as 12 g O_2 m^{-2} d^{-1} (Brix, 1993b; Butler *et al.*, 1993).

2.3.1 Removal of Organic Matter

Organic matter is removed by aerobic and anaerobic processes. Aerobic biochemical degradation of organic matter is facilitated by bacteria in water, attached to plant stems in the top layer of sediments, and in aerobic pockets near plant roots and rhizomes. Anaerobic decomposition of organic matter occurs in sediments and anaerobic water. Since BOD_5 is produced within wetlands due to the decomposition of plant litter and other naturally occurring organic materials, a wetland treatment system never achieves complete BOD_5 removal, and a residual of 2 to 7 mg/l typically is present in treated effluent (Reed *et al.*, 1995). BOD and TSS are non-specific lumped parameters and do not yield helpful information regarding the type of organic matter, attenuation mechanisms, or particle size distribution (Tchobanoglous, 1993). Improved characterization of wastewater organic matter would support more effective wetland designs (Wieder *et al.*, 1989).

2.3.2 Nitrogen Removal

Nitrogen removal occurs through several biologically mediated reactions known as mineralization (or ammonification), nitrification, and denitrification. Nitrogen also can be removed by harvesting plant biomass. Primary wastewater consists of nitrogen in the organic form (60%), ammonia form (40%), and very little (<1%) in the oxidized forms of nitrite and nitrate (Sedlak, 1991). Ammonification is the process by which organic nitrogen is transformed to ammonia nitrogen through microbial decomposition of proteinaceous matter and hydrolysis of urea. Nitrification is the biological oxidation of ammonia nitrogen to nitrite and then to nitrate by autotrophic nitrifiers, and requires aerobic conditions (Sedlak, 1991). Denitrification is "anaerobic respiration whereby nitrate (or nitrite) is used as the terminal electron acceptor for oxidation of organic compounds, and is ultimately reduced to gaseous end products N_2O or N_2" (Gersberg *et al.*, 1989b).

Nitrification is carried out by nitrifying organisms primarily residing in the top layer of humic sediment and on the roots and rhizomes of plants. Nitrification requires an aerobic environment (~4.5 mg O_2/mg N) with sufficient alkalinity and a suitable temperature (Reed *et al.*, 1995). Some rooted plants (*e.g.*, water hyacinth) can transfer oxygen to their root zone and rhizomes and in this way, small pockets for aerobic microbial activity are created (Reed *et al.*, 1995). However, the ability of reeds to transport O_2 to the rhizosphere is not sufficient for quantitatively significant nitrification (Brix, 1993b). In an artificial wetland study, ammonia removal differed between vegetated and unvegetated beds with 94% ammonia removal occurring with bulrush wetlands, 78% with reeds, and 28% with cattails, as compared to only 11% ammonia removal with an unvegetated bed (Gersberg *et al.*, 1989b). Lamb *et al.* (1987), in a study of recirculating sand filters and Ruck multimedia filters, observed a correlation between log temperature and nitrification; both filters achieved 70 to 90% nitrification at effluent temperatures above 10°C but the percent nitrification dropped off significantly in the winter months as temperature decreased. Reducing the organic loading (*i.e.*, lowering the TOC/TN ratio), allows autotrophic nitrifiers to compete more efficiently with heterotrophic organisms for available oxygen since microbes using ammonia for energy have lower growth rates than those using carbon (Hilton, 1993; Reed *et al.*, 1995; Kemp and George, 1997).

Bacteria residing in anaerobic water and sediments carry out denitrification, a heterotrophic process that requires a carbon source. Approximately 4 mg of BOD_5 are required for every milligram of nitrate reduced (Kemp and George, 1997). A TOC/TN ratio of at least 2:1 is necessary to achieve complete denitrification in natural systems (Lamb *et al.*, 1987; Metcalf & Eddy, 1991). Greywater or methanol can be a satisfactory carbon source for denitrification. Greywater is superior to septic tank effluent as a carbon source since it has a lower TKN and higher mean TOC. Methanol was best as a carbon source since its TKN = 0 mg/l and TOC could be easily calculated to achieve appropriate ratio (Lamb *et al.*, 1987). Constructed wetlands in Santee, CA demonstrated high denitrification rates (>95%) at secondary wastewater application rates as high as 102 cm/d when methanol was added as an electron donor to drive denitrification (Gersberg *et al.*, 1989b).

Nitrogen removal efficiencies have been reported as high as 98% to 99% for wetland systems receiving nitrogen in a nitrate (oxidized) form, as opposed to 40-60% for wetland system receiving nitrogen in an ammoniacal organic form (Novotney and Olem, 1994). "Under conditions where dissolved organic carbon is not limiting (as when primary wastewaters are applied), the factor most limiting nitrogen removal appears to be the supply of O_2 necessary to sustain nitrification" (Gersberg *et al.*, 1989b). Watson and Danzig (1993) experimented with the use of vertical-flow and shallow horizontal-flow constructed wetland cells to increase dissolved oxygen levels and improve nitrification. At several TVA constructed wetlands demonstration sites, aeration systems were added in an attempt to increase dissolved oxygen concentrations through the cell but their attempts were unsuccessful (Choate *et al.,* 1993). Unless a wetland is specifically managed to enhance nitrification (*e.g.*, by alternate draining and flooding of the wetland) it may be difficult to nitrify the ammoniacal nitrogen and hence denitrification may be minimal or greatly reduced. Generally, wetlands require a start-up period of 2-3 growing seasons for full development of nitrification and denitrification (Novotney and Olem, 1994; Reed *et al.*, 1995).

2.3.3 Phosphorus Removal

Phosphorus removal mechanisms include: plant uptake and harvesting; bacteria assimilation; and removal by bed matrix material through adsorption, ion exchange, and chemical reactions to an inert insoluble form. Cooper (1993) reports that significant phosphate removal is more likely if media are high in iron, calcium, or aluminum. Clay, with an abundance of aluminum, calcium, and iron and large surface area, has the greatest potential to absorb and trap phosphorus, but the use of clay in a constructed wetland is prohibitive due to its low hydraulic conductivity (Davies and Cottingham, 1993). Phosphorus removal in many wetlands is not effective due to the limited opportunity of phosphates to interact with soils and other adsorbing media. The efficiency of wetlands for phosphorus removal is generally lower than that for nitrogen (Novotney and Olem, 1994).

2.3.4 Removal of Pathogens

There are four groups of pathogens (bacteria, viruses, protozoa, and worms); however, the focus is on bacteria and viruses since they cause most waterborne disease in North America. The minimum infective dose (MID) for most bacterial-caused diseases is 10^4 to 10^9 cells, whereas the MID for viral diseases can be as low as one virus particle. Table 2-4 provides a characterization of typical raw wastewater. Fecal coliforms are commonly used as an indicator for waterborne pathogens of fecal origin (see definition in Appendix A). Bacterial viruses (*e.g.*, MS-2 bacteriophage) can be used as an indicator of viral behavior (Gersberg *et al.,* 1989a).

Pathogen reduction within a wetland is due to natural die-off rates, predation, sedimentation, and unfavorable environmental conditions (*i.e.,* temperature and water chemistry). Reed *et al.* (1995) state that the principal removal mechanism of pathogens in SF wetlands is physical entrapment (*i.e.*, filtration). For several North American constructed wetlands (both FWS and SF), coliform removal efficiencies ranged from 82 to nearly 100% (Watson *et al.*, 1989). Permit standards for surface discharge may require the inclusion of a common add-on disinfection process such as chlorination/decholorination, ozonation, or ultraviolet light disinfection (Kadlec and Knight, 1996). Constructed wetlands can make an important contribution as wastewater treatment systems, not only through their ability to reduce bacteria and virus levels but also due to their ability to remove SS and ammonia, both of which interfere with efficient disinfection (Gersberg *et al.*, 1989a).

2.4 Design and Analysis Models

Modeling is useful to better understand the behavior of wetlands for wastewater treatment with various temperature, flow and loading conditions. Once a system or process can be modeled with sufficient accuracy, this model can be used in design and analysis of wetland systems. There are basically three wetland design approaches: (1) areal loading models, (2) regression models based on analysis of performance data from operating systems, and (3) process models based on biological reactions for attached-growth wastewater treatment (Reed *et al.*, 1995). This section discusses general definitions and a water balance in addition to areal loading, regression, and process models.

2.4.1 Relationship Definitions

Hydraulic loading rate (HLR) can be calculated using the following standard equation:

$$\mathrm{HLR} = \frac{Q}{A} \tag{2-1}$$

where HLR = hydraulic loading rate (m/d),

Q = average flow (m^3/d), and

A = surface area (m^2).

Hydraulic residence time (HRT) can be calculated with the following equation (Reed *et al.*, 1995):

$$\mathrm{HRT} = \rho\frac{V}{Q} \tag{2-2}$$

where HRT = hydraulic residence time (d),

V = active volume of wetland (m^3),

ρ = porosity (or the ratio of water volume to total volume), and

Q = average flow (m^3/d).

2.4.2 Water Balance

A water balance involves the analysis of inflow, outflow, evapotranspiration (ET), and precipitation. Typically, seepage is neglected in a constructed wetland water balance due to the presence of a clay liner. Kadlec and Knight (1996) stress the importance of water balances with the following statements: "Water mass balances form the basis for all reliable data analysis and design calculations. Data sets that do not include this vital information must be viewed with some suspicion because rainfall, evapotranspiration, and leakage can all have large effects on performance of treatment wetlands."

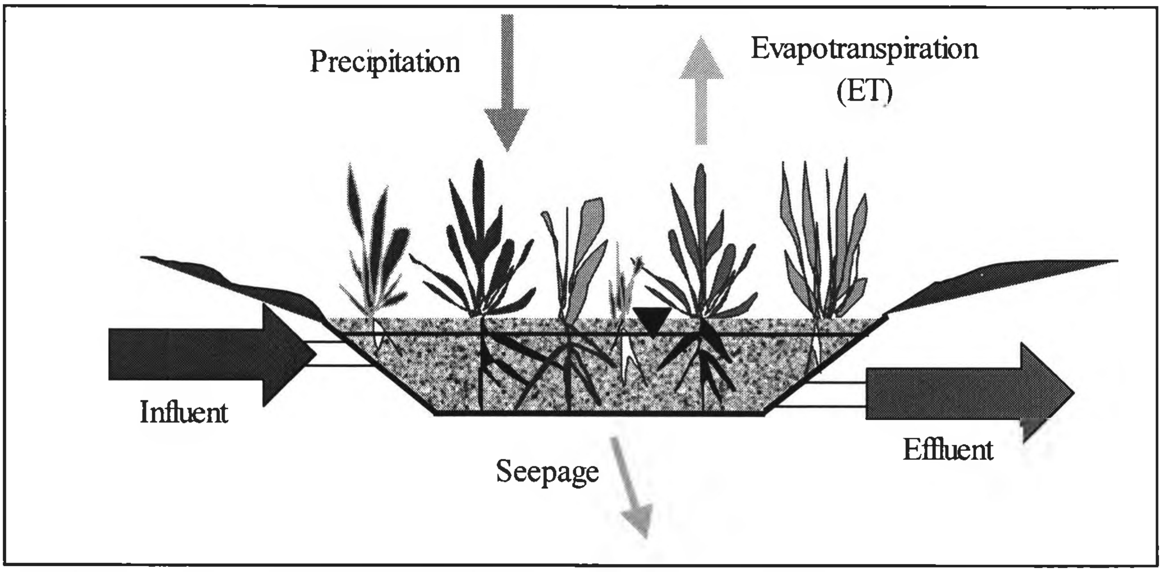


Figure 2-2: Water Balance Components for a Constructed Wetland

Evapotranspiration (ET) is more difficult to measure or estimate than other water balance terms such as inflow, outflow, and precipitation; however, ET is an important component of a wetland performance analysis and should not be neglected. ET includes water losses to the atmosphere from the soil and water of a wetland (evaporation) and from the emergent portions of plants (transpiration) (Kadlec, 1989). ET is controlled by atmospheric conditions including solar radiation, air temperature, relative humidity, and wind speed. ET is seasonally variable, being most significant in the warmer season and substantially less in the colder season. Evaporative water losses in summer decrease a system's water volume; therefore, pollutant concentrations tend to increase although treatment may be effective on a mass-removal basis (Reed *et al.*, 1995). "ET slows water flow and increases contact times, whereas rainfall has the opposite effect" (Kadlec, 1989). Evapotranspiration for FWS wetlands, over the growing season, is wellrepresented by about 0.70 to 0.80 times the Class A pan evaporation from an adjacent open site (Reed *et al.*, 1995; Kadlec and Knight, 1996). In effect, this estimate for wetland ET is the equivalent of lake evaporation, indicating that the reduction in evaporation caused by the presence of plants (shading and reducing wind at the surface) compensates for the transpiration by plants.

Kadlec and Knight (1996) provide equations for estimating SF wetland ET based on a water budget approach. These ET estimation equations for a SF wetland with and without plants and their associated correlations are as follows:

ET Estimate for SF Wetland with Plants

$$ET = 0.948\ EP - 0.0027\ \text{mm/d} \qquad (2\text{-}3)$$
$$R^2 = 0.93$$
$$12 < T_{air} < 25\ ^{\circ}C$$

ET Estimate for SF Wetland without Plants

$$ET = 0.0757\ EP - 0.028\ \text{mm/d} \qquad (2\text{-}4)$$
$$R^2 = 0.15$$
$$12 < T_{air} < 25\ ^{\circ}C$$

where ET = evapotranspiration (mm/d),
EP = pan evaporation rate (mm/d), and
T_{air} = average daily air temperature (°C).

Huang (1995) demonstrated that chloride concentration could be used as an indicator for dilution or concentration of contaminants in SF wetlands since chloride is chemically and essentially biologically inert. At the Whitethorne Plantation SF wetland site in Virginia, chloride concentration increased with longer detention time, indicating the effect of greater ET than rainfall.

2.4.3 Areal Loading Models

Cooper (1993) details one method of sizing a wetland within European guidelines based on an areal loading approach with 5 m^2/PE for settled sewage with normal strength (150-300 mg/l BOD_5), where one population equivalent (PE) is defined with Q = 200 L d^{-1} $capita^{-1}$ and

BOD_5 = 40 g d^{-1} $capita^{-1}$. The Tennessee Valley Authority (TVA) method for sizing a wetland also utilizes an areal loading model. The TVA recommends using a surface HLR criteria of 31.9 m^2 total surface area per cubic meter per day (1.3 ft^2 per gpd) for a 30 cm (12-in.) deep bed to determine the surface area of a SF wetland (Steiner *et al.*, 1993). Sauter and Leonard (1997) compared the TVA areal loading model with the EPA kinetic design model for a temperate climate application and recommend use of a conservative design to ensure adequate treatment by either design approach. Lekven *et al.* (1993) designed a SF constructed wetland using the following criteria to ensure aerobic conditions:

$$\text{Required } O_2 = 1.5L_o \quad (2\text{-}5)$$

$$\text{Available } O_2 = (TrO_2)(As) \quad (2\text{-}6)$$

where O_2 = required or available oxygen (kg/d),
L_o = BOD_5 loading rate (kg/d),
TrO_2 = oxygen transfer rate for the vegetation = 0.02 kg m^{-2} d^{-1}, and
As = surface area (m^2).

2.4.4 Process Models

A first order kinetics plug-flow reactor model (Equation 2-7) can be used to analyze the performance of a wetland treatment system (Reed *et al.*, 1995). This model allows analysis of removal of BOD, TSS, and nutrients with specific temperature-dependent reaction rate constants and hydraulic residence time.

First Order Kinetics Plug-Flow Reactor Model

$$\frac{C_e}{C_o} = e^{-(K_T HRT)} \quad (2\text{-}7)$$

where C_e = effluent concentration (mg/l),
C_o = influent concentration (mg/l),
K_T = temperature dependent first-order removal coefficient (d^{-1}), and
HRT = hydraulic residence time (d), as calculated by Equation 2-2.

A tracer test can be performed to ensure that the assumption of plug-flow is valid and to determine a correlation between actual and theoretical hydraulic residence time. A plug flow assumption for SF wetlands can lead to an overestimation of treatment efficiency (Shilton and

Prasad, 1996). Reed *et al.* (1995) detail the results of a tracer test performed on a SF wetlands in Louisiana using an inorganic conservative tracer substance such as lithium chloride. The test revealed that the wetlands did not exhibit ideal plug flow; however, the flow characteristics were more closely described by plug flow than by a complete-mix alternative. Models describing this type of intermediate flow regime have been developed; however, they are of limited use since it is difficult to evaluate an axial dispersion coefficient.

The BOD removal can be calculated by using the first order kinetic model (Equation 2-7) with the following equation to calculate a temperature corrected BOD rate constant (Reed *et al.*, 1995).

<u>BOD Rate Constant</u>

$$K_T = K_{20}(1.06)^{(T-20)} \tag{2-8}$$

where K_T = BOD rate constant (d^{-1}) at air temperature T (°C), and

K_{20} = BOD rate constant for 20°C = 1.104 d^{-1} for SF wetlands.

The rate constant for SF wetlands is consistently higher than the rate constant for FWS wetlands, probably due to the greater availability of surface area for microbial activity. Reed *et al.* (1995) recommend using a rate constant of K_{20} = 0.828 d^{-1} (75% of the base value, 1.104 d^{-1}) as a safety factor for the design of small, on-site systems.

The nitrogen removal model described by Reed *et al.* (1995) involves the use of the first order kinetic model (Equation 2-7) with a temperature dependent rate constant for nitrification calculated using equations 2-9 through 2-12.

<u>Nitrification Rate Constant</u>

$$K_{NH} = 0.01854 + 0.3922(rz)^{2.6077} \tag{2-9}$$

$$\text{At } T = 0\ ^\circ C \qquad K_T = 0 \tag{2-10}$$

$$\text{At } T = 1\ ^\circ C \qquad K_T = K_{NH}(0.4103) \tag{2-11}$$

$$\text{At } T > 1\ ^\circ C \qquad K_T = K_{NH}(1.048)^{(T-20)} \tag{2-12}$$

where K_{NH} = nitrification rate constant at 20 °C (d^{-1}),

rz = decimal fraction of SF bed depth occupied by the root zone, and

K_T = rate constant for nitrification (d^{-1}) at temperature, T (°C).

This nitrogen removal model is intended for long-term performance. During the first and second years of system operation, ammonia removal may exceed expectations due to soil adsorption and plant uptake by the rapidly expanding vegetative cover. Near the end of the second growing season, wetland ecosystems begin to approach equilibrium and ammonia removal stabilizes. The recommended model for nitrogen removal assumes that ammonia is due entirely to nitrification and does not consider the removal by plant uptake since plant harvesting is normally not practiced. If harvesting is practiced routinely, the amount of nitrogen removed via this pathway can be estimated using tissue concentrations for each plant species (Reed *et al.*, 1995).

Generally, most of the nitrate produced in a wetland is denitrified and removed within the same area provided for nitrification without the addition of supplemental carbon sources (Reed *et al.*, 1995). Nitrification and denitrification can occur within the same reactor volume when both aerobic and anaerobic microenvironments are present. The recommended model for estimating nitrate removal via denitrification is the first order kinetic model (Equation 2-7) with the following temperature dependent rate constant for denitrification:

<u>Denitrification Rate Constant</u>

At $T = 0\ ^{\circ}C$	$K_T = 0\ (d^{-1})$, and
At $T > 1\ ^{\circ}C$	$K_T = (1.15)^{(T-20)}\ (d^{-1})$

Kemp and George (1997) observe that their data more closely correlate with a plug-flow variable-order kinetic model for ammonia removal ($R^2 = 0.94$) than with a first order kinetic model ($R^2 = 0.86$). This plug flow variable-order kinetic model is defined as follows:

$$v\left(\frac{dNH_4}{dz}\right) = k\frac{NH_4}{(K + NH_4)} \qquad (2\text{-}13)$$

where v = the pore velocity of water (m/d),

z = the distance along the flow path (m), and

k and K = regression coefficients.

Based on an analysis of the North American Data Base, Kadlec has proposed a first-order rate constant equal to 10 m/yr for estimating phosphorus removal in constructed wetland systems. This rate is equivalent to an average daily rate of 2.74 cm/d for use in Equation 2-14 (Reed *et al.*, 1995).

Phosphorus Removal Model

$$\frac{C_e}{C_o} = e^{-\left(\frac{K_P}{HLR}\right)} \tag{2-14}$$

where C_e = effluent phosphorus concentration (mg/l),

C_o = influent phosphorus concentration (mg/l),

K_P = first-order phosphorus removal rate = 2.74 cm/d, and

HLR = average annual hydraulic loading rate (cm/d).

2.4.5 Regression Models

Knight *et al.* (1993) discuss the development of the North American Database for Wetlands compiled for the EPA, and includes data detailing the site, type of system, permit requirements, description of cells, operation and performance, and people involved and available literature. The goals of this effort were to summarize information obtained from existing and future wetlands for (1) resource for wetland designers, constructors, and operators, (2) research tool for wetland ecology, and (3) standardization of monitoring and reporting efforts. This analysis included typical configurations of both FWS and SF wetlands, and warm-weather temperature conditions. Knight *et al.* (1993) have proposed Equation 2-15 based on a regression analysis of the entire North American Data Base including both FWS and SF wetlands. Equation 2-15 predicts an effluent BOD concentration that is approximately equivalent to that predicted by the kinetic model (Equation 2-7) when using a rate constant of K_{20}= 0.678 d^{-1}, which is typical of FWS wetland configuration and warm-weather temperature conditions (Reed *et al.,* 1995).

BOD Regression Model

$$C_e = (0.192)C_o + (0.097)HLR \tag{2-15}$$

where C_e = effluent BOD concentration (mg/l),

C_o = influent BOD concentration (mg/l), and

HLR = hydraulic loading rate (cm/d).

The removal of TSS in wetlands is not likely to be a limiting design parameter since TSS removal is very rapid as compared with either BOD or nitrogen removal (Reed *et al.*, 1995). The regression derived from SF municipal wastewater wetlands for TSS removal versus hydraulic loading rate (Reed *et al.*, 1995) is given by the following equation:

TSS Regression Model

$$C_e = C_o[0.1058 + (0.0011)HLR] \quad (2\text{-}16)$$

where C_e = effluent TSS (mg/l),

C_o = influent TSS (mg/l), and

HLR = hydraulic loading rate (cm/d); model valid for HLR = 0.4 to 75 cm/d.

2.5 Design Considerations

2.5.1 General Design

Girts and Knight (1989) emphasize the importance of designing wetland treatment systems for management and operational flexibility. Breen (1990) emphasizes the importance of hydraulic design to optimize influent/root zone contact and prevent short-circuiting within the critical zone. Many factors need to be considered when designing a constructed wetland treatment system for operational efficiency and treatment performance including media type, cell configuration, and use of multiple cells.

The type of medium used is a factor in influencing plugging tendency, treatment performance and plant growth. Burgoon *et al.* (1989) compared two plastic substrates to a 1-cm gravel substrate and generally found that wastewater contaminant removal and plant growth were better in gravel medium than in plastic medium. However, a plastic medium of higher specific surface area may allow for improved treatment performance and high porosity plastic media may help to prevent plugging. Soil beds provide superior treatment to gravel beds if surface flow is avoided (Hobson, 1989). The permeability of gravel substrates varies along the bed length with higher solids accumulation in the inlet zone, and over time since pore spaces filled with solids may be opened by root and rhizome growth (Steiner and Freeman, 1989). To take advantage of the higher removal efficiency of the inlet zone and enhance oxygenation, Šálek *et al.* (1996) recommend building SF wetlands as cascades with several shorter filtration beds in series instead a single long bed.

The design of the constructed wetland cells involves the consideration of aspect ratios, cell flow patterns, inlet and outlet structures, and various cell configurations. The aspect ratio (length-to-width ratio) typically varies from 4:1 to 10:1; however, a 1:1 ratio may be more effective in minimizing short-circuiting and optimizing solids removal (Steiner and Freeman, 1989; Tchobanoglous, 1993). Cells can be configured with one of three primary flow patterns: plug flow (once-through), step feed (multiple influent ports along wetland length, and recirculation (circulating a portion of the effluent back through the cell). Although step feed and recirculation require more piping and equipment, these flow patterns offer pollutant removal benefits. Step feed allows use of more of the bed for solids removal and can provide carbon for nitrogen removal in the lower bed. Recirculation decreases odor potential, increases retention times, and enhances nitrogen removal. In addition, Cooper (1993) indicated that it is essential to provide good distribution at the inlet and to provide a method for raising and lowering the outlet water level. Alternative constructed wetland configurations are used for various purposes: a single cell serves small systems, parallel cells provide operational flexibility, and series cells allow optimization of pollutant removal mechanisms (Steiner and Freeman, 1989).

A multiple-staged system provides more control and operational flexibility, and allows optimization of units for specific removal functions (Brix, 1993b). It is not cost-effective to achieve both nitrification and denitrification in a single constructed wetland unit; mulitiple units or wrap-around configuration with recycle flows are more effective (Tchobanoglous, 1993). Kemp and George (1997) suggest that a rational approach to the design of SF systems for removal of BOD, TSS, and nitrogen would be to size a first-stage cell for BOD removal followed by two second-stage cells for nitrogen removal (specifically, NH_4^+ removal) operated in parallel and subjected to drawdown. Cooper (1993) also advocates using staged systems. Recognizing the limited capacity of constructed wetlands for phosphorus removal, Davies and Cottingham (1993) propose using a staged system with an initial wetland designed for BOD and TSS removal, followed by a pond for dosing of alum to precipitate and allow sedimentation of phosphorus, and then a final wetland for removal of insoluble phosphate carryover. Thus, the design and/or operation of staged systems can be optimized for specific removal objectives by applying an understanding the removal mechanisms and the treatment environment provided by various types of units (*i.e.*, wetlands, ponds, and filters).

Although the design of constructed wetlands is site-specific and dependent on treatment objectives, general guidelines are available and can be helpful. The TVA guidelines for design, construction, and operation are available in summary form (Steiner *et al.,* 1993) or as a full design manual (Steiner and Watson, 1993). The EPA design methodology uses a kinetic plug flow model, and is explained in USEPA (1993). Cooper (1993) details the European design recommendations for SF wetlands.

2.5.2 Cold Climate Provisions

Although year-round operation of subsurface wetlands in cold climates has been successfully conducted (Jenssen *et al.*, 1994), a sufficiently large database has not yet been compiled (Kadlec and Knight, 1996). The presence of insulation and use of longer hydraulic residence times has improved winter performance of wetland systems.

The presence of insulation (snow, additional depth of media, or polystyrene plates) and absence of long-term cold spells of less than -20°C have allowed for successful wetland operation through the winter months in cold climate regions (Wittgren and Mæhlum, 1997). Reed *et al.* (1995) state that the presence of snow cover reduces heat losses by about 40%.

Long hydraulic residence times tend to compensate for the lower reaction times during the winter months (Reed *et al.*, 1995). In results from a New Zealand SF wetland for treatment of dairy farm wastewaters, the removal of BOD, TSS, FC, TN, and TP improved with an increase in nominal retention time from 2 to 7 days (Tanner *et al.*, 1995a; Tanner *et al.*, 1995b). An evaluation of constructed wetlands operating in the Northwest Territories and the Yukon concluded that an HRT of 7 days was optimal and that HRTs > 21 days did not improve effluent quality (Doku and Heinke, 1995).

Removal rates for nitrogen are temperature dependent; whereas, in many cases, BOD removal of cold climate wetlands has not shown a temperature dependence (Kadlec and Knight, 1996). A strong correlation exists between mean daily water temperatures and mean daily air temperatures; information from 15 treatment wetlands produced the following correlation (Kadlec and Knight, 1996):

Water Temperature to Air Temperature Correlation for Wetlands

$$T_w = (0.99 \pm 0.08) \cdot \hat{T}_a \qquad (2\text{-}17)$$

where T_w = water temperature (°C),
$\hat{T}_a$ = mean daily air temperature (°C),
$R^2 = 0.87$, N=15,
Standard error in T_w = 2.1°C,
$0 < T_w < 27$°C, and
$0 < T_a < 27$°C.

2.5.3 Regulatory Implications for Design

Slayden and Schwartz (1989), in a May 1988 telephone survey, generally found that the engineering and regulatory community is cautious and views wetland systems as experimental. However, they cited several states (TN, KY, PA, and SD) that had allowed regulatory flexibility for constructed wetland systems during the startup period (1-3 years) to accommodate plant establishment. The details of permits are determined on a site-specific basis. Generally, BOD_5 and TSS are most commonly permitted (limits are 10-30 mg/l); other permitted variables include NH_3/NH_4^+-N, DO, pH, FC, and less commonly TN and TP (Knight *et al.*, 1993). The location of the point of compliance, monitoring requirements, and other permit details are critical in evaluating the feasibility of a given treatment technology.

2.6 Operation and Maintenance

2.6.1 Level and Flow Control

In order to take full advantage of plant-mediated removal mechanisms (*e.g.*, plant uptake of nutrients and diffusion of O_2 to create aerobic microenvironments in media), it is essential that good influent/root zone contact be maintained. This can be accomplished through ensuring a good hydraulic design to avoid short-circuiting (see section 2.5.1), and penetration of the root system through the full bed depth (Reed *et al.*, 1995). Any water that flows beneath the root zone is in a completely anaerobic environment, inhibiting nitrification. Root depths vary with the plant species used; Steiner and Freeman (1989) recommend maximum bed depths of 0.76 m for *Scirpus* (bulrush), 0.6 m for *Phragmites* (reed), and 0.3 m for *Typha* (cattail). While maintaining the water level ~2-5 cm below the bed surface is generally recommended for plant health (Cooper, 1993), operational methods such as lowering the water level gradually each fall may help to induce deeper root penetration. Three growing seasons were required to achieve full penetration by *Phragmites* using this method (Reed *et al.*, 1995).

Rest periods for cells are important to avoid plugging and to allow introduction of oxygen. Cooper (1993) suggests an operational routine of dosing for 1-2 days and resting for 4-8 days. This type of operation requires the use of parallel cells or storage capacity. Oxygen may be supplied by air movement into the bed as feedwater level falls during the flow-off period in an intermittent flow regime and possibly as a result of flow around gravel and through air-filled pores (Butler *et al.*, 1993). In response to hydraulic problems of overloaded SF wetlands, as manifested in media plugging and surface flow, recent European designs have incorporated vertical flow and batch loading to allow for effective wetting and drying cycles and more air entrainment to enhance nitrification (Bastian and Hammer, 1993). Busnardo *et al.* (1992) studied the effect of hydroperiod on nutrient removal in replicate wetland mesocosms, and found that the average phosphate removal efficiency was 20-30% higher and inorganic nitrogen removal was 5-20% higher in alternate draining and flooding regimes than in continuous flow regimes.

Siphons are used in some passive treatment systems to improve inlet distribution by providing flow surges rather than continuous tricking of flow. However, these siphons require some attention to ensure that they are working properly. Converse *et al.* (1984) describe how a siphon works, common problems, and recommended maintenance procedures. They advise that observations down the vent pipe are critical for detecting malfunctions. Falkowski and Converse (1987) performed a three-year field evaluation of 50 systems using siphons and found that 50% of the siphons malfunctioned at some time. One common problem, referred to as trickling (water rising above the high water line and trickling through the lip of the trap under the bell) can be corrected by blowing air under the bell. A delay at the discharge point before full discharge may indicate inadequate driving head and can be corrected by lengthening the long leg of the trap or by adding a smaller diameter trap in parallel to trigger the larger trap. A well-designed siphon should have few joints to seal, be simple to install, and sized to discharge well above the minimum driving head (Falkowski and Converse, 1987).

2.6.2 Planting and Plant Harvesting

Cooper (1993) recommended using seedlings over rhizome sections because they tend to spread more rapidly. After the first growing season, seedlings substantially covered the wetland with greater shoot density and more uniform cover. Cooper (1993) recommends a planting density of 4 seedlings/m^2 or 2 rhizome segments/m^2. When using clumps of reeds (~20 cm x 20 cm blocks) from existing reed beds at 1 clump/m^2, the reeds survived but tended not to spread outwards to fill in gaps as quickly as other methods (Cooper, 1993). Hilton (1993) encountered recurring plugging problems and reduced hydraulic conductivity due to large root masses. However, Butler *et al.* (1993) prefer the use of plant clumps over rhizomes since rhizomes are particularly susceptible to drought and nutrient deficiency. Butler *et al.* (1993) recommend that clumps are planted in contact with the liner and maintained adequately immersed in sewage. Allen *et al.* (1989) recommend a transplanting period extending from the fall after dormancy has begun to the first third of the summer (early spring was most successful).

Harvesting is recommended to extend the system's ability to remove nutrients by keeping the plant uptake mechanism active and permanently removing nutrients from the system, which may otherwise be returned. In a small-scale, controlled, wetland study with synthetic wastewater, Adler *et al.* (1996) found that ~50% of the nitrogen and ~80% of the phosphorus were removed from the effluent in the biweekly grass clippings. Generally, the practice of harvesting plants to remove wastewater contaminants taken up by plants is inefficient; however, its usefulness depends on several factors including climate, plant species and specific wastewater objectives (Wieder *et al.*, 1989). In order to achieve the largest removal of nutrients, plant harvesting should be timed before senescence (Guntenspergen *et al.,* 1989), and both below-ground and above-ground tissues may need to be harvested (Wetzel, 1993).

2.7 Evaluation

Evaluating the effectiveness of SF constructed wetland treatment systems is a multifaceted objective and involves consideration of cost-efficiency, typical removal efficiencies for various pollutants, and operational strategies for long-term performance optimization. This knowledge base is steadily growing with continued research efforts; however, the use of constructed wetlands for wastewater treatment is an emerging technology and its true potential is not yet fully understood.

Moderately loaded constructed wetlands provide low-cost, low-maintenance, efficient wastewater treatment to meet stringent discharge limits (Bastian and Hammer, 1993). Gersberg *et al.* (1989b) concluded, based on results of a study involving a SF wetland planted with *Scirpus sp.* at Santee, CA, that at an application rate of 5 cm/d, about 7.5 to 8 ha of constructed wetlands would be required to treat 3785 m^3 (1 MGD) of primary wastewater to secondary treatment levels (< 30 mg/l for BOD_5 and TSS). The O&M costs for this 1 MGD constructed wetland were estimated to be less than half the cost of conventional secondary treatment, and capital costs were estimated to be $1.7 million as compared to $2.5 million for a conventional secondary treatment facility.

Constructed wetlands are capable of effectively removing TSS and BOD_5 to near secondary treatment quality; however, the removal of N and P is variable and dependent on loading rate, type of substrate, and wastewater composition (Brix, 1993b). Bastian and Hammer (1993) report the following ranges of removal efficiencies observed within constructed wetland systems: 50-90% for BOD_5, 40-94% for TSS, 30-98% for nitrogen, and 20-90% for phosphorus.

Cooper (1993) reported general removal efficiencies observed in European constructed wetlands systems as: BOD removal of 80-90%, TN removal of 20-30% and TP removal of 30-40%. Brix and Schierup (1989), in an analysis of 25 Danish SF constructed wetlands, primarily with a soil medium, observed general removal efficiencies of 70-90% for BOD_5, 25-50% for TN, and 20-40% for TP. Typical BOD_5 mass removal efficiencies are near 70% at mass loading rates of up to 280 kg $ha^{-1}d^{-1}$ and lower efficiencies occur at mass loading rates of less than 50 kg ha^{-1} d^{-1} (Knight *et al.*, 1993). Both types of constructed wetlands at Arcata, CA and Santee, CA were shown capable of removing bacterial and viral indicators of pollution at efficiencies of 90–99% with HRTs of 3-6 days (Gersberg *et al.*, 1989a).

During startup, in many systems, fluctuating treatment efficiencies are observed that are not related to loading or environmental conditions. Removal efficiencies for wastewater constituents of operating constructed wetland systems improve with system maturity (Brix and Schierup, 1989; Green and Upton, 1996; Vrohovšek *et al.*, 1996). It is important to focus on maximizing the system's long-term viability and maintaining conditions required for healthy vegetation rather than sacrificing the long-term viability in an effort to improve short-term performance (Girts and Knight, 1989). Peak performance of constructed wetlands should not be expected until the system has experienced 2-3 growing seasons to achieve some measure of maturity (Bastian and Hammer, 1993). Operational flexibility (*e.g.,* control of loading with additional wastewater influent storage and/or effluent recirculation) may be helpful for systems that have not yet reached maturity. Allen *et al.* (1989) go so far as to recommend allowing plantings to become well-established before wastewater is introduced into the system (1-2 growing seasons).

There is a need for a long-term record under one set of stabilized operating conditions, and for more information than input/output analyses of permit discharge parameters (Bastian and Hammer, 1993). "Efforts are currently underway to generate the data needed to overcome the constraints and limitations associated with systems in operation today and to help develop better technical guidance for designing and operation constructed wetlands wastewater treatment and recycling systems" (Bastian and Hammer, 1993). Freeman (1993) cautions those involved in review, approval, design and construction of wetland systems, since more definitive information is needed regarding the design protocols and expected performance of such systems.

"Much remains to be learned about constructed wetlands for wastewater treatment. Constructed wetlands will not solve all of the wastewater problems facing society today. Nonetheless, with perseverance, creativity and innovation, the bounds of this emerging technology will become increasingly well defined. Progress will develop most rapidly through an interdisciplinary approach involving designers, engineers and scientists" (Wieder *et al.*, 1989).

2.8 SUMMARY

Subsurface flow constructed wetlands are complex biochemical and physical treatment reactors that can be used to treat domestic wastewater cost-effectively. Understanding the treatment performance in varying operational and climatic conditions can lead to more appropriate designs for greater treatment efficiency.

3. WETLAND SITE AND DESIGN

Highlands Presbyterian Camp is a retreat and conference center, which is challenged with the question of how to best provide wastewater treatment for its planned expansion. The camp is located in a high altitude and cold climate region, experiences high attendance during the summer months and various weekends through the year, and has limited financial resources. Subsurface flow (SF) constructed wetlands represent a passive wastewater treatment technology that may meet the camp's needs. In this study, a pilot SF constructed wetland system constructed at the camp was evaluated to determine its performance capabilities. This section describes the site and the design of the pilot SF constructed wetland system.

3.1 SITE DESCRIPTION

Highlands Presbyterian Camp is located on 245 acres, approximately one mile southeast of Allenspark, in Boulder County, Colorado (Figure 3-1) at an elevation of ~2530 m (8300 ft). The camp is located less than two miles from the eastern border of Rocky Mountain National Park in a small sub-basin tributary to Rock Creek, which eventually feeds into North Saint Vrain Creek. The soils and geology of the Highlands Camp property are typical of a mountainous environment, consisting of rock outcroppings, deep well-draining granular soils on the hillsides, and organic soils in the meadow areas. The site vegetation consists of stands of ponderosa pines and aspens, and various species of shrubs and grasses (TEC, 1991). Scenes typical of summer and winter conditions at Highlands Camp are shown in Figure 3-2 and Figure 3-3. Both photographs were taken from near the pilot SF constructed wetland system looking west toward the camp's ballfield and an existing leachfield with Mount Meeker in the background.

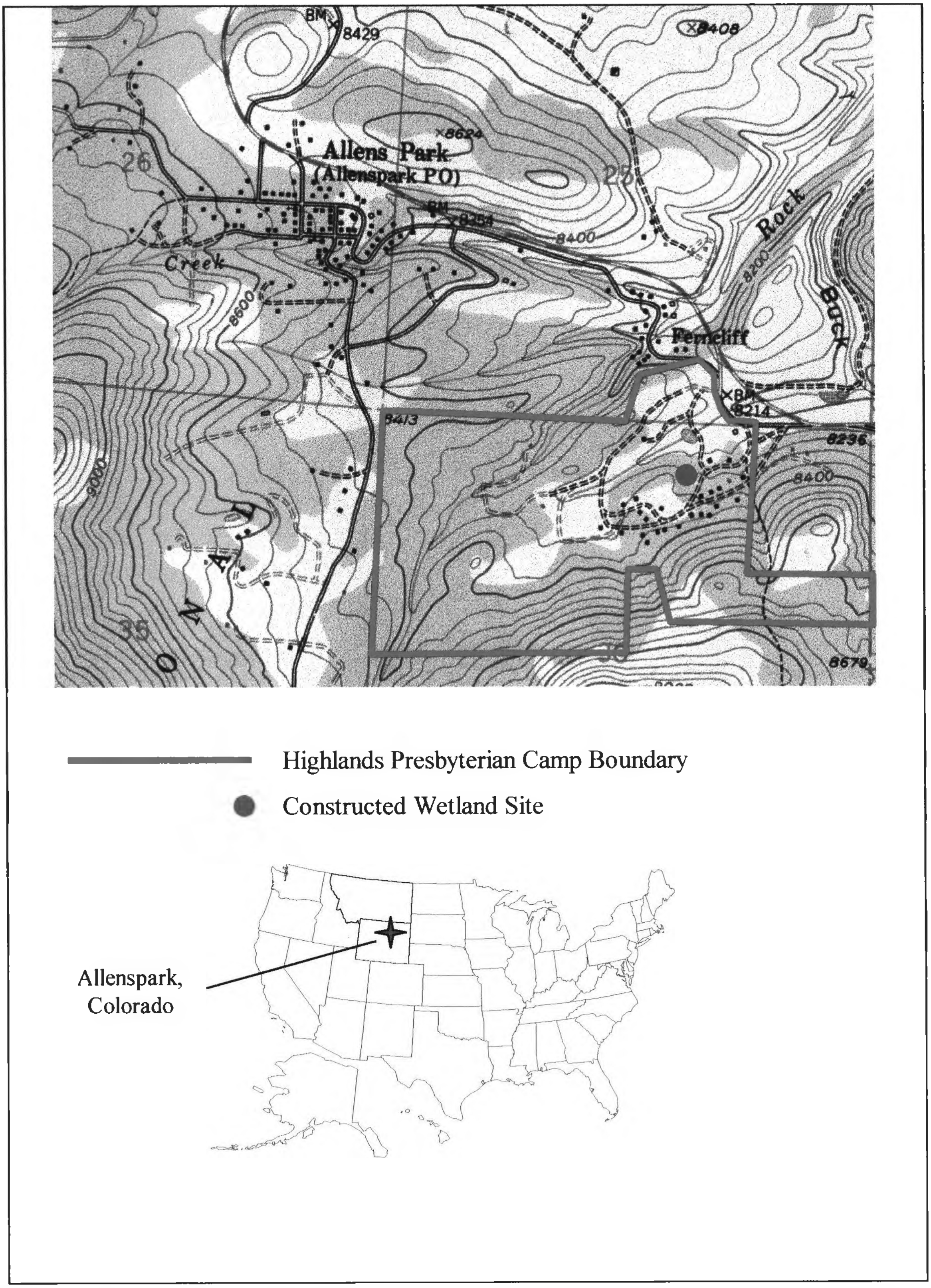


Figure 3-1: Constructed Wetland System Site Location at Highlands Presbyterian Camp near Allenspark, CO

Figure 3-2: Highlands Camp in the Summer

Figure 3-3: Highlands Camp in the Winter

The camp's climate can be classified as a "cold temperate climate" in accordance with the Köppen-Geiger-Pohl classification. Wittgren and Mæhlum (1997) use this definition in their analysis of cold climate wetlands. The definition provides that the mean temperature of the coldest month is below -3°C (26.6°F) and the mean temperature of the warmest month is above 10°C (50°F). According to approximately 45 years of meteorologic records for Allenspark (Weather Station No. 05-0183-04, Latitude: 40°32', Longitude: 105°32', Elevation: 8320 ft), the mean temperature of the coldest month is -4°C and the mean temperature of the warmest month is 16°C. There are three months of the year with a mean temperature below -3°C and four months of the year with a mean temperature above 10°C. Allenspark receives an annual average of 53 cm (21 in.) of total precipitation and 396 cm (156 in.) of snow. Refer to Table B - 1 of Appendix B for the historic weather data summary.

The facilities at Highlands Presbyterian Camp consist of approximately 35 buildings including several cabins, a chapel, an office, and a dining hall. The camp serves 180 people at full capacity. The camp operates at or near capacity through much of the summer and for various weekends through the year. At other times, the camp is primarily occupied by its staff (< 15 people). Currently, the wastewater treatment needs of the camp are provided by seven ISDSs of various sizes. There is an intermittent sand filter system permitted for 2000 gpd, a septic tank and leachfield system permitted for 1875 gpd (known as the ballfield system), and several smaller septic tank and leachfield systems. The two larger systems are located in separate drainages. In 1995-96, the ballfield system had been showing some symptoms of being overloaded (Strom, 1997).

Highlands Presbyterian Camp is planning a large expansion to upgrade their facilities and increase their capacity from ~180 to 270 people. This expansion includes the construction of a dining hall, retreat lodge, activity center, and the renovation of some existing buildings. The projected wastewater flows for this expansion exceed 38 m^3/d (10,000 gpd). The camp's consulting engineers [The Engineering Co. (TEC), Fort Collins, CO] examined several alternatives for the expansion of the wastewater treatment system including on-site systems (trench and bed, or an intermittent sand filter), a centralized mechanical treatment facility, and an off-site regional treatment facility. Potential treatment options would need to be feasible, effective, low-maintenance, cost-effective, and capable of complying with applicable regulations.

A SF constructed wetland system was proposed as a potential treatment option. A pilot constructed wetland treatment system was designed with a dual objective: (1) to relieve the loading of two existing leachfields and prolong their life, and (2) to provide data regarding the suitability of a wetland treatment system for the proposed camp expansion and aid in its subsequent design. The camp's usage pattern involves high summer and low winter loading which would coincide with the treatment capacity of a wetland.

The site is within the regulating authority of the Boulder County Department of Health and the Colorado Department of Public Health and the Environment (CDPHE). The Boulder County ISDS Regulations essentially echo the State of Colorado ISDS Guidelines; however, different approval processes and permits are required. County ISDS regulations pertain to wastewater treatment systems with design capacities less than 2,000 gpd (Boulder, 1985). State site approval and discharge permits are required for systems with a design capacity greater than or equal to 2,000 gpd (Colorado, 1994). The capacity of the Highlands wetland treatment system is rated at 500 gpd, thus falling under county jurisdiction; however, a full-scale wetland system at Highlands would have a capacity of ~10,000 gpd and would require state site approval and discharge permits. The monitoring data gained from operation of the wetland pilot system would be useful in obtaining state approval for a full-scale wetland treatment system.

3.2 System Description

The constructed wetland pilot system (Figure 3-4) consists of the following major components:

- an existing, three-compartment, 23,500 liter (6,200 gallon) septic tank modified by the addition of an Orenco biotube effluent filter at the septic tank outlet for TSS and BOD reduction;
- an upflow anaerobic filter designed to provide ammonification, filtration, sedimentation, and methane fermentation, and to dose the next filter;
- a vertical flow aerobic filter designed to enhance nitrification by aeration and the support of large nitrifier populations, provide sites for phosphorus sorption, and provide additional filtration for BOD and TSS reduction;
- a constructed wetland designed to provide nitrification, denitrification, plant uptake of nutrients, and additional filtration and sedimentation; and
- an automatic dosing siphon tank that doses the infiltrators.

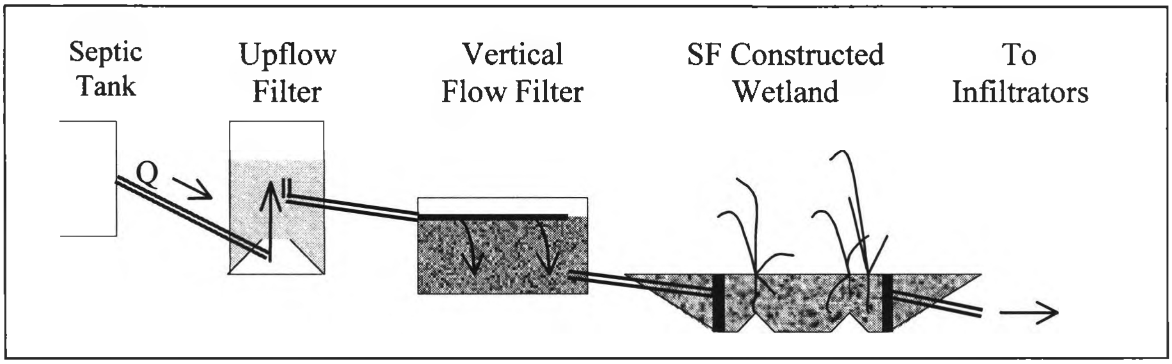


Figure 3-4: Profile View of the Highlands Camp Constructed Wetland System ***(from O'Connor et al., 1998)***

During the late summer of 1996, an existing wastewater treatment system at Highlands Camp (*i.e.,* the ballfield system) was modified with the construction of a pilot wetland treatment system. The ballfield system consisted of a septic tank discharging its effluent through a six-inch clay pipe to two leachfields. The existing septic tank, built in 1957, consists of three concrete compartments with a total capacity of ~23,500 liters (6,200 gallons). As part of the new treatment train construction, the existing septic tank was modified with the addition of an Orenco biotube effluent filter to the third compartment at the septic tank outlet, and convenient access ports for each compartment to replace heavy concrete lids. The biotube filter was intended to reduce the TSS and BOD, providing pretreatment for the subsequent filters. A diverter valve was added just down gradient of the septic tank outlet to allow the ability to divert the flow to either the existing leachfields or the new constructed wetland system, or to split the flow between the existing and new systems (Aldrich, 1996).

The next filter, the upflow anaerobic filter was designed to provide additional treatment through the processes of filtration, sedimentation, methane fermentation, and ammonification. The septic tank effluent flows up through approximately one meter (3 ft) of lava rock media contained inside a 6,060 liter (1,600 gallon) tank. As wastewater reaches near the upper surface of the media, it is collected and directed into an automatic siphon dosing tank located in the center of the filter. Within the 36 cm (14 in.) working range of the siphon, the filter environment alternates between saturated and unsaturated conditions. Below the working range of the siphon, the filter maintains an anaerobic environment designed to provide ammonification (mineralization of organic nitrogen) (Aldrich, 1996).

The automatic siphon doses the next component of the multi-stage filter system, the vertical flow aerobic filter. This filter consists of layered media with a 31 cm (1 ft) depth of a

75% coarse sand/25% lava rock mixture on top of a 46 cm (1.5 ft) depth of 13 mm (½-inch) gravel chips in a 3790 liter (1000 gallon) rectangular tank. The wastewater is distributed by a 46 cm (18-inch) wide and 3 m (10 ft) long flat pipe lying on top of the media, percolates through the media, and is collected by a flat pipe of the same dimensions at the bottom of the filter. A vent pipe was provided to the base of the filter to allow introduction of atmospheric air, and fitted with an activated carbon filter to prevent the escape of malodors. The filter was equipped with a port to allow backwashing of the filter media when the need should arise. The filter was insulated to help maintain temperatures, thereby creating an environment for greater microbial activity. The vertical flow aerobic filter was designed to provide aeration of the wastewater and, therefore, facilitate nitrification. The surface area provided by the sand and lava rock media was intended to support of large populations of nitrifiers and provide sorption sites for phosphorus adsorption (Aldrich, 1996).

The effluent from the vertical flow aerobic filter flows by gravity into the inlet distribution of the SF wetland. The inlet was designed to distribute the flows across its entire cross section in order to prevent problems associated with partial plugging at the inlet and hydraulic short-circuiting within the wetland that have been observed in other operating constructed wetlands. The inlet distribution was configured with two infiltrator units positioned perpendicular to the flow direction and drilled with horizontal perforations. The outlet collection baffle, consisting of a 0.6 m (24-inch) wide flat perforated pipe positioned vertically, was designed to collect water from the entire wetland cross section. The flow from the collection baffle is directed into an outlet level control structure. The outlet level control structure was located inside the berm for greater protection against freezing. A flexible RV type sewer hose functions as an overflow outlet and allows adjustment of the wetland water level for various seasonal and operational modes. There are patents pending on various features of this wetland design (Grove, 1997).

The wetland site was located within a snow shadow (*i.e.*, snow cover is sustained longer over the wetland than the immediate surrounding area). Snow helps to insulate the wetland during the colder months, possibly allowing for improved treatment performance. The design parameters for the constructed wetland are detailed in Table 3-1. The SF wetland consists of a 56 m^2 (600 ft^2) surface area with approximately a 0.75 m (2.5 ft) depth of angular 19 mm (¾ in.) andesite gravel and a shallow layer of pea gravel on the surface. The water depth was designed to be maintained within the range of 0.45 to 0.6 m (1.5 - 2 ft), well below the wetland gravel surface. The SF wetland was fully lined with a watertight composite bentonite and geotextile liner. Vegetation selected for the wetland consist of various indigenous species including sedges (*Carex sp.*), rushes (*Juncus* and *Scirpus sp.*), iris, silverweed, plantains, and a few willows (*Salix sp.*). Plants were transplanted in the early fall of 1996 as 8 to 15 cm (3 to 6 inch) diameter plugs from nearby riparian areas to ensure acclimation to the high altitude and cold climate conditions. The planting density was approximately 2.5 plugs per m^2 (0.23 plugs per ft^2). This is considered a high planting density by Kadlec and Knight (1996). Although the transplant survival was nearly 100% (with the exception of the willows), the planting density was approximately doubled in late June 1997 with additional transplants.

The effluent from the constructed wetland outlet drains to an automatic siphon dosing tank that doses the infiltrators. The surge flow, provided by the automatic siphon, allows wastewater to flow to the end of the infiltrators, thereby preventing plugging at the entrance and possibly lengthening the functional life of the infiltrators.

Table 3-1: Design Parameters for Highlands Constructed Wetland ***(from TEC, 1996)***

Influent Characteristics: Flow: 1.9 m^3/d (500 gpd),
BOD_5: 210 mg/l, TSS: 50 mg/l

Wetland Surface Area: 56 m^2 (600 ft^2)

Aspect Ratio (length:width): Approximately 3:2, 9 m x 6 m (30 ft x 20 ft)

Hydraulic Residence Time: 7 days

BOD_5 Loading: 71 kg ha^{-1} d^{-1} (63 lb ac^{-1} d^{-1})

Hydraulic Loading Rate: 3.4 cm/day (0.83 gpd/ft^2)

4. MONITORING AND ASSESSMENT METHODS

This section presents the monitoring program and the data analysis protocols adhered to in this study of the Highlands constructed wetland treatment system.

4.1 MONITORING PROGRAM

The monitoring program was designed to provide data for evaluation of the constructed wetland treatment system's treatment performance and comparison of the observed performance to regulatory effluent standards and design model predictions. This section describes the monitoring variables, sampling locations and frequencies, quality control, and operational details.

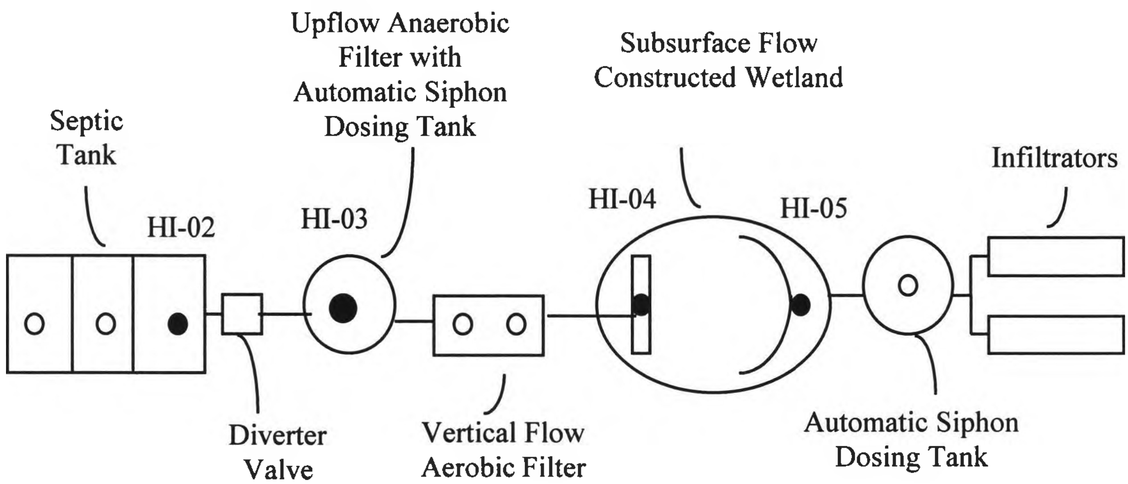
4.1.1 Monitoring Variables

The monitoring variables in this program included climatic, field, and lab variables. Daily climatic data included maximum and minimum air temperature, precipitation, and snow, and were obtained from a local volunteer weather spotter (Weather Station No. 05-0183-04, Latitude 40°32', Longitude 105°32', Elevation 2636 m or 8320 ft) through the Colorado Climate Center. Field variables included: flow, temperature, pH, total dissolved solids (TDS), specific conductance, oxidation-reduction potential (ORP), and dissolved oxygen (DO). Climatic and field data were useful as model inputs and as an aid in the interpretation and explanation of treatment performance. Samples were collected for lab analysis of the following variables: BOD_5, TOC, TSS, NH_3/NH_4^+, NO_2^-/NO_3^-, TP, and FC. The lab data were necessary to evaluate the treatment performance of the system.

4.1.2 Sampling Locations and Frequencies

4.1.2.1 Sampling Locations

The sampling locations were selected by isolating the major units (the upflow anaerobic filter, vertical flow aerobic filter, and the constructed wetland), thereby allowing for the determination of each unit's contribution to the overall system's treatment performance. The system was designed and constructed with access ports for sampling located upstream and downstream of each major unit. Figure 4-1 contains a diagrammatic plan view of the system highlighting the location of each monitoring port and provides a table with a detailed description of the corresponding macrolocation and the microlocation.



I.D.	Macrolocation	Microlocation
HI-02	Septic Tank Outlet	3rd Compartment of septic tank within biofilter at 15 cm (6 in.) depth
HI-03	Upflow Anaerobic Filter Outlet	center of dosing tank at 15 cm (6 in.) depth
HI-04	Wetland Inlet	center of port at 15 cm (6 in.) depth
HI-05	Wetland Outlet	center of level control tank at 15 cm (6 in.) depth

Figure 4-1: Location of Monitoring Ports for the Highlands Constructed Wetland System (from Andre *et al.*, 1997)

Additional monitoring sites were considered but rejected for various reasons. Sampling within the first compartment of the septic tank was not possible due to the significant scum layer and the constraints of sampling equipment. Sampling at the automatic siphon dosing tank located downgradient of the wetland would have provided data redundant to the wetland outlet. Monitoring at the infiltrators also was considered. Two ports were placed in the system during construction to allow sampling at two-foot and four-foot depths within the soil profile. These ports were not sampled because during initial sampling insufficient water had collected within these ports to run any lab analyses or to obtain any field measurements, and during periods of higher flows it was not possible to know how long this water had been stagnant.

4.1.2.2 Sampling Frequencies

On-site monitoring and sample collection were initiated in October 1996 and were continued through September 1997 on an approximately biweekly basis. This sampling frequency is more frequent than typical regulatory monitoring requirements (*i.e.,* monthly, quarterly). Fieldwork was conducted on Tuesdays to best accommodate coordination of the FC and BOD_5 testing.

The monitoring schedule approximated a biweekly schedule with flexibility to allow for the greater information yield with the effort expended. Frequent sampling during the winter months was not deemed beneficial due to the low biological activity and low flows. However, during the summer, when there is substantial biological activity and the flow through the wetland is significantly higher, frequent sampling was deemed more advantageous.

4.1.3 Quality Control

Data quality was maintained at high confidence levels through adherence to a quality assurance plan (USEPA, 1996b) formulated specifically for this project. This plan describes the procedures followed in all field and laboratory work. The use of these procedures assures that the collected data were of known statistical accuracy and quality. Appropriate chain-of-custody procedures were adhered to for all samples collected. The use of replicates, spikes, standards, regular instrument calibration, and other techniques assured the development of accurate and precise statistics for the variables measured. These assessment methodologies are defined in the Federal Register (40 CFR 136, 1992), USEPA (1982), USEPA (1974), and USEPA (1973).

Data quality objectives for precision, accuracy, representativeness, completeness, and comparability were used to establish good baseline data. Precision (a measure of the closeness with which multiple analyses of a given sample agree with each other) was assured through use of: (1) instrument check records, (2) instrument calibration records, (3) lab quality control measures (±20% agreement of spike and replicate samples), and (4) field duplicate samples at ~10% frequency (±20% agreement). Accuracy (a measure of the nearness of the sample to true value) was assured through use of: (1) spiked samples, and (2) standard additions to samples.

Representativeness (the degree to which the data accurately and precisely represent parameter conditions at the sampling site) was assured through consistent sampling in the center of each sampling port at 15 cm (6 in.) depth using the same technique and performed by the same person. Completeness (the quantity of valid data obtained from actual measurements compared to the quantity planned and expected to be obtained under normal conditions) was assured since the quantity of data collected was greater than the 80% data collection standard established as sufficient for a useable baseline. Comparability (confidence with which one data set can be compared to another) was assured by using consistent methods, reporting units, using standardized analytical methods, and conscientious data formatting. Samples that failed to meet the data quality objectives were not resampled due to time and budget constraints. All data were retained and evaluated appropriately. The raw laboratory data are contained in Appendix D. The comment column of tables within Appendix D contains a description and an estimate of incurred bias for data that did not fully meet quality control.

For three of the sampling events, it was necessary to conduct 6-day BOD tests instead of the standard 5-day tests. The inorganic chemists at the EPA Region VIII Laboratory did extensive testing to conclude that, for this site, there was only a 5% positive bias incurred by using 6-day BOD tests. Therefore, the results from these 6-day sampling tests are considered valid and included with the BOD_5 results.

4.1.4 Operational Details

Approximately every two weeks for one year, samples and field measurements were obtained from four sampling ports of the constructed wetland system (the monitoring protocol is summarized in Table 4-1). Field monitoring and sampling activities adhered to applicable requirements presented in USEPA (1996a).

Upon arriving at the site, observations of ambient environmental conditions, including weather, ground surface conditions, and wetland plant appearance, were recorded in a field logbook. Sampling order progressed from downstream to upstream ports, to minimize the effects of monitoring disturbance on the sample results. The samples were obtained before field measurements in each port. A customized sample collection device with a vacuum pump was used to siphon wastewater samples from a 15 cm (6 in.) depth within the center each port. The tubing was replaced with decontaminated tubing at each sampling port to prevent cross-contamination between sampling ports. Water quality field variables were measured at each sampling location with a Hydrolab H20 probe. Field data were collected continuously at 30-second intervals for five to ten minutes.

Table 4-1: Monitoring Protocol for Highlands Constructed Wetland System

<u>Field Variables:</u>

Flow	Total Dissolved Solids (TDS)	Dissolved Oxygen (DO)
Temperature	Specific Conductance	Oxidation-Reduction Potential (ORP)
pH		

<u>Lab Variables:</u>

Biochemical Oxygen Demand (BOD_5)	Ammonia/Ammonium (NH_3/NH_4^+)
Total Suspended Solids (TSS)	Nitrite/Nitrate (NO_2^-/NO_3^-)
Total Organic Carbon (TOC)	Total Phosphorus (TP)
Fecal Coliforms (FC)	

<u>Sampling Locations:</u>

Macrolocation	Microlocation
Septic Tank Outlet	center of biofilter at 6" depth
Upflow Anaerobic Filter Outlet	center of dosing tank at 6" depth
Wetland Inlet	center of port at 6" depth
Wetland Outlet	center of level control tank at 6" depth

<u>Sampling Frequency:</u> approx. biweekly for one year.

Flow was determined from dosing counters installed at the system's automatic siphon dosing tanks located upstream and downstream of the SF wetland (Figure 4-1). Each automatic siphon dosing tank was equipped with a counting device, which displays the cumulative number of doses. The dosing volume of both dosing tanks was measured in the fall of 1996 at the beginning of the project; the upper dosing tank dosed 205 gallons per dose while the lower dosing tank dosed 126 gallons per dose. The dosing volume of the upper dosing tank was measured again in July 1998 as 145 gallons per dose. The cumulative volumes dosed were recorded manually on a weekly or biweekly basis during the winter months and on a daily basis during the summer months. A water meter was placed downstream of the wetland in early July 1997 since the lower dosing siphon was no longer functioning properly due to ice buildup during the winter. The cumulative number of gallons was read from this meter daily during the summer months of 1997. This data record was used to estimate the average daily flow through the constructed wetland (refer to Section 5.2.1 for further discussion of flow records and calculations).

Laboratory analysis, sample containers, and preservatives were provided by EPA Region VIII. Sample container types, preservation requirements, maximum holding times, minimum sample volumes, lab analysis methods, and minimum detection limits are detailed for each lab-analyzed variable in Table 4-2. Samples were labeled and recorded in accordance with the chain of custody procedures provided in USEPA (1996a). Samples were transported in coolers packed with ice to the USEPA Region VIII Laboratory in Lakewood, Colorado on the same day as sampled, or the following day if necessary, with careful consideration of holding times. EPA custody seals were placed on the ice chests to indicate that there was no tampering with samples between the field and lab. A chain of custody record accompanied all samples delivered to the lab and was checked by the lab's sample custodian. Procedures for laboratory analyses followed USEPA (1973). Lab personnel compiled analytical results within two months of submission for analysis.

Table 4-2: Laboratory Analysis Protocol for Highlands Constructed Wetland System *(from USEPA, 1996b)*

Laboratory Variables:	Container[1]	Preservation	Holding Time Maximum	Sample Size Minimum	EPA/Std.[2] Method	Minimum Detection Limits
Total Phosphorus	P	Cool, 4°C, H_2SO_4 to pH< 2	28 days	250 ml	365.4/4500-P F.	0.01 mg/l
Nitrite/ Nitrate	P	Cool, 4°C, H_2SO_4 to pH< 2	28 days	250 ml	353.2/4500-NO_3^- F.	0.05 mg/l
Ammonia/Ammonium	P	Cool, 4°C, H_2SO_4 to pH< 2	28 days	250 ml	350.3/4500-NH_3 H.	0.05 mg/l
BOD_5	P	Cool, 4°C	28 days	250 ml	351.1/5210	2 mg/l
TOC	P	Cool, 4°C, H_2SO_4 to pH< 2	28 days	250 ml	415.1/5310	1.5 mg/l
TSS	P	Cool, 4°C	7 days	1000 ml	160.2/2540 D.	4 mg/l
Fecal Coliforms	G	Cool, 4°C	9 hours	250 ml	MF[3]/9222 D.	1/100 ml

Notes:
[1] Polyethylene (P) or Glass (G)
[2] Standard method corresponding to EPA method (*Standard*, 1992)
[3] EPA lab performs 0.45 µm membrane filter (MF) technique, single step.

4.2 ASSESSMENT METHODS

4.2.1 Data Analysis and Reporting Protocols

A data analysis and reporting protocol was prepared for each of the thesis objectives which details steps that were taken through data analysis and reporting to adequately address each objective.

Objective #1: Describe the contribution of each unit to the overall wastewater treatment provided by the system.

Data Analysis Procedure: Created temporal plots displaying the spatial progression for all monitoring locations of each of the climatic, field, and lab variables. Created a plot for the treatment system depicting the influent concentration (C_o) vs. the effluent concentration (C_e) for each lab-analyzed variables (BOD_5, TSS, TOC, NH_3/NH_4^+, NO_2^-/NO_3^-, TP, and FC). Sampling events plotting beneath the line of $C_o=C_e$ were considered to have experienced a reduction. Averaged the concentrations of each lab-analyzed variable through the monitoring period at each monitoring port. Using the average concentrations for each monitoring port, calculated the average percentage contribution of each treatment unit to the overall treatment system performance (*e.g.*, the average percentage contribution of the wetland to the overall system treatment would be $(C_{\text{wetland outlet}} - C_{\text{wetland inlet}})/(C_{\text{wetland outlet}} - C_{\text{septic tank outlet}}) \times 100\%$).

Reporting: Provided plots of concentration vs. time with traces for each monitoring location, plots of C_o vs. C_e for each lab variable displaying lines corresponding to percentage reduction, a table of average concentrations of each lab variable at each monitoring port, and a table of the average percentage contribution of each treatment unit to the overall treatment system performance.

Objective #2: Quantify the seasonal variation of pollutant removal efficiencies through the system.

Data Analysis Procedure: Calculated the nonparametric summary statistics (*i.e.*, minimum, maximum, interquartile ranges, and median) for pollutant removal efficiencies $[(C_o-C_e)/C_o]$ through the system for the winter/spring, summer, and the entire monitoring period. Prepared a box and whisker plot for each season (*i.e.*, winter/spring and summer) displaying the removal efficiencies for each of the following variables: BOD_5, TSS, FC, TOC, NH_3/NH_4^+, NO_2^-/NO_3^-, and TP. Analyzed whether the winter/spring and summer removal efficiencies for each lab variable were significantly different using the Mann-Whitney Test (described in Section 4.2.2.1).

Reporting: Provided a table of summary statistics and box and whisker plots detailing removal efficiencies of each lab-analyzed variable for the winter/spring and summer. Provided an assessment of whether the difference between winter/spring and summer removal efficiencies for each lab variable was significant.

Objective #3: Compare the system's treatment performance to secondary treatment standards.

Data Analysis Procedure: Reviewed wetland effluent data for BOD_5, TSS, and pH for all sampling events and compared the measured values with the secondary treatment standard specified in Section 2.2.4.

Reporting: Provided an assessment of whether the treatment provided by the constructed wetland system met secondary treatment standards, or if not, described how close it was to meeting the standard for each variable. Provided scatter plots displaying the range of observed wetland effluent data in comparison to the secondary treatment standards.

Objective #4: Compare the observed results to those predicted by existing design models.

Data Analysis Procedure: Analyzed whether the observed results fit existing design models (described in Section 2.4). Prepared scatter plots, temporal plots, and/or regression plots to compare observed vs. modeled data. Visually determined whether the model appeared to fit the data. When applicable, used the Sign Test (described in Section 4.2.2.2) to compare the observed vs. modeled data and analyze for significant differences in the medians of the paired data populations.

Reporting: Reported an assessment of whether the observed results fit the existing design models for temperature correlations, evapotranspiration estimates, and BOD and TSS removal.

4.2.2 Statistical Tests for Comparing Data Populations

4.2.2.1 Mann-Whitney Test

The Mann-Whitney Test, also known as the Wilcoxon Rank Sum Test, is a nonparametric test used for the comparison of two independent (unpaired) data sets. The test procedure is provided as follows (Gilbert, 1987; and Devore, 1991):

For data sets 1 and 2 (n_1 need not equal n_2), we test the null hypothesis, H_0: *The populations from which the two data sets have been drawn have the same mean,* versus the alternative hypothesis, H_A: *The populations have different means.*

1) Consider all $n_1 + n_2 = m$ data as one data set. Rank the m data from one to m (*e.g.*, assign the rank of one to the smallest datum and the rank of m to the largest datum). If several data have the same value, assign them average ranks.
2) Sum the ranks assigned to data set 1 and denote this sum as W_{rs}.
3) For $n_1 > 8$ and $n_2 > 8$, and without ties, compute the large sample statistic:

$$Z_{rs} = \frac{W_{rs} - n_1(m+1)/2}{[n_1 n_2 (m+1)/12]^{1/2}} .$$

4) For a two-tailed α level test, reject H_0 and accept H_A if $Z_{rs} \leq -Z_{1-\alpha/2}$ or if $Z_{rs} \geq Z_{1-\alpha/2}$.
5) For a one-tailed α level test of H_0 versus the H_A that the population 1 measurements tend to exceed those from population 2, reject H_0 and accept H_A if $Z_{rs} \geq Z_{1-\alpha}$.
6) For a one-tailed α level test of H_0 versus the H_A that the population 2 measurements tend to exceed those from population 1, reject H_0 and accept H_A if $Z_{rs} \leq -Z_{1-\alpha}$.

4.2.2.2 Sign Test

The Sign Test is used for testing hypotheses about the median of a continuous, nonparametric distribution. It is a simple test to compare paired data by looking at the signs of the set of differences. The Wilcoxon signed rank test is a more powerful but less versatile test since it requires that the underlying distribution be symmetric. The sign test procedure is provided as follows (Gilbert, 1987; and Devore, 1991):

For the set of differences, $D_i = x_{2i} - x_{1i}$, of paired data (x_{1i}, x_{2i}), we test the null hypothesis, H_0: *The median of the population of all possible differences is zero,* versus the alternative hypothesis, H_A: *The median difference does not equal zero.*

1) Determine the sign test statistic, B, as the number of pairs (x_{1i}, x_{2i}) for which $x_{1i} < x_{2i}$ (*i.e.*, the number of positive differences of D_i). The signs and not the magnitudes of D_i are considered. If any D_i is zero, so that a "+" or "–" sign cannot be assigned, this data pair is dropped from the data set and n is reduced by one.
2) For n > 20, compute:

$$Z_B = \frac{2B - n}{\sqrt{n}} .$$

3) For a two-sided test, reject H_0 and accept H_A if $Z_B \leq -Z_{1-\alpha/2}$ or if $Z_B \geq Z_{1-\alpha/2}$.

4) For a one-sided test of H_0 versus the H_A that the x_2 measurements tend to exceed the x_1 measurements more often than the reverse, reject H_0 and accept H_A if $Z_B \geq Z_{1-\alpha}$.

5) For a one-sided test of H_0 versus the H_A that the x_1 measurements tend to exceed the x_2 measurements more often than the reverse, reject H_0 and accept H_A if $Z_B \leq -Z_{1-\alpha}$.

5. MONITORING RESULTS

The monitoring results document a baseline for the Highlands treatment system's startup performance during its first-year of operation. This section describes how each of the climatic, field, and lab variables varied over the monitoring period of October 22, 1996 through September 9, 1997.

5.1 CLIMATIC VARIABLES

The monthly historic weather data summary and daily weather data for the monitoring period for Allenspark (Weather Station No. 05-0183-04, Latitude 40°32', Longitude 105°32', Elevation 2536 m or 8320 ft) are detailed in Appendix B. The weather data include maximum and minimum daily air temperature, daily precipitation, and daily snowfall.

5.1.1 Air Temperature

The monthly mean air temperature measured during the monitoring period was 4.4°C (39.9°F) in October 1996, dropped to approximately –6°C (21.2°F) from December 1996 through February 1997, and rose to a high monthly mean temperature of 15°C (59°F) in July 1997. The lowest daily minimum air temperature was –29.4°C (-21°F) on January 12, 1997, and the highest daily maximum was 29.4°C (85°F) on July 17-18, 1997. The monthly mean minimum and maximum air temperatures for the monitoring period were fairly consistent with the average trend for the historic record (refer to Figure 5-1 and Figure 5-2). The monthly mean minimum air temperature averaged only 0.6°C (1.1°F) less than the average historical record, while the monthly mean maximum averaged 2.1°C (3.8°F) less than the average historical record. The temperature band width between minimum and maximum historic monthly mean temperatures is smaller in the summer than in the winter (approximately 5°C (9°F) and 10°C (18°F), respectively). Therefore, according to the historic record, average monthly air temperatures in the summer are more consistent and predictable than average monthly air temperatures during the winter. Section 6.4.1 discusses the correlation between average daily air temperature and water temperature measured at the wetland outlet.

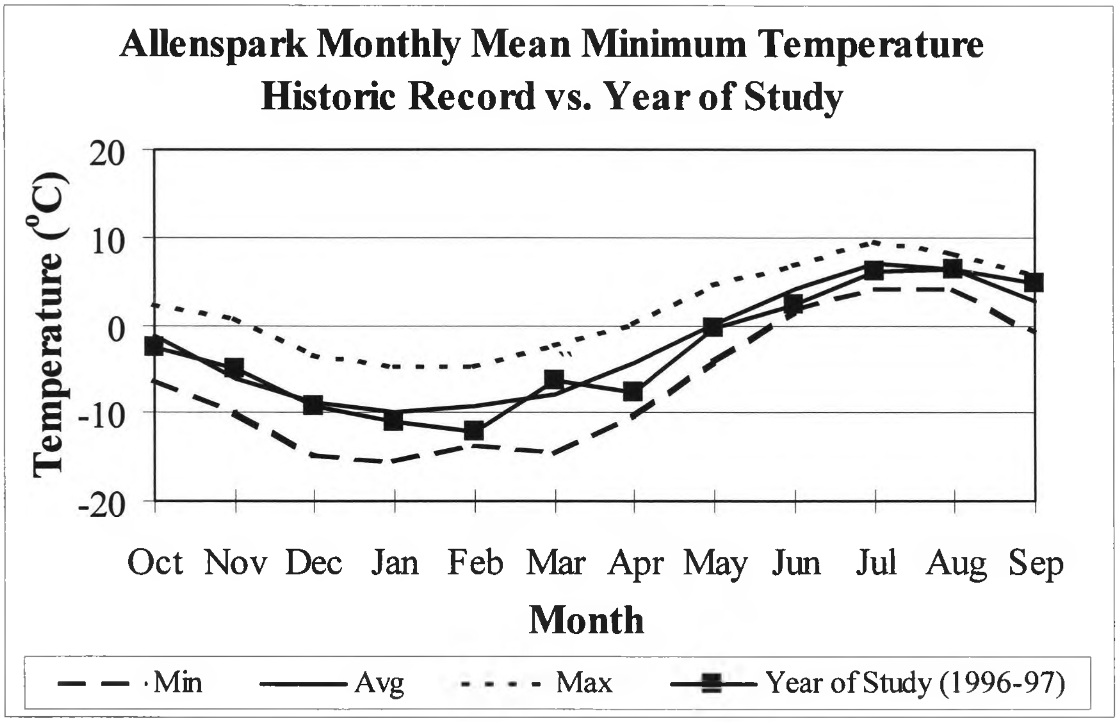


Figure 5-1: Allenspark Monthly Mean Minimum Temperature for the Historic Record vs. the Year of Study ***(Source of Data: Colorado Climate Center)***

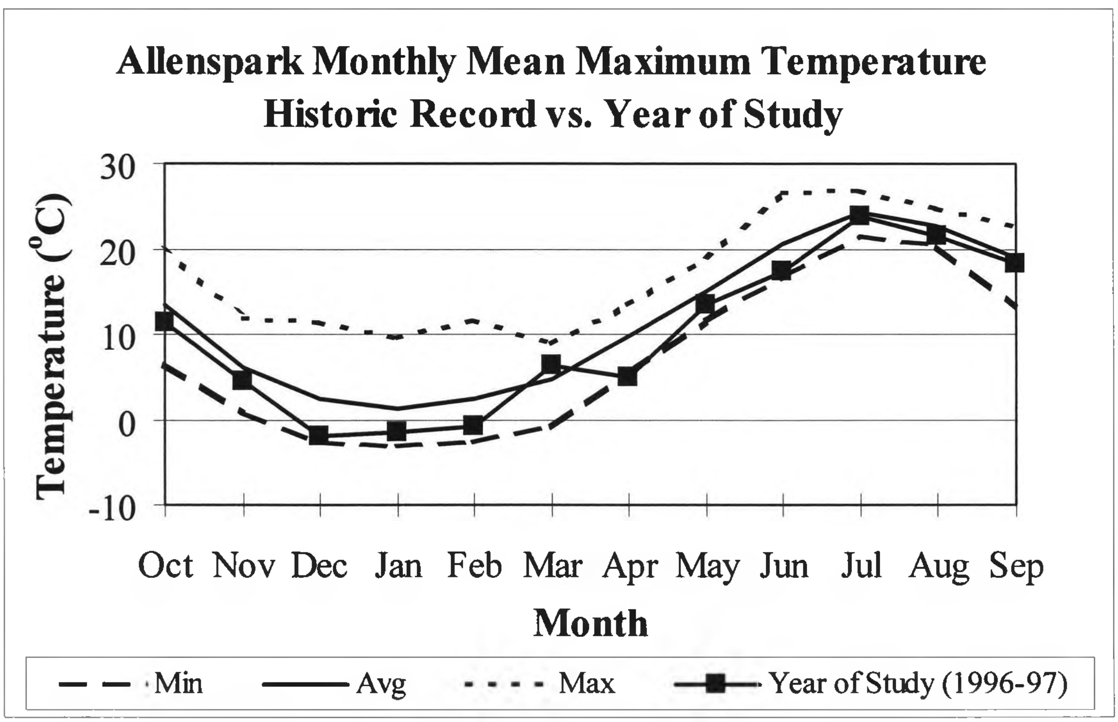


Figure 5-2: Allenspark Monthly Mean Maximum Temperature for the Historic Record vs. the Year of Study ***(Source of Data: Colorado Climate Center)***

5.1.2 Precipitation

The historic record for Allenspark indicates that most precipitation typically occurs during late spring and summer (refer to Figure 5-3 and Figure 5-4). However, total precipitation for a given month can vary significantly between its historic minimum and maximum. For example, there have been summer months in the historic record that have been virtually dry and others in which 20-25 cm (8-10 in.) of precipitation were received. The total monthly precipitation received during the monitoring year is similar to average historic values except for significantly above average precipitation in April 1997. In that month, 16.2 cm (6.36 in.) of precipitation (which includes 169.2 cm (66.6 in.) of snow) was received in comparison to the historic monthly average for April of 5.7 cm (2.24 in.) of precipitation (which includes 65.3 cm (25.7 in.) of snow). From October 1996 through September 1997, 69.4 cm (27.34 in.) of total precipitation was received, which includes 503.2 cm (198.1 in.) of snowfall. The maximum annual precipitation recorded for Allenspark is 73.2 cm (28.8 in.). In section 6.4.3, the inclusion of precipitation in the water balance is discussed.

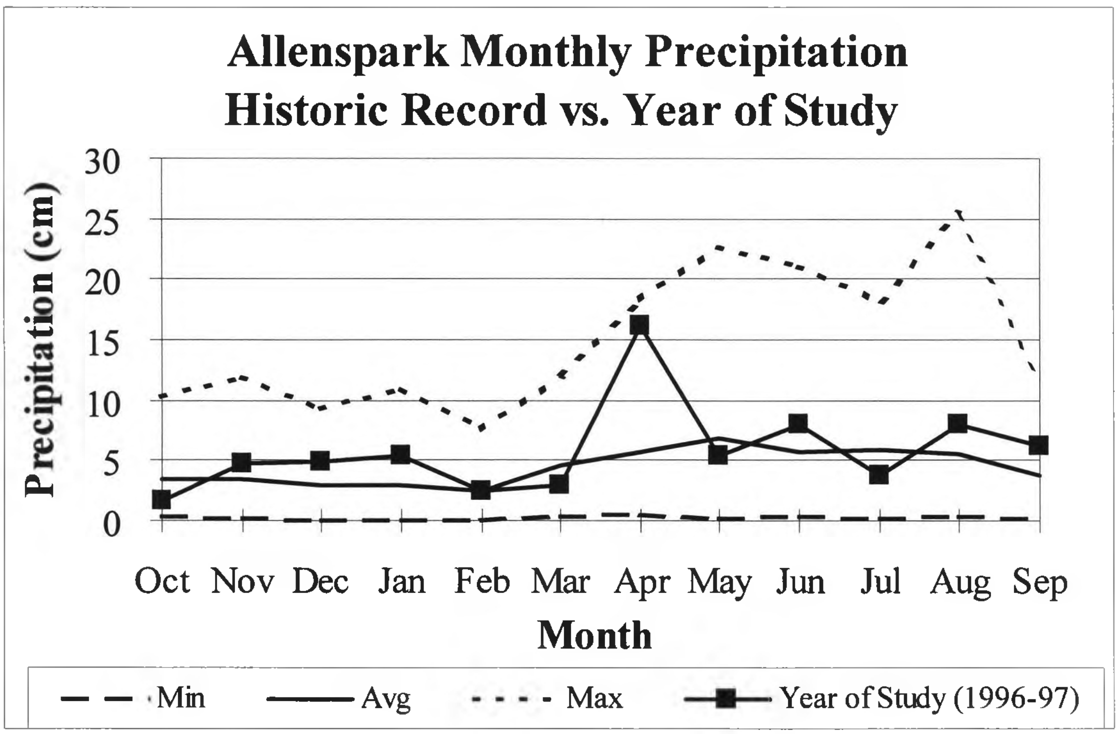


Figure 5-3: Allenspark Monthly Precipitation for the Historic Record vs. the Year of Study ***(Source of Data: Colorado Climate Center)***

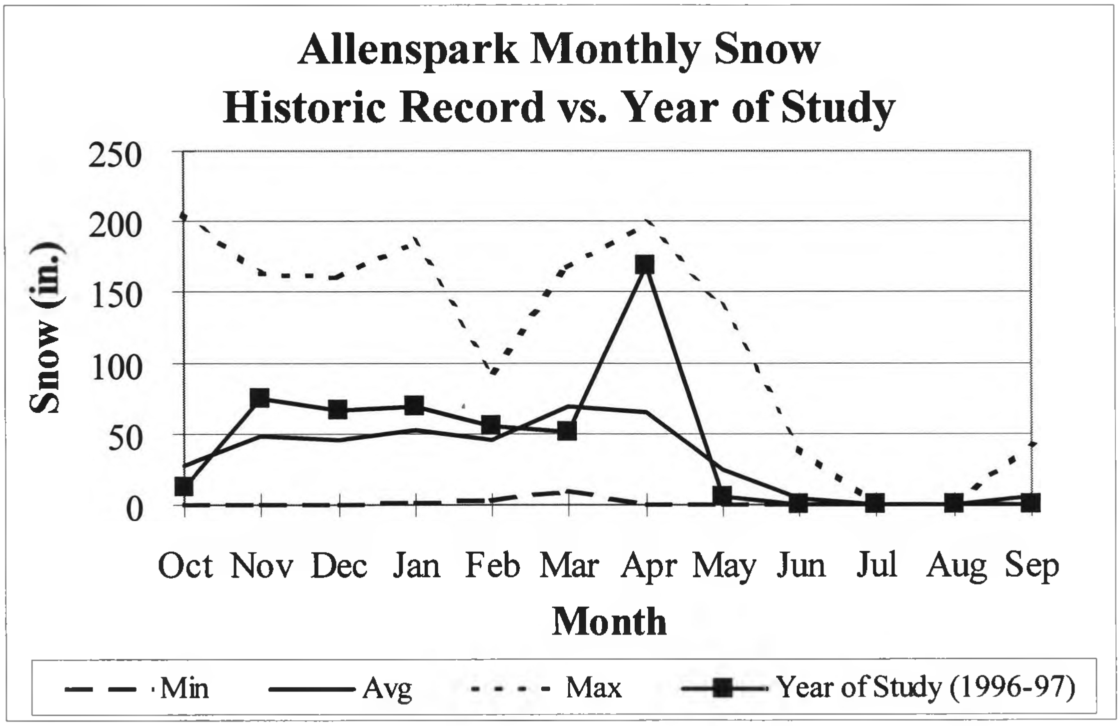


Figure 5-4: Allenspark Monthly Snow for the Historic Record vs. the Year of Study ***(Source of Data: Colorado Climate Center)***

5.2 Field Variables

The field variables include flow (*i.e.*, discharge) and variables measured using a probe (*i.e.*, water temperature, pH, total dissolved solids, specific conductance, dissolved oxygen, and oxidation-reduction potential). Appendix C contains the raw field data.

5.2.1 Flow

Camp usage is variable throughout the year. Wastewater flow generation is related to camp attendance. However, since the camp's main two sewage collection and treatment systems are used to varying degrees by each group of guests, it is difficult to accurately correlate the camp's attendance with the wastewater flow. Most of the camp's heavy usage occurs during the warmer months; however, the camp does host large weekend groups in the fall and spring. During the winter months, primary usage is by the regular winter staff (*e.g.*, in December 1996, no large groups used the camp).

Flow data were obtained from the readings of dosing counters located at the automatic siphon dosing tanks upstream and downstream of the wetland. These counters were read approximately biweekly through the winter and spring and daily during the summer. The lower dosing siphon froze in March 1997, and the siphon stopped functioning. The readings obtained from this tank during cold periods are suspect since an ice layer may have encapsulated the bubble float preventing all of the actual doses from being counted. A water meter was placed downstream of the wetland in early July 1997, and the cumulative number of gallons was read from this meter daily during the summer months. There is a discrepancy between the wetland inflow (obtained from the upflow anaerobic filter doses) and the wetland outflow (obtained from the meter readings) during the summer months (refer to Section 6.4.3 for water balance analysis).

A plot of the average daily wetland influent is shown in Figure 5-5. This plot was created using the dose volume counts read at the beginning of each month. In October 1996, the dosing volume was measured as 205 gallons/dose, and in July 1998, the dosing volume was measured as 145 gallons/dose. The change in dosing volume may be due to sedimentation of pore spaces and settling of filter media. Tables C-7, C-8, and C-9 detail the recorded readings for the cumulative dosed volumes and the corresponding gallons/dose as interpolated based on a flow volume gradient rather than a time gradient.

The flow was much lower in the winter than in the summer. The average daily influent varied between 0.11 and 1.8 m^3/d (30 and 475 gpd) during the colder months and averaged 2.04 m^3/d (540 gpd) during the summer months (June-August). This corresponds to an average hydraulic residence time (HRT) of 15 days for the period monitored with an average of 8 days for the summer months (June-August). The water level was maintained at ~0.6 m (2.0 ft) during the warmer months and was lowered to ~0.45 m (1.5 ft) during the colder months for additional insulation. The longest calculated HRT was 46 days, which occurred from late November through December, a period of minimal usage (average daily flow of 0.26 m^3/d (70 gpd)). A plot of HRT through the monitoring period is shown in Figure 5-6.

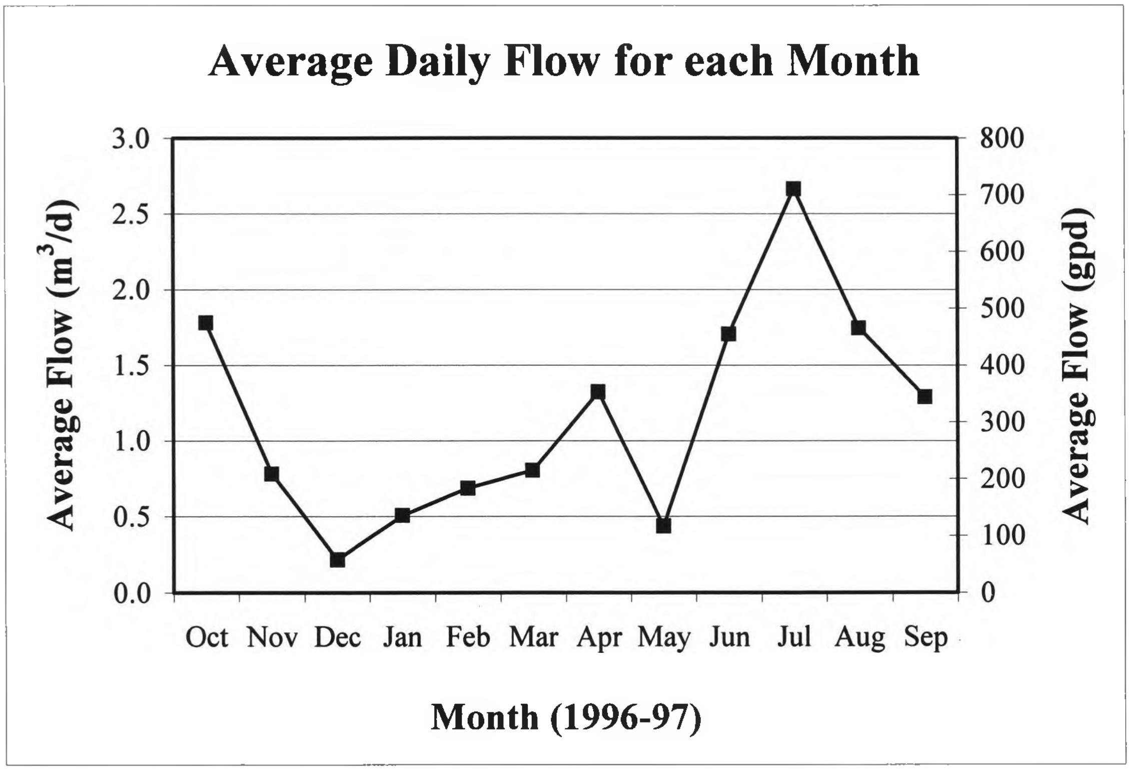


Figure 5-5: Average Daily Flow into the Highlands Wetland

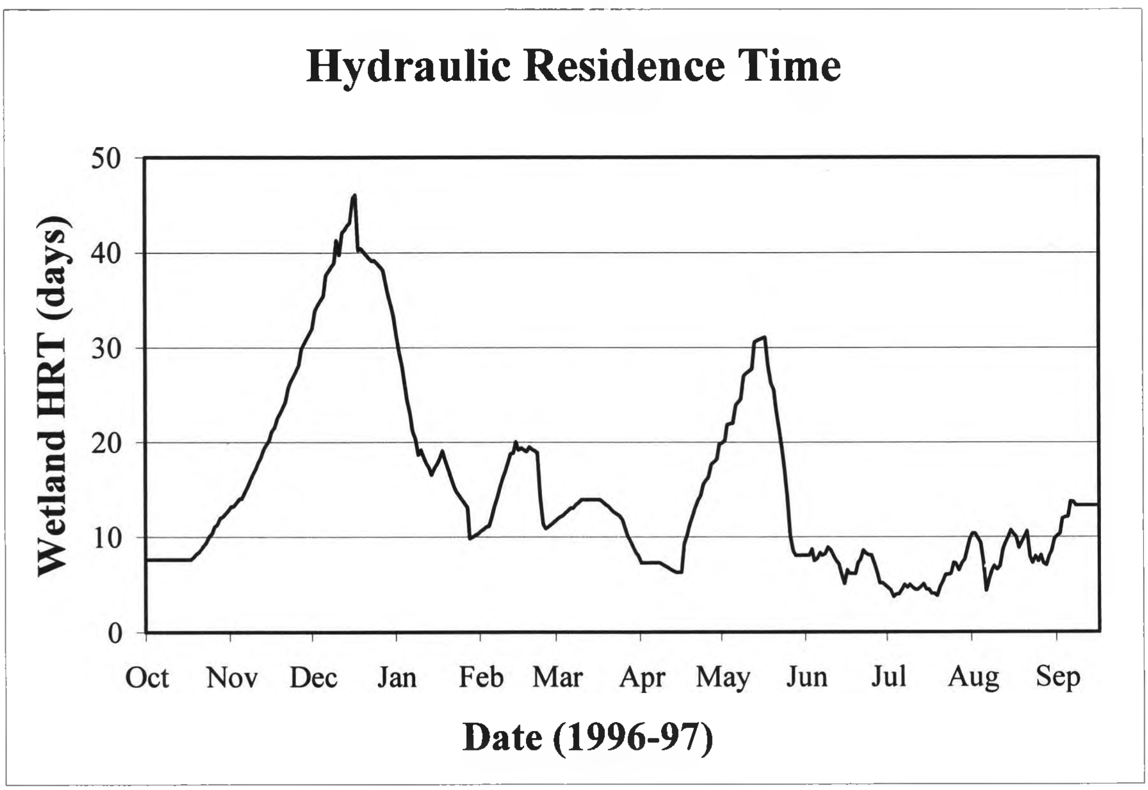


Figure 5-6: Highlands Wetland Hydraulic Residence Time (HRT)

5.2.2 Water Temperature

The water temperature at the septic tank outlet sharply declined from 11°C in October 1996 to 2°C in January 1997 corresponding to the general decline in flow and air temperature. Refer to Section 6.4.1 for an analysis of the correlation between air temperature and water temperature at the wetland outlet. The water temperature stabilized at ~4°C from January through May 1997, then began sharply increasing and reached a peak of ~18°C in July 1997. The water temperature generally decreased 3°C through the system for any given sampling event. These trends are illustrated in Figure 5-7.

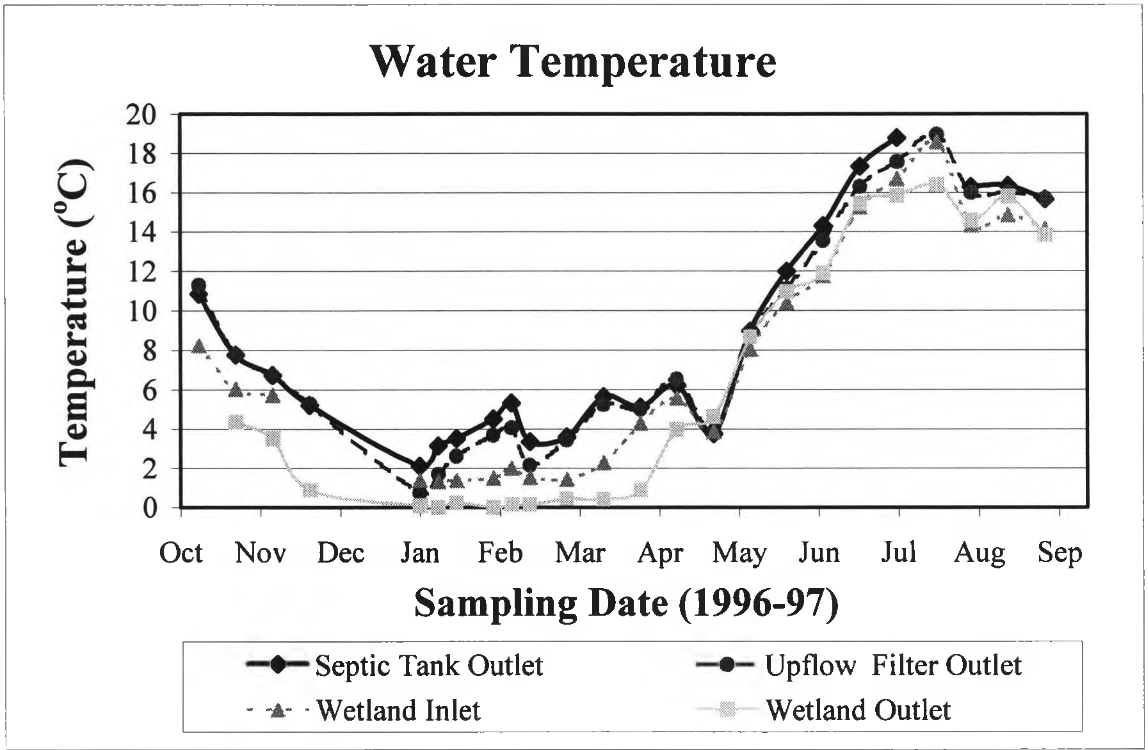


Figure 5-7: Water Temperature Monitoring Results

5.2.3 pH

The pH was relatively stable near neutral (range of 5.8 to 7.0) during the entire period monitored (refer to Figure 5-8). In general, the pH increased by approximately 0.5 units through the system for each monitoring event.

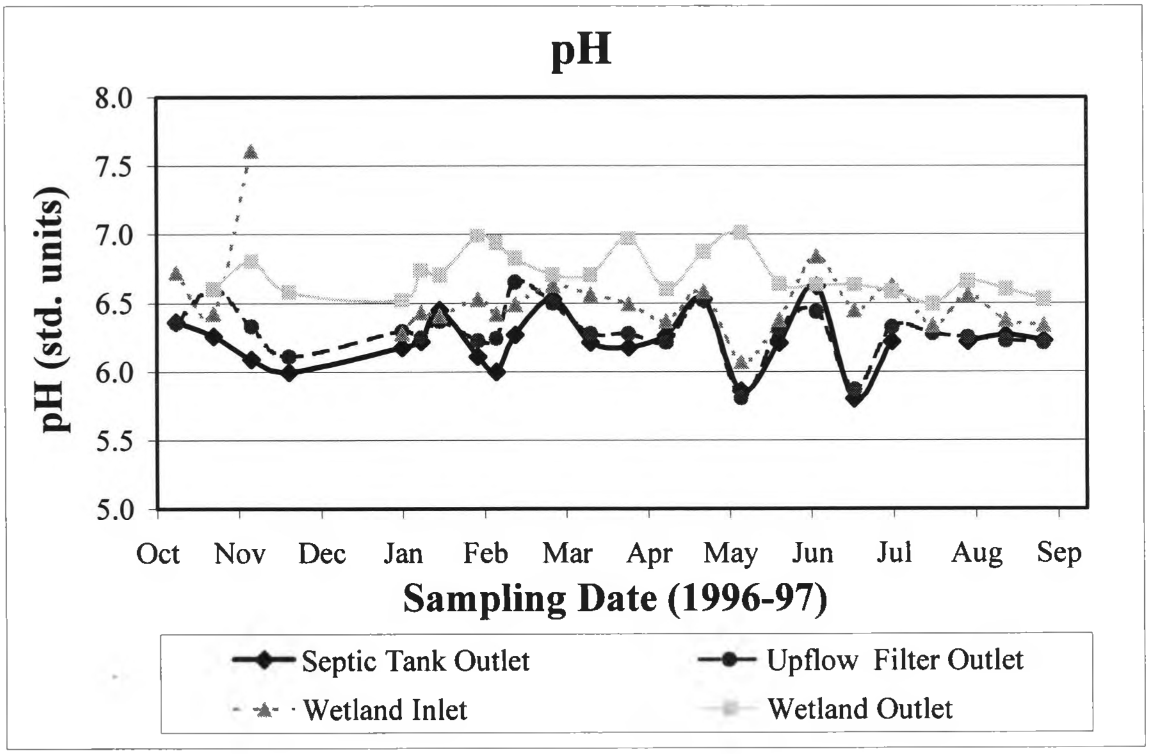


Figure 5-8: pH Monitoring Results

5.2.4 Total Dissolved Solids and Specific Conductance

Total dissolved solids (TDS) and specific conductance are closely related; TDS (mg/l) can be calculated by multiplying specific conductance (mS/cm) by a factor of 640. For this reason, data for TDS and specific conductance are plotted together in Figure 5-9 with the primary and secondary y-axis labeled respectively. For any given sampling event, the TDS and specific conductance values were nearly equivalent for the first three monitoring ports (septic tank outlet, upflow anaerobic filter outlet and the wetland inlet). However, the value obtained at the wetland outlet generally was noticeably higher (TDS values were 50 to 200 mg/l higher and specific conductance values were 0.1 to 0.2 mS/cm higher).

Also, there is a trend of higher TDS and specific conductance in the winter months as compared to the summer months. Before May 1997, TDS measurements were consistently in a range of 500 to 700 mg/l and afterwards the levels decreased to a range of 300 to 500 mg/l; similarly, specific conductance decreased from a range of 0.7 to 1.1 mS/cm to 0.5 to 0.6 mS/cm. The low point on this graph (May 6, 1997) corresponds with a period when groundwater levels were elevated and there was considerable infiltration and inflow into the sewer collection system upstream of the septic tank that diluted the wastewater. The lower summer values of TDS and specific conductance may be explained by the fact that the sludge within the septic tank was pumped out on May 20, 1997 and that there were higher flows in the summer months.

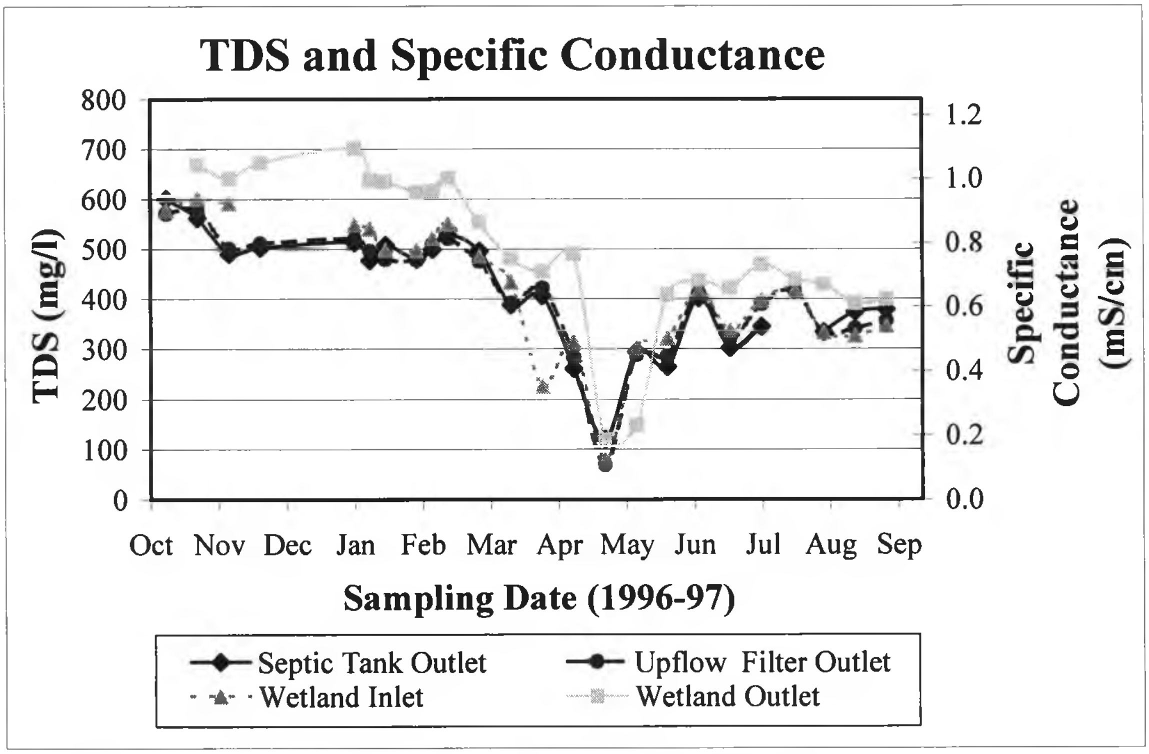


Figure 5-9: Total Dissolved Solids (TDS) and Specific Conductance Monitoring Results

5.2.5 Dissolved Oxygen

The data obtained for dissolved oxygen (DO) concentrations appears to be erroneous (See Table C-5 of Appendix C). There are questions about the calibration procedures followed, and since the probe was calibrated at the site for each monitoring event, there is not a universal factor or relationship that could be applied to the data set to correct it. There were large fluctuations observed between monitoring events (*e.g.*, 0 mg/l DO on 12/3/96, ~10 mg/l DO on 1/14/97, ~4 mg/l DO on 1/21/97, and ~10 mg/l DO on 1/28/97). There does not appear to be a good correlation between these fluctuations and common factors (water or air temperature and salinity) associated with influencing the DO concentration values and the calculated percent saturation values (*Standard*, 1992).

5.2.6 Oxidation-Reduction Potential

Oxidation-reduction potential (ORP) provides an indication of whether the environment is appropriate for specific reactions to occur. Notice in Figure 5-10 that the redox potential is primarily negative during the entire period sampled. This indicates that the conditions were primarily anaerobic. The only sampling event in which positive values were measured within all of the ports except for the wetland outlet was May 6, 1997, corresponding with a period of considerable inflow and infiltration into the sewer collection system upstream of the septic tank. This event greatly diluted the wastewater strength as evidenced by the considerable dilution of BOD_5, TSS, TOC, TP and FC (See Figures 5.11 to 5.16). It is also interesting to note that this day also corresponded with detectable nitrite and nitrate levels. A redox potential in the range of 50 to 100 mV is considered optimal for nitrification.

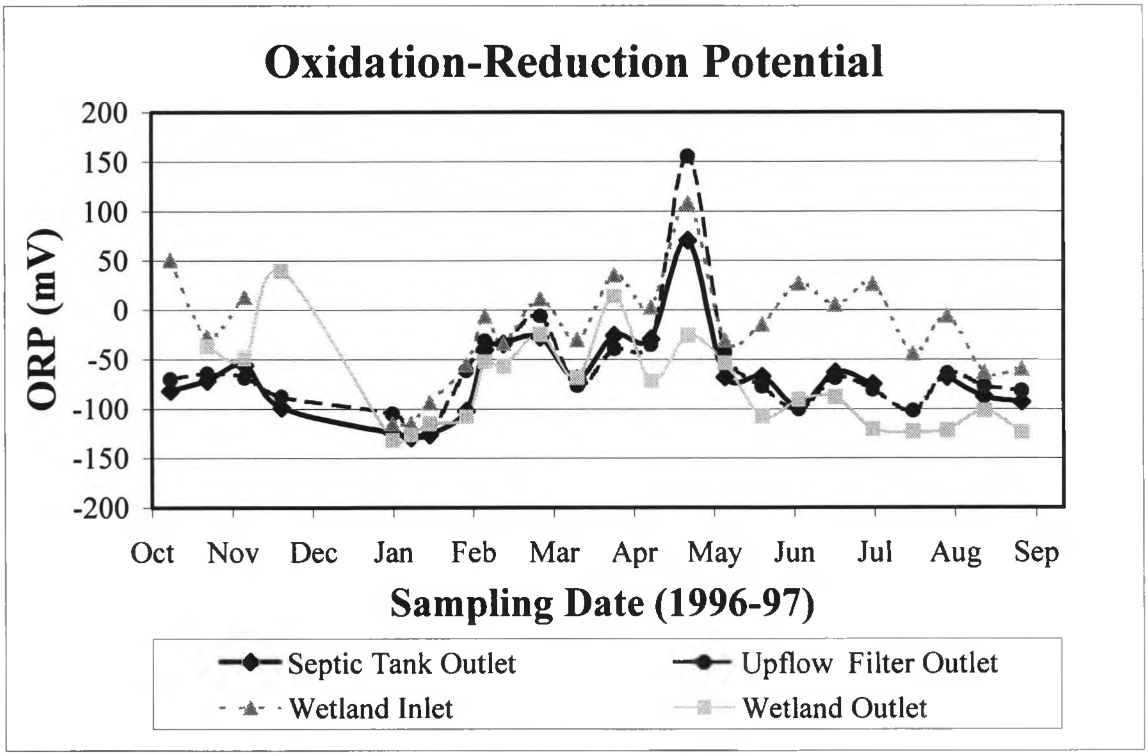


Figure 5-10: Oxidation-Reduction Potential Monitoring Results

5.3 LAB VARIABLES

This section presents the monitoring results and calculated removal efficiencies for each of the laboratory-analyzed variables (BOD_5, TSS, TOC, NH_3/NH_4^+-N, NO_2^-/NO_3^--N, TP, and

FC). Chapter 6 analyzes these results and discusses the treatment performance of the Highlands constructed wetland system with respect to each of the objectives.

The monitoring results for BOD_5, TSS, TOC, NH_3/NH_4^+, TP, and FC are graphically illustrated in Figures 5.11 through 5.16. (The raw lab data are contained in Appendix D.) These figures each include two charts illustrating the results obtained for each constituent sampled. The first chart chronologically displays the values obtained for a constituent at each of the four monitoring ports. The second chart is a scatterplot depicting the overall percentage reduction of this constituent through the system for each sampling event. The second chart distinguishes between winter/spring (October 22, 1996 – May 6, 1997) and summer (May 20 - September 9, 1997) sampling events by using different marker shapes.

There are two sampling events for which explanation of external circumstances is necessary to interpret the results presented in Figures 5-11 to 5-16; these are March 11, 1997 and May 6, 1997. Wastewater sampled on March 11, 1997 had higher concentrations of each measured constituent at the wetland outlet than at septic tank outlet, resulting in calculation of negative removal efficiencies. However (as explained further in Section 6.1.4), this may be the result of a large attendance event which occurred during the previous week. Wastewater sampled on May 6, 1997 had been diluted considerably by inflow and infiltration into the sewage collection system upstream of the septic tank. This elevated groundwater phenomenon was not observed for any other sampling events during the monitoring period.

The summary statistics characterizing the removal efficiencies of the lab-analyzed variables for the winter/spring, summer, and entire monitoring period are contained in Table 5-1. The summary statistics are nonparametric and include the minimum, maximum, interquartile range (25^{th} and 75^{th} %), and median.

Table 5-1: Summary Statistics for Removal Efficiencies of Lab-analyzed Variables between the Highlands Septic Tank Outlet and Wetland Outlet

Winter/Spring (10/22/96-5/6/97)	BOD_5	TSS	TOC	NH_3/NH_4^+-N	TP	FC
minimum	-21%	-126%	-20%	-475%	-68%	-534%
25th %	35%	42%	18%	-51%	-14%	58.0%
median	53%	65%	39%	-33%	22%	86.3%
75th %	60%	92%	45%	-17%	41%	96.6%
maximum	67%	98%	51%	16%	56%	99.92%
Summer (5/20/97-9/9/97)						
minimum	24%	29%	20%	-28%	12%	36%
25th %	38%	72%	32%	7%	21%	92%
median	52%	84%	43%	14%	25%	98%
75th %	65%	85%	56%	26%	25%	99%
maximum	91%	94%	86%	70%	91%	99.98%
Year (10/22/96-9/9/97)						
minimum	-21%	-126%	-20%	-475%	-68%	-534%
25th %	35%	49%	25%	-43%	3%	65.3%
median	53%	84%	40%	-17%	23%	92.1%
75th %	63%	90%	47%	13%	36%	98.1%
maximum	91%	98%	86%	70%	91%	99.98%

5.3.1 Biochemical Oxygen Demand

The BOD_5 values generally showed a decrease of more than 50% as the wastewater flowed through the system. This removal efficiency was consistent through the year with a median removal efficiency of 53% in the winter/spring and 52% in the summer. The concentration of the septic tank effluent through the monitoring period ranged from a low of 30.8 mg/l on May 6, 1997 (corresponding to the event of considerable inflow and infiltration into the collection system) to a high of 608 mg/l on February 18, 1997. Generally, the BOD_5 concentration of the wetland effluent was > 100 mg/l. However, there were two events for which $BOD_5 \leq 30$ mg/l (May 6 and 20, 1997) and these corresponded with a period of considerable inflow and infiltration into the collection system.

5.3.2 Total Suspended Solids

TSS removal through the system was above 90% for more than one quarter of the sampling events, above 84% for half of the sampling events, and above 50% for three-quarters of the sampling events. TSS values were generally < 100 mg/l; however, there were three values measured near 200 mg/l. Two of these high TSS values were measured at the septic tank outlet. The third measurement of high TSS concentration (200 mg/l) occurred at the wetland inlet on July 1, 1997. This sampling event took place during the week following the first backwashing of the vertical flow aerobic filter (Strom, 1997). The backwashing of this filter could have released some particulates, which influenced this sample.

5.3.3 Total Organic Carbon

The TOC values generally showed a net decrease of 40% through the system. Visually, the TOC values plotted over time for each of the monitoring ports (see Figure 5-13) appear to parallel the BOD_5 values (see Figure 5-11). The average and standard deviation of BOD_5 to TOC ratios for each monitoring port are provided in Table 5-2. The average BOD_5 to TOC ratio is highest at the septic tank outlet with a value of 2.13 and steadily declines through the system to a low of 1.71 at the wetland outlet. These BOD_5 to TOC ratios are higher than the typical range for domestic sewage, which is reported by Metcalf & Eddy (1991), as 1 to 1.6.

Table 5-2: BOD_5 to TOC Ratios for Highlands Treatment System

Statistical parameter	Monitoring Port			
	septic tank outlet (HI-02)	upflow filter outlet (HI-03)	wetland inlet (HI-04)	wetland outlet (HI-05)
average	2.13	1.91	1.82	1.71
standard deviation	0.51	0.29	0.31	0.36

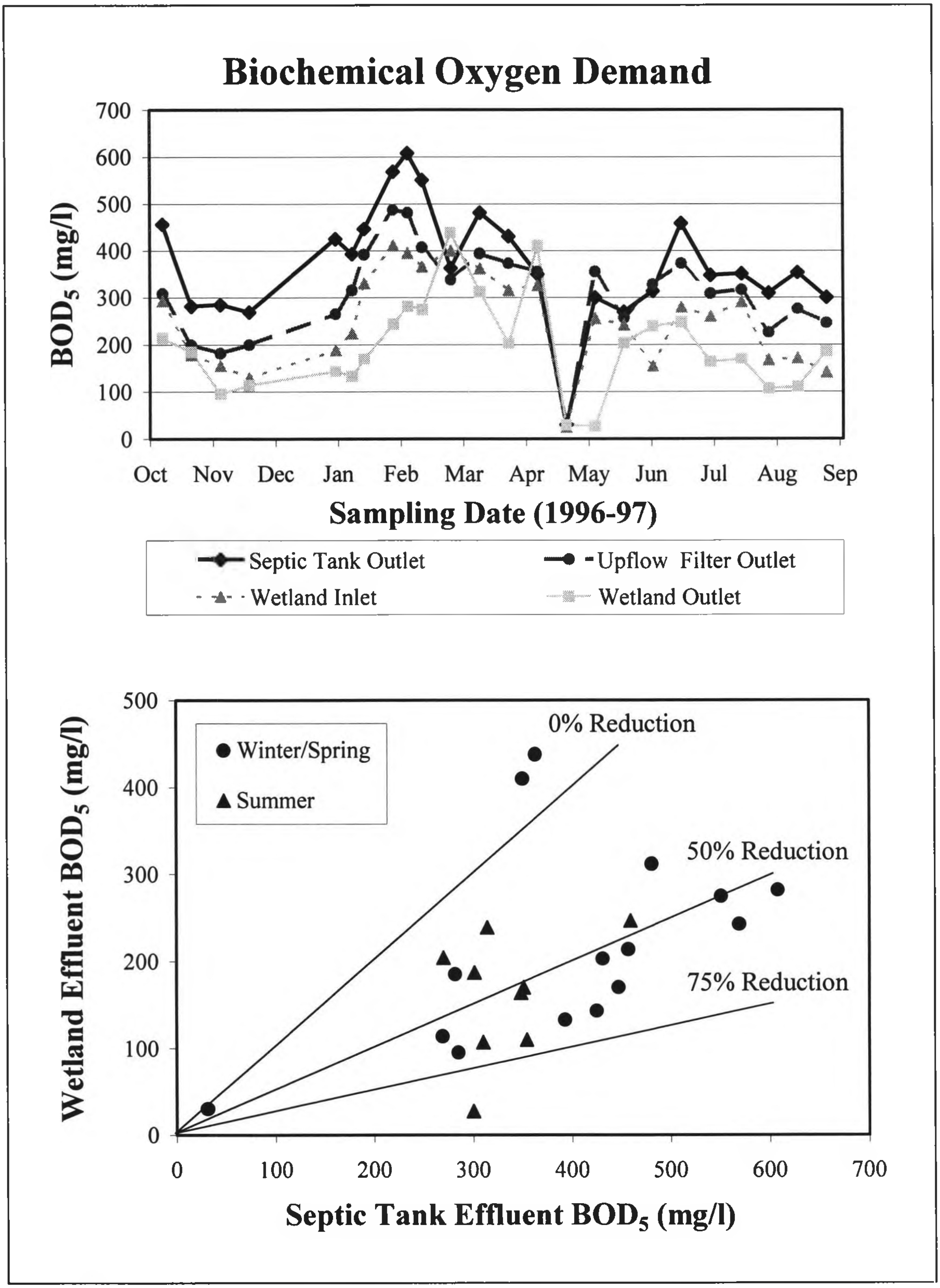
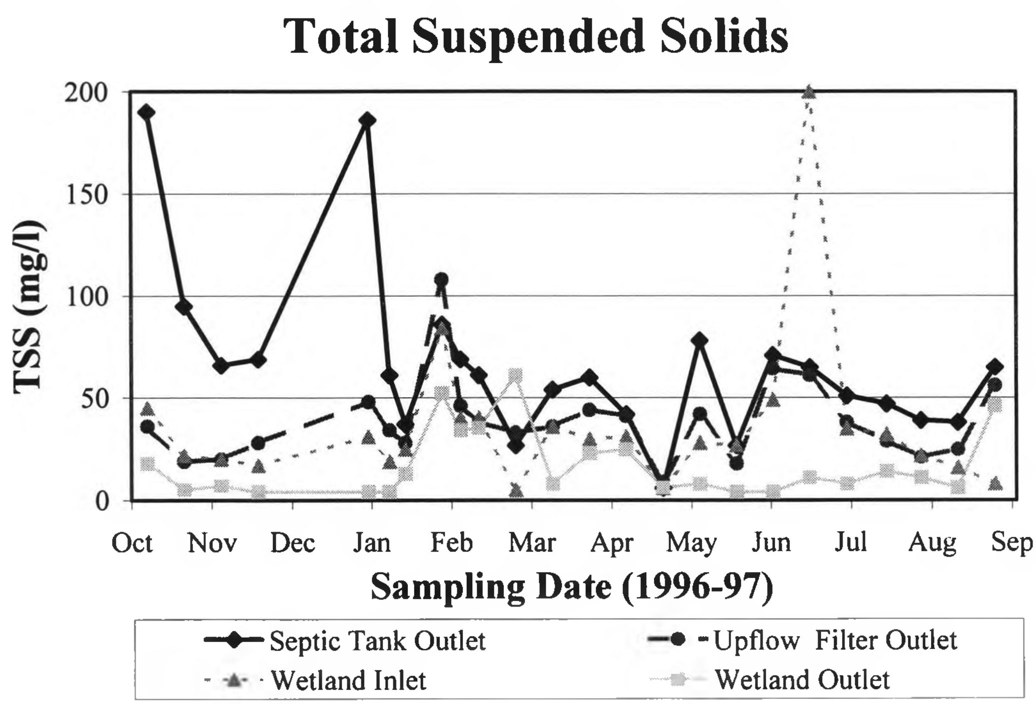


Figure 5-11: Biochemical Oxygen Demand (BOD_5) Monitoring Results and Percentage Reduction between the Septic Tank Effluent and the Wetland Effluent



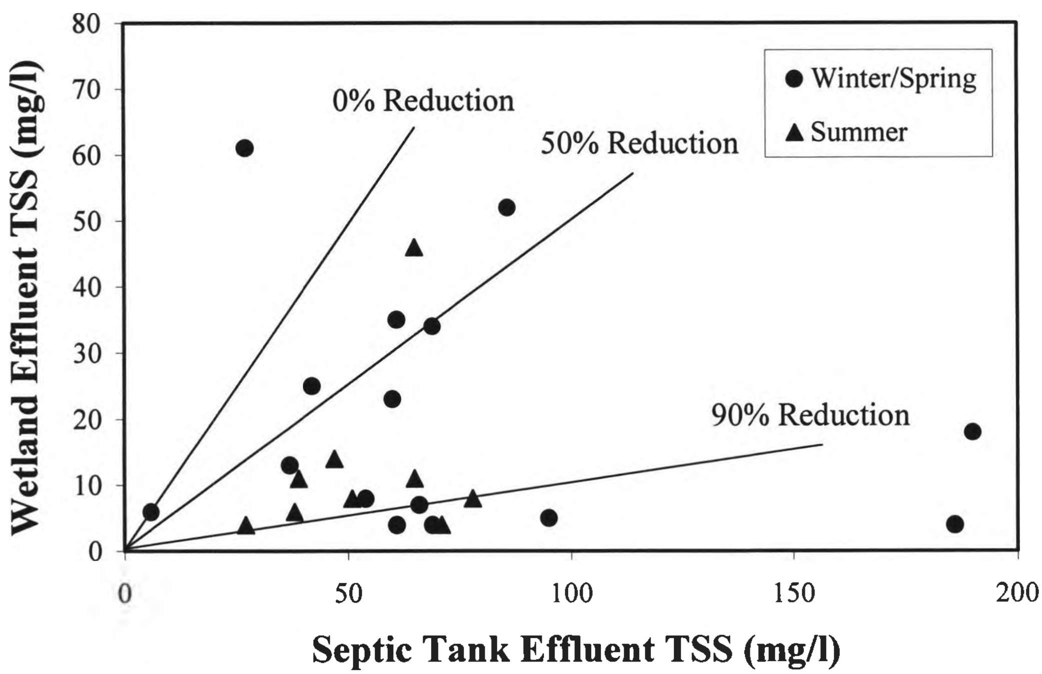


Figure 5-12: Total Suspended Solids (TSS) Monitoring Results and Percentage Reduction between the Septic Tank Effluent and the Wetland Effluent

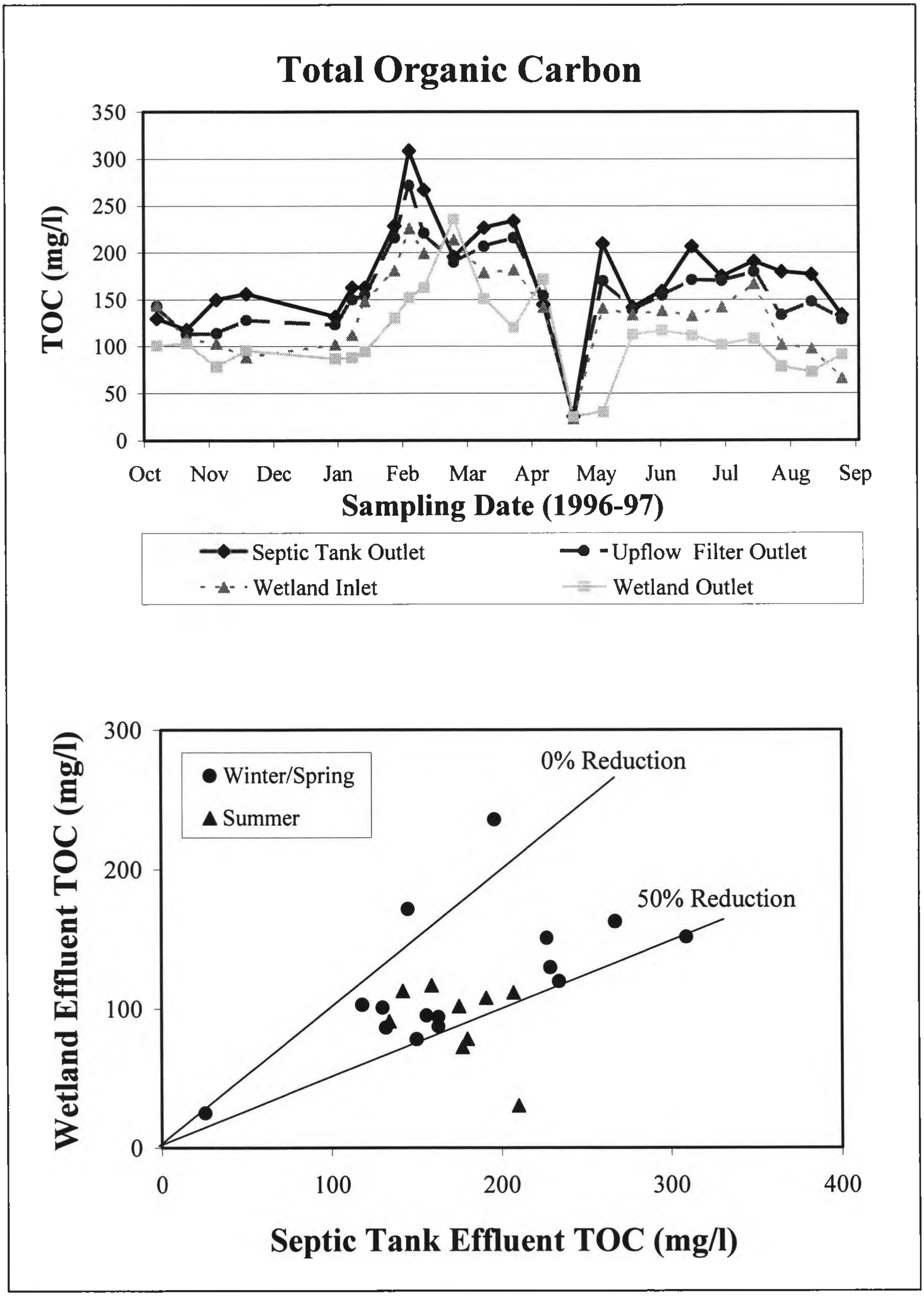


Figure 5-13: Total Organic Carbon (TOC) Monitoring Results and Percentage Reduction between the Septic Tank Effluent and the Wetland Effluent

5.3.4 Nitrogen

In general, the concentrations of each of the monitored wastewater variables decline as the wastewater flows through the system; however, measurements of ammonia/ammonium and nitrite/nitrate are exceptions. The monitoring results for ammonia/ammonium (Figure 5-14) show a generally increasing trend through the system in the winter/spring indicating the system is mineralizing organic nitrogen into an ammoniacal form of nitrogen. In the summer, there is a decline in ammonia/ammonium concentrations through the system. However, there is not evidence for nitrification, the next stage of nitrogen removal, in which ammoniacal nitrogen is converted to nitrite and then nitrate. The nitrite/nitrate values were consistently <0.05 mg/l except for one sampling event (May 6, 1997). (See Table D – 6 for the nitrite/nitrate data.) On May 6, 1997 considerable inflow and infiltration into the sewer collection system upstream of the septic tank diluted the concentration of most of the constituents monitored (TDS, specific conductance, BOD_5, TSS, TOC, NH_3/NH_4^+-N, TP, and FC). This was the only sampling event for which nitrates were measured above detection limits and the only event for which the ORP was positive.

5.3.5 Phosphorus

The phosphorus loading of the system varied from 0.5 to 8.5 mg/l and averaged 5.9 mg/l during the period of study. The median TP removal efficiency was 23% through the system for the monitoring period.

5.3.6 Fecal Coliforms

The FC values showed a decrease through the system of up to 99.9 % removal (*i.e.*, 3 log removal), but wide variations were observed. The median removal efficiency for the monitoring period was 92% with > 65% removal for three-quarters of the sampling events. The values reported for fecal coliforms are not absolute numbers (as noted in Note 2 of Table D-6). The 95% confidence limits have not been displayed in Figure 5-16 because this would clutter visual interpretation of the fecal coliform data presented. Approximate 95% confidence limits can be calculated by using the following normal distribution equations (*Standard*, 1992):

$$\text{Upper limit} = c + 2\sqrt{c}$$
$$\text{Lower limit} = c - 2\sqrt{c}$$

where c = fecal coliform colonies counted for a 100 ml sample.

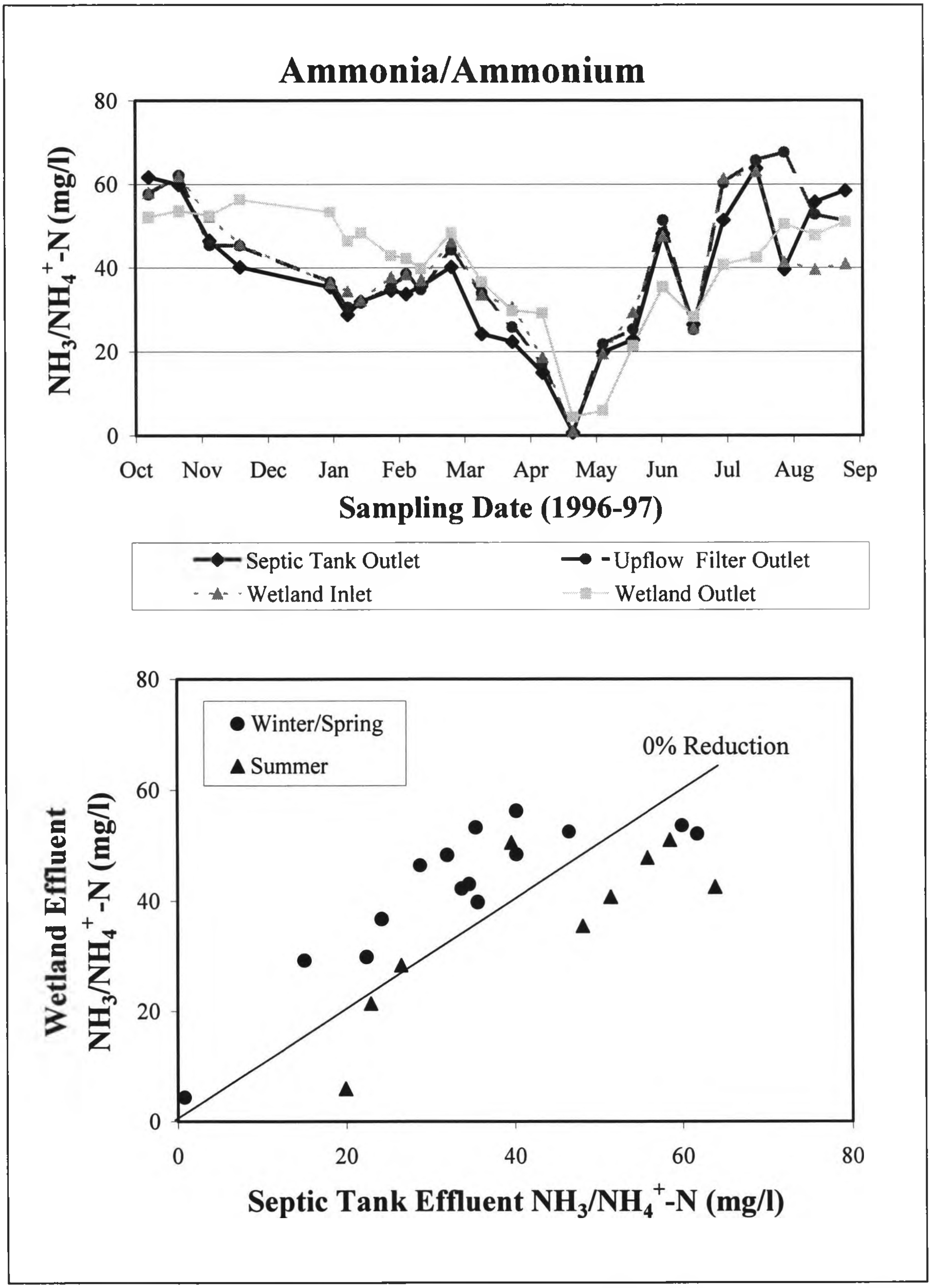


Figure 5-14: NH_3/NH_4^+ Monitoring Results and Percentage Reduction between the Septic Tank Effluent and the Wetland Effluent

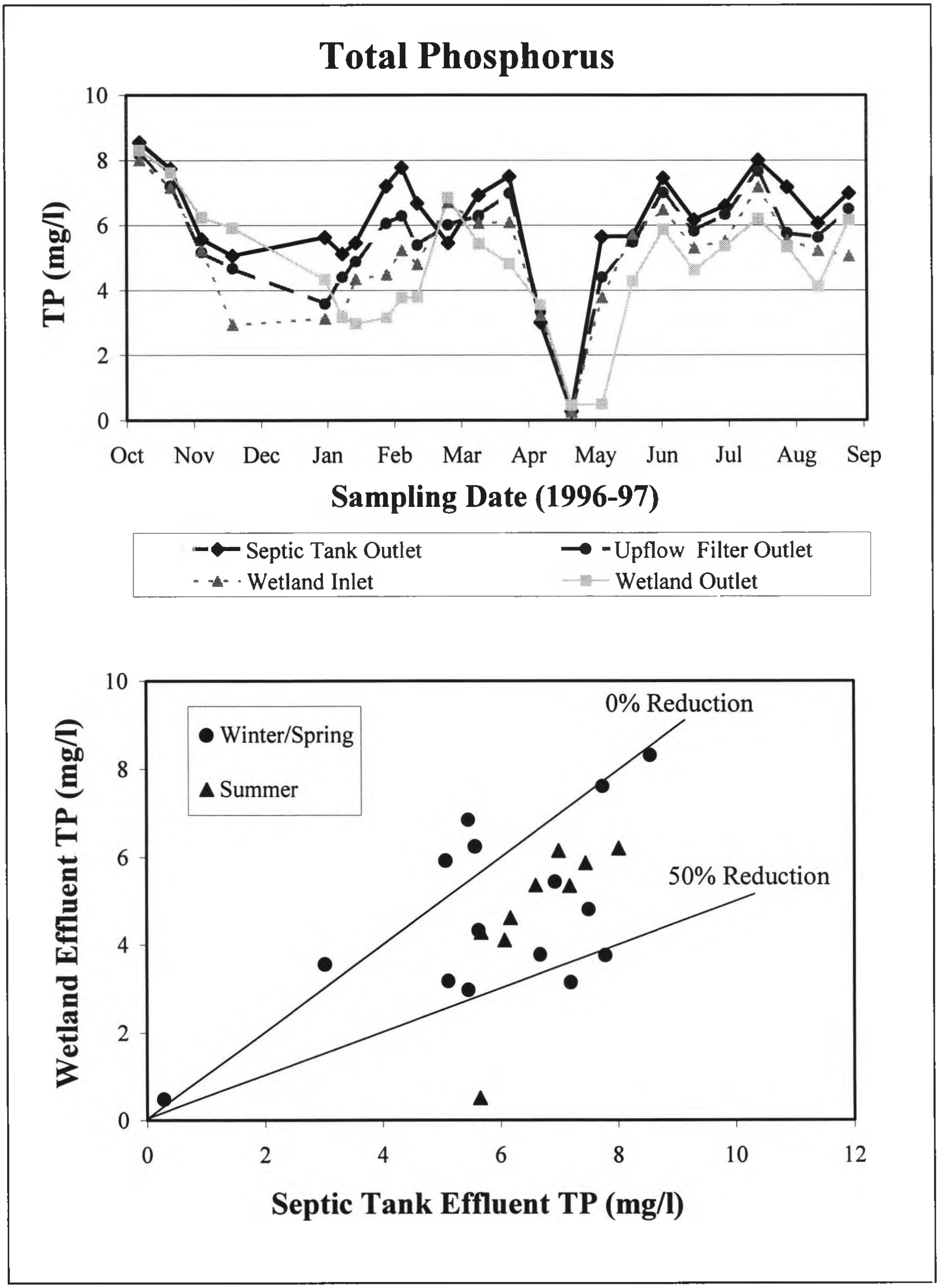


Figure 5-15: Total Phosphorus (TP) Monitoring Results and Percentage Reduction between the Septic Tank Effluent and the Wetland Effluent

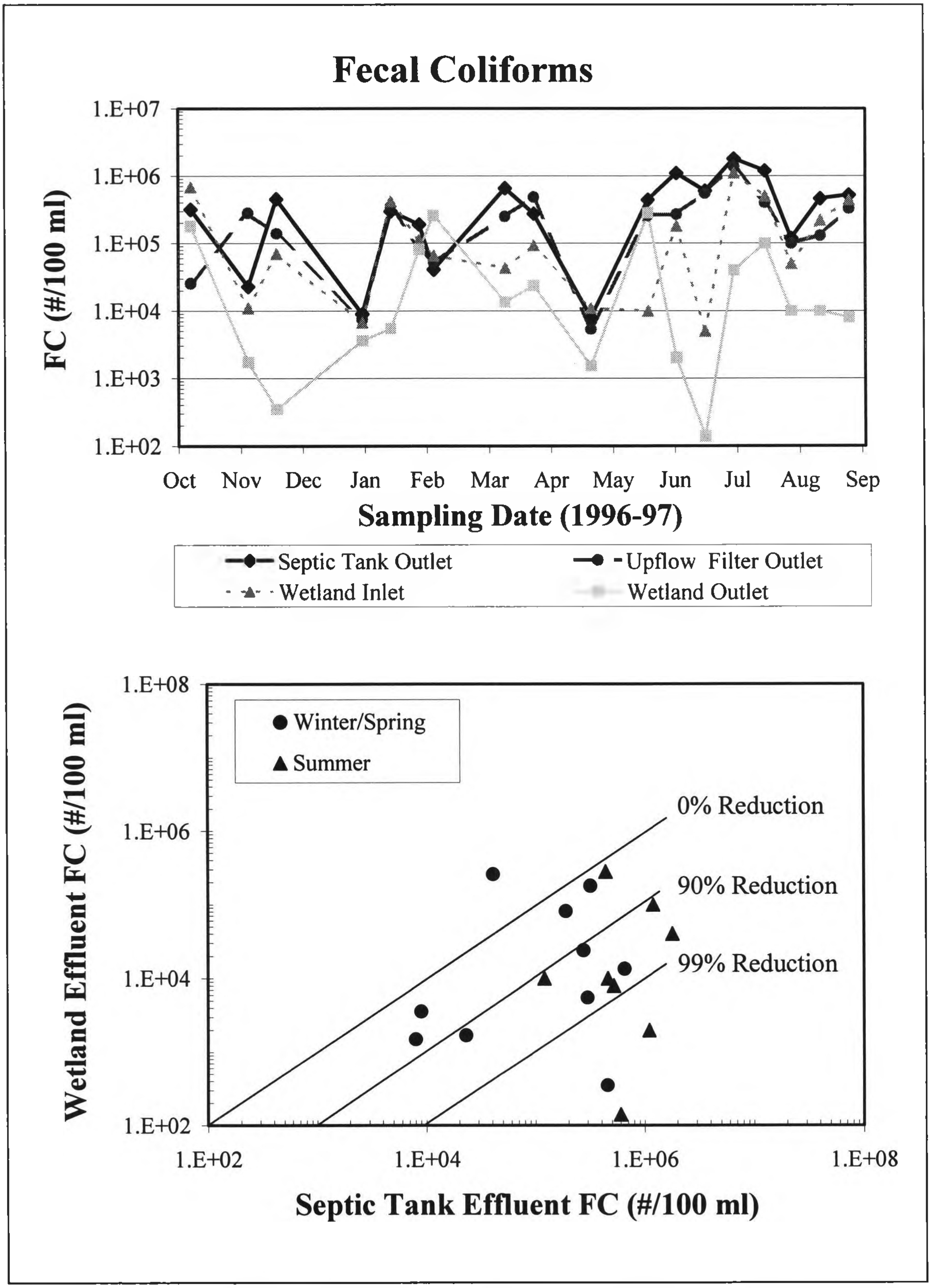


Figure 5-16: Fecal Coliform (FC) Monitoring Results and Percentage Reduction between the Septic Tank Effluent and the Wetland Effluent

5.3.7 Septic Tank Sludge Results

The septic tank performance was assessed by analyzing sludge samples collected from each of the three compartments when the septic tank was pumped on May 20, 1997. The sludge samples were analyzed for BOD_5, TSS, Volatile Suspended Solids (VSS), NH_3/NH_4^+-N, NO_2^- /NO_3^--N, and TP. The results are presented in Figure 5-17, and the raw data are contained in Table D-8. The third compartment of the septic tank had been pumped out in 1996, and the first compartment of the septic tank had been pumped out in 1994; however, the second compartment had never been pumped out (Strom, 1997). On May 20, 1997, the first compartment had 20 cm (8 in.) of sludge on top of the water column and none on the bottom, the second compartment had 20 cm (8 in.) of sludge on the bottom and none on top, and the third column had 13 cm (5 in.) on the bottom and less than 2.5 cm (1 in.) on top. The concentrations of all of the monitored variables declined substantially between the second and third compartments.

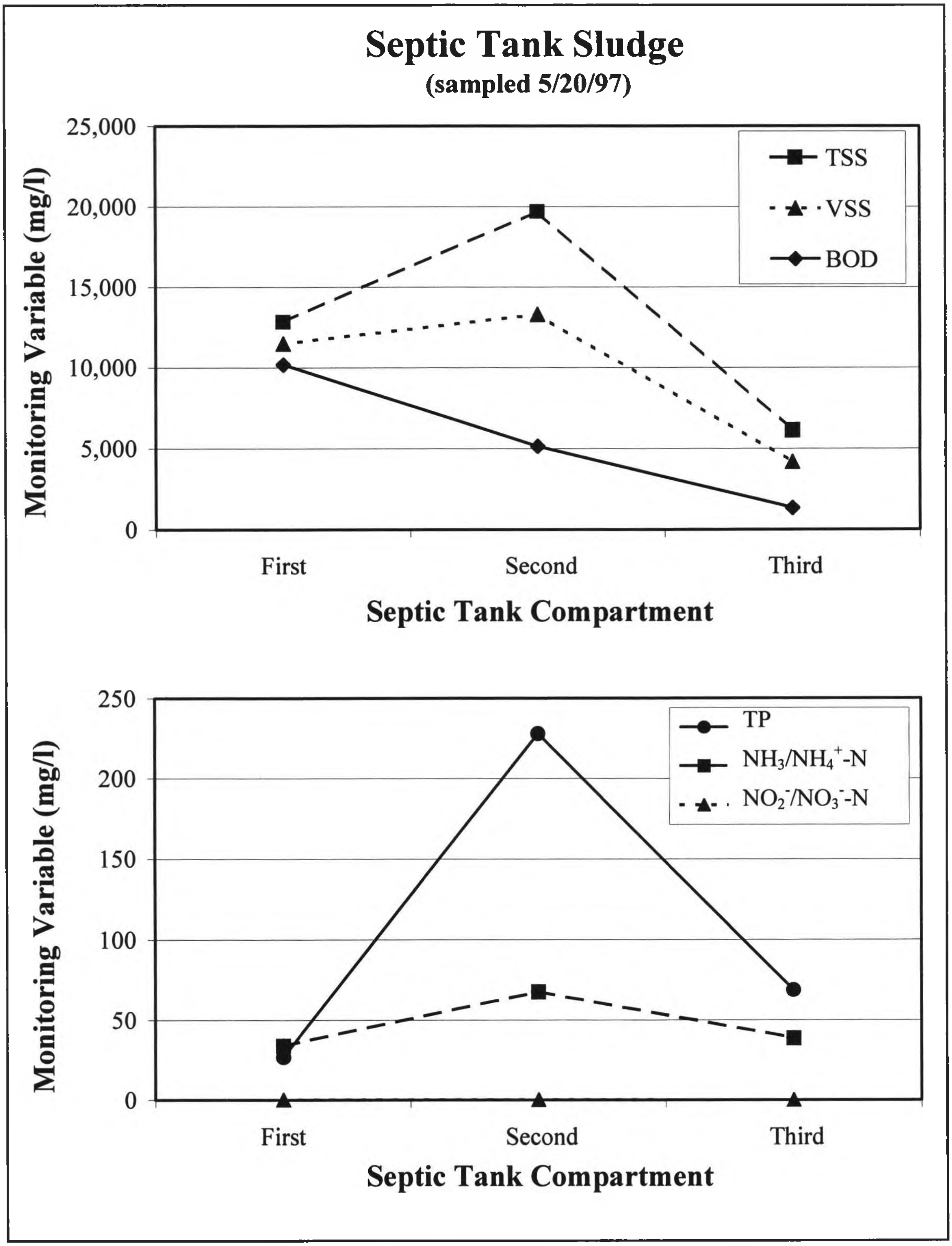


Figure 5-17: Septic Tank Sludge Analysis (May 20, 1997)

6. Discussion and Analysis

In this section, the results obtained from monitoring the Highlands Camp treatment system during its first year of operation are discussed and analyzed with respect to the thesis objectives. This includes a discussion of each unit's contribution to wastewater treatment, an analysis of seasonal trends in pollutant removal efficiency, an assessment of whether secondary treatment standards were achieved, and a comparison of the observed results to model predictions. The models analyzed include an air temperature to water temperature correlation, water balance, evapotranspiration, and models for BOD and TSS removal.

6.1 Contribution of Each Treatment Unit

6.1.1 Septic Tank

The first unit of the treatment train, the septic tank, appears to be functioning adequately. A comparison of septic tank influent and effluent characteristics could not be performed since the raw wastewater entering the septic tank was not sampled as part of this study. Instead, a single analysis of sludge from each septic tank compartment was conducted (see Section 5.3.7) to obtain an indication of how the septic tank was functioning. The depth of sludge within each of the septic tank compartments was not excessive, which indicates that anaerobic digestion processes are occurring within septic tank. The concentrations reported for each of the monitored variables except BOD_5 (TSS, VSS, NH_3/NH_4^+-N, NO_2^-/NO_3^--N, and TP) were highest within the second compartment most likely because it had never been pumped out. It is possible that the concentration of BOD_5 was also higher in the third compartment. The values reported by the lab for the BOD_5 in the second and third compartments were estimated because the dissolved oxygen depleted during the test was <2 mg/l at all dilutions (see comment in Table D - 1).

Generally, the measured concentrations of BOD_5, TSS, VSS, and TP were within a typical range characterizing septage (see Table 2-3). The concentrations of NH_3/NH_4^+-N ranged from 34.1 to 67.7 mg/l, which is below the typical range of ammonia/ammonium for septage reported in Table 2-3 as 100 to 800 mg/l. The concentrations of NO_2^-/NO_3^--N were low at ≤ 0.21

mg/l for all three compartments; this is also typical for septage (Metcalf & Eddy, 1991). It would have been interesting to test for TKN (organic and ammoniacal nitrogen) in the septage to assess how the organic nitrogen concentration compared with the typical range.

6.1.2 Upflow Anaerobic Filter

The upflow anaerobic filter was designed to provide additional treatment through the processes of filtration, sedimentation, methane fermentation, and ammonification. Although the effectiveness of these processes was not evaluated directly, an indication of the filter performance was obtained by analyzing the concentration of measured variables upstream and downstream of the upflow anaerobic filter. Concentrations of TSS decreased by an average of 27.8 mg/l, BOD_5 decreased by an average of 63.9 mg/l, and NH_3/NH_4^+-N increased by an average of 2.7 mg/l. The decline in TSS and a portion of the BOD decline are attributable to filtration/sedimentation. The BOD decline may also be attributable to anaerobic microbial degradation. Methane, the principal by-product of anaerobic decomposition of organic matter (Metcalf & Eddy, 1991), was not directly measured; however, low redox potentials (average of –61 mV at the upflow anaerobic filter outlet) indicate that anaerobic conditions predominated within the filter. Quantification of ammonification (mineralization of organic nitrogen to ammoniacal nitrogen) cannot be assessed since organic nitrogen concentrations were not monitored. Generally, this filter unit appeared to be successful in achieving its design intentions; however, there is a maintenance concern. The filter may eventually plug with sediment, and there is not an easy way to rejuvenate the media (*i.e.*, backwash) without replacing it.

6.1.3 Vertical Flow Aerobic Filter

The vertical flow aerobic filter was intended to aerate the wastewater flowing through to facilitate nitrification within the constructed wetland and provide sorption sites for phosphorus adsorption. Although, measurements of DO were not considered reliable, significant aeration was not likely. Black mud was observed within the media indicating the presence of anaerobic conditions. Also, ORP averaged –17.8 mV at the wetland inlet, which is indicative of anaerobic conditions; however, ORP measurements were ~60% higher downstream of the vertical flow filter than upstream. The ORP measured at the wetland inlet was consistently higher than measured for the other ports (see Figure 5-10). Backwashing the filter produced channeling within the media, which allowed hydraulic short-circuiting and shortened retention time. Figure 6-1 illustrates the effect observed when the siphon within the upflow anaerobic filter dosed approximately six minutes after the probe had started taking measurements at the wetland inlet. There was an increasing trend for ORP and water temperature, while there was a decreasing trend for pH and specific conductance. The ORP increased from 15 to 35 mV and the water temperature increased from 2.9 to 4.3°C.

The effect of the vertical flow filter on phosphorus removal was determined by analyzing the difference between monitoring results obtained from the upflow anaerobic filter outlet and the wetland inlet, the two ports upstream and downstream of the filter. The TP concentration was reduced by an average of 0.5 mg/l. Approximately 36% of the overall system removal of TP were contributed by the vertical flow filter. This filter also contributes more than 30% of the overall system reduction of TOC and BOD_5 as discussed in Section 6.1.5.

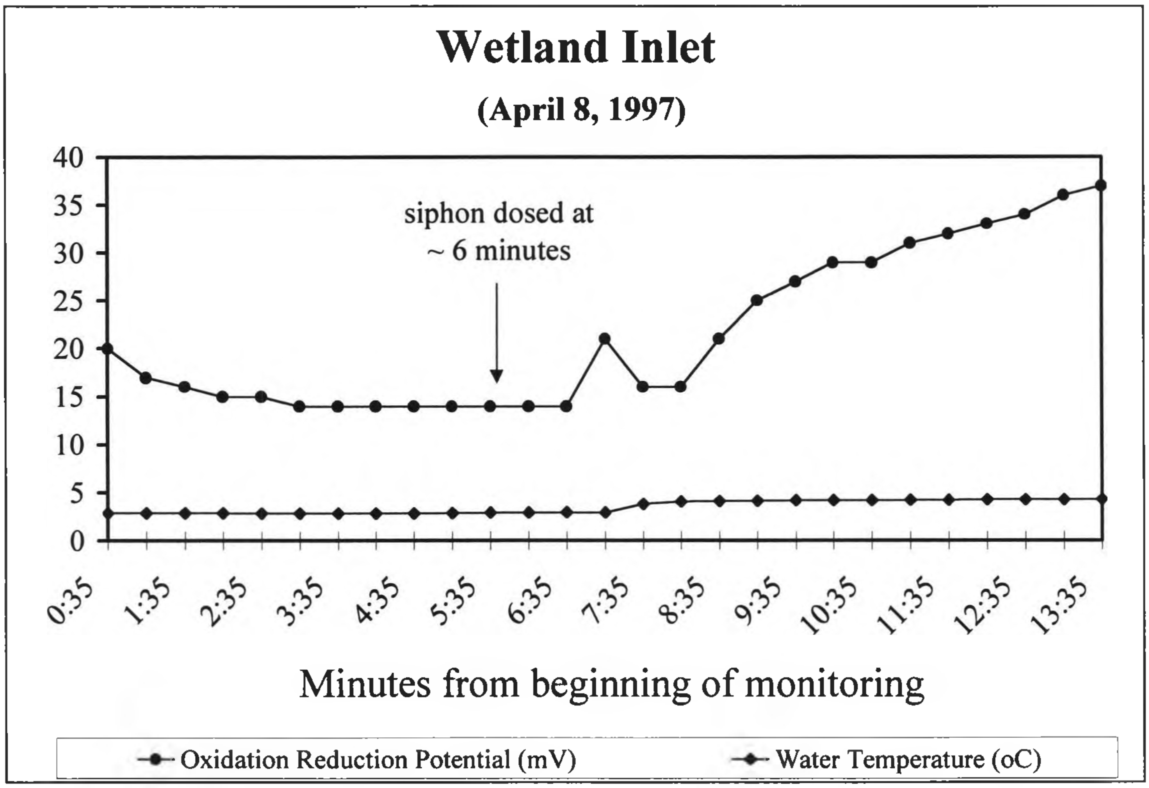


Figure 6-1: Highlands Wetland Inlet Field Monitoring Results for ORP and Water Temperature as Siphon Dose Entered Wetland (April 8, 1997)

6.1.4 Subsurface Flow Constructed Wetland

The SF constructed wetland was designed primarily for BOD and TSS reduction. Table 6-1 details how the design parameters differed from the operating parameters during the monitoring period. The BOD_5 concentration of the wetland influent was higher than the design concentration for 15 of the 24 sampling events; however, the hydraulic loading rate was lower than its design for the entire monitoring period except for 42 days during the summer months of 1997. Low HLRs compensated for the high BOD_5 concentrations except for the month of July 1997 when the BOD_5 loading rate was more than 30% above the design BOD_5 loading rate.

Table 6-1: Design versus Operating Parameters for Highlands SF Wetland

	Design	Operation (10/22/96 - 9/9/97)	
		average	range
Flow	1.9 m^3/d (500 gpd)	1.2 m^3/d (308 gpd)	0 - 4.6 m^3/d (0 - 1221 gpd)
Influent BOD_5	210 mg/l	253 mg/l	25.4 - 411 mg/l
Influent TSS	50 mg/l	36 mg/l	5 - 84 mg/l[1]
HRT	7 days	15 days	4 - 46 days
BOD_5 loading	71 kg $ha^{-1}d^{-1}$ (63 lb $ac^{-1}d^{-1}$)	55 kg $ha^{-1}d^{-1}$ (49 lb $ac^{-1}d^{-1}$)	4.5 -156 kg $ha^{-1}d^{-1}$ (4 -139 lb $ac^{-1}d^{-1}$)
HLR	3.4 cm/day (0.83 gpd/ft^2)	2.1 cm/day (0.53 gpd/ft^2)	0.5 - 6.5 cm/day (0.11 - 1.60 gpd/ft^2)

Note:
1) The TSS measurement of 200 mg/l on 7/1/97 is considered an outlier.

The average removal efficiencies for BOD_5, TSS, TOC, TP and FC for the SF wetland are reported in Table 6-2. Although the first-year removal efficiencies may not be indicative of long-term performance, the BOD_5, TSS, and FC removals are within the range of those measured in other subsurface wetland evaluations conducted. Thomson *et al.* (1996a and 1996b) report similar removal efficiencies for BOD and TSS in their evaluation of 15 SF wetland in New Mexico that were less than 4 years old. As plant and microbial communities establish with system maturation, there is a potential for improved removal or at least continuation of present removal efficiencies for BOD, TSS, and FC.

Table 6-2: Highlands Wetland Average Removal Efficiencies

Monitoring Variable				
BOD_5	**TSS**	**TOC**	**TP**	**FC**
22%	53%	20%	7%	75%

Data from March 11, 1997 indicate a concentration at the wetland outlet which is higher than the contemporaneous concentration at the septic tank outlet for BOD_5, TOC, TSS, NH_3/NH_4^+-N, and TP (FC was not monitored on this date). Since the downstream concentration is greater than the upstream concentration, negative removal efficiencies are calculated for this date. However, the occurrence of greater concentrations downstream can be explained by the fact that this sampling event was preceded by a large attendance event at the camp one week previous

(Strom, 1997), corresponding approximately to the HRT within the system. Kadlec and Knight (1996) recognize that data can be difficult to interpret when a wetland is subjected to fluctuating inputs or pulses of pollutants. When wetland outputs are compared with simultaneous inputs, there are detention time lag errors, which are hydrodynamic (due to turnover time of water within wetland) and chromatographic (due to the filling and emptying of sorption and biomass compartments). Without continuous flow measurements and laboratory analysis, which would be prohibitively expensive and practically infeasible, the magnitude and timing of this pulse is unknown.

The Highlands Camp wetland was in its first year of operation during the monitoring period. Figure 6-2 provides a series of photographs illustrating seasonal differences and the progression of plant growth observed at the Highlands Camp constructed wetland through its first year of operation. Plugs were transplanted into the wetland during the fall of 1996. The plant survival rate was excellent through the winter (nearly 100%), and the plants appeared to thrive during the warmer months, greatly increasing their aboveground biomass. Additional plants were transplanted into the wetland in late June 1997. However, the wetland plant density was sparse at the end of its first growing season. Full plant establishment is not expected until at least three growing seasons have passed.

6.1.5 Overall System

The input and output concentrations for each of the system's major components after the septic tank (upflow anaerobic filter, vertical flow aerobic filter, and SF constructed wetland) were compared to evaluate the contribution of each component to the overall system's treatment. The average concentrations of each lab-analyzed variable for each monitoring port are displayed in Table 6-3, and the average percentage contributions of each treatment unit to the overall system treatment are displayed in Table 6-4. The upflow anaerobic filter generally had the largest impact on the overall reduction of BOD_5, TSS, TOC, TP, and FC (between 25 and 57%). This may be explained by considering that this filter is removing the most easily removed portion of the pollutants, the particulate fraction. The reduction attributed to the vertical flow aerobic filter consisted of generally 5 to 36% of the overall reduction. The SF wetland was responsible for contributing approximately one-third to the overall reduction of BOD_5, TSS, TOC, TP, and FC. Although a substantial portion of the particulate fraction was removed by the upstream filters, the wetland sustained a high removal efficiency of the monitored variables, probably due in part to a considerably longer hydraulic residence time than that of the other filters. For BOD_5

reduction, each of the filters contributed an approximately equivalent proportion of overall system reduction.

Table 6-3: Average Lab Variable Concentrations for Highlands (10/22/96 – 9/9/97)

Monitoring Variable	Monitoring Port			
	septic tank outlet (HI-02)	upflow filter outlet (HI-03)	wetland inlet (HI-04)	wetland outlet (HI-05)
BOD_5 (mg/l)	373	309	253	196
TSS (mg/l)	66	38	36	17
TOC (mg/l)	176	159	136	109
NH_3/NH_4^+-N (mg/l)	37.4	40.1	38.9	40.0
NO_2^-/NO_3^--N (mg/l)	<0.05	<0.05	<0.05	<0.05
TP (mg/l)	6.2	5.6	5.0	4.7
FC (#/100 ml)	473,111	284,489	223,244	56,738

Table 6-4: Average Percentage Contribution of each Treatment Unit to Overall Treatment

Treatment Unit	Monitoring Variable				
	BOD_5	TSS	TOC	TP	FC
Upflow Anaerobic Filter	36%	57%	25%	41%	45%
Vertical Flow Aerobic Filter	32%	5%	34%	36%	15%
SF Constructed Wetland	32%	39%	41%	23%	40%

Fall, 10/22/96

Winter, 1/14/97

Summer, 7/30/97

Late Fall, 11/19/96

Early Summer, 6/17/97

Summer, 8/12/97

Figure 6-2: Highlands Wetland Progression through the First Year of Operation Displaying Seasonal Changes

6.2 Seasonal Variation

The treatment capacity of a constructed wetland system changes through the seasons due to changing climatic conditions (particularly temperature). In the winter, plants are dormant and the activity of microbial populations is reduced; whereas, in the summer, the biological treatment potential is higher.

The difference between the winter/spring and summer removal efficiencies for each of the monitored wastewater variables is detailed in Table 5-1 and illustrated using box and whisker plots in Figure 6-3. The BOD_5 removal for the system is characterized by a year-round median of 53%; the seasonal removal efficiencies for BOD_5 did not appear to be different. The winter/spring removal efficiencies for TSS, TP, and FC were more widely variable while their respective summer removal efficiencies were more consistent (smaller range between 25th and 75th quartiles) with medians of higher magnitude. For example, the removal efficiency of TP is characterized by an inner quartile range of –14 to 41% with a median of 22% in the winter/spring and by a tighter inner quartile range of 21 to 25% with a higher median of 25% in the summer. The removal efficiency of NH_3/NH_4^+-N was negative during the winter/spring (median = -33%) and positive during the summer (median = 14%). Negative removal efficiencies for NH_3/NH_4^+-N indicate that ammonia/ammonium concentrations were increasing through the system due to the mineralization of organic nitrogen.

There was a significant difference between winter/spring and summer removal efficiencies for ammonia/ammonium, TOC, and FC; however, there was not a significant difference between seasonal removal efficiencies for BOD_5, TSS, and TP. The mean of the winter/spring removal efficiencies was compared with the mean of the summer removal efficiencies for each lab-analyzed variable using the Mann-Whitney Test (see Section 4.2.2.1 for a description of this test). The null hypothesis of no difference between the means of the data populations was rejected in favor of the alternative hypothesis that there is a difference (α = 0.05) for ammonia/ammonium. Using a one-tailed test, the summer removal efficiencies for TOC and FC were found to exceed winter/spring removals significantly (α = 0.1). However, the summer removal efficiencies did not exceed the winter/spring removals significantly (α = 0.2) for BOD_5, TSS, and TP.

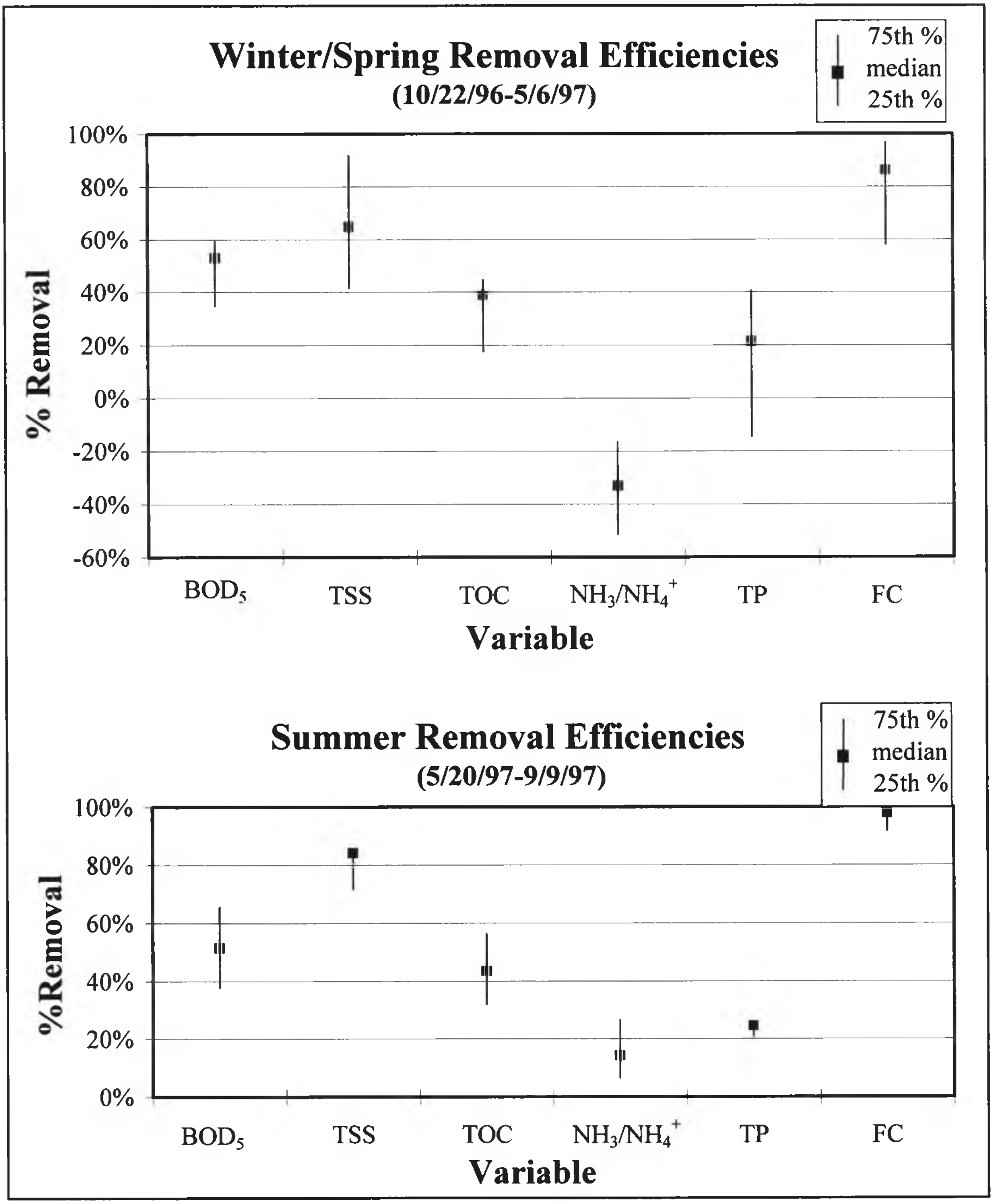


Figure 6-3: Seasonal Variation in Pollutant Removal Efficiencies between the Septic Tank Outlet and the Wetland Outlet

6.3 Comparison to Secondary Treatment

The Highlands constructed wetland system met secondary treatment standards for pH but failed to consistently meet standards for TSS and BOD_5. The wetland treatment system operated at secondary treatment standards for pH ($6 < pH < 9$) as shown in Figure 6-4 with pH values consistently circum-neutral. The wetland treatment system operated near secondary treatment standards for TSS (TSS < 30 mg/l for 30-day average, and TSS < 45 for 7-day average) as shown in Figure 6-5. The TSS concentration averaged 17 mg/l for all of the sampling events. However, there were three events with wetland effluent TSS concentrations in exceedence of the standard (*i.e.*, between 45 and 61 mg/l). The system only met the BOD_5 standard (BOD_5 < 30 mg/l for 30-day average, and BOD_5 < 45 for 7-day average) for two of the monitoring events (May 6 and 20, 1997) as shown in Figure 6-6. These two passing BOD_5 effluent values corresponded with an event of considerable dilution due to inflow and infiltration into the collection system upstream of the septic tank. The BOD_5 concentration of the wetland effluent was consistently > 100 mg/l, with two sampling events > 400 mg/l. However, the septic tank effluent analyzed for this system had much higher BOD_5 concentrations than typical septic tank effluent (see Table 2-4). The BOD_5 concentration of the septic tank effluent (269 - 608 mg/l) was two to three times the BOD_5 concentration of typical septic tank effluent (140 - 200 mg/l). The high BOD_5 concentrations may be explained by the contributions of a kitchen and cafeteria facility and water conservation practices of attending campers.

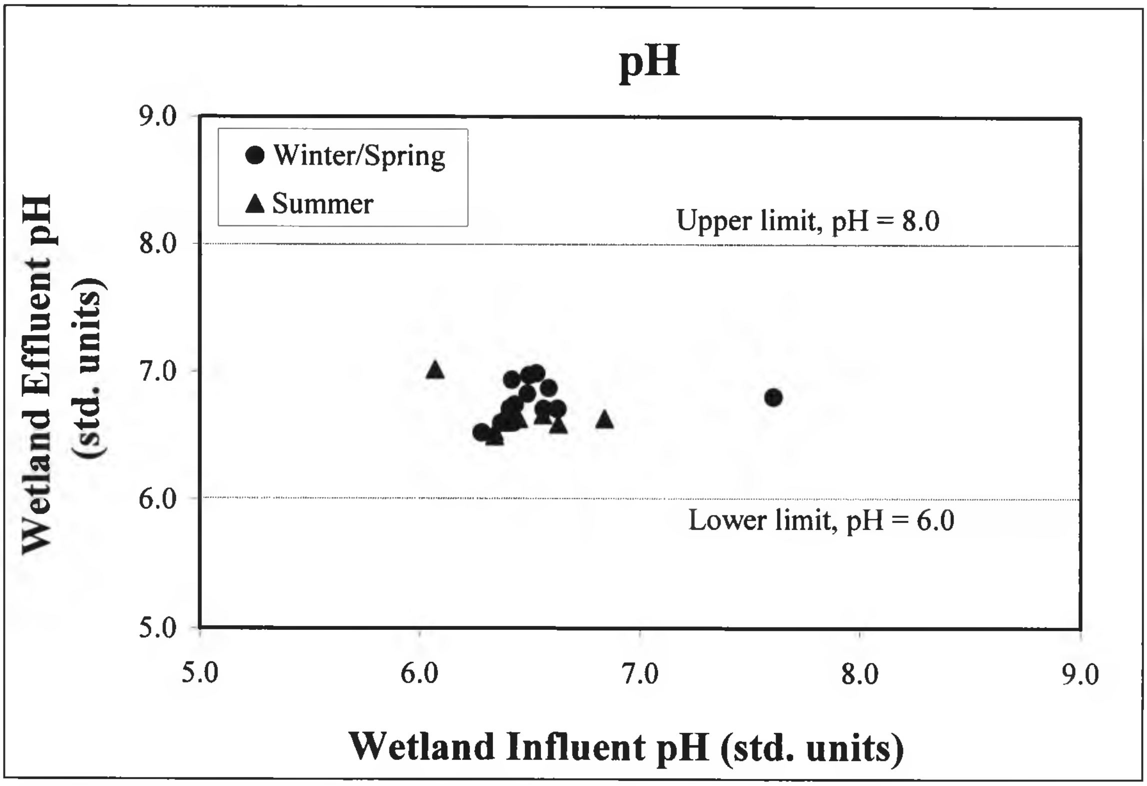


Figure 6-4: Secondary Treatment Limits for pH

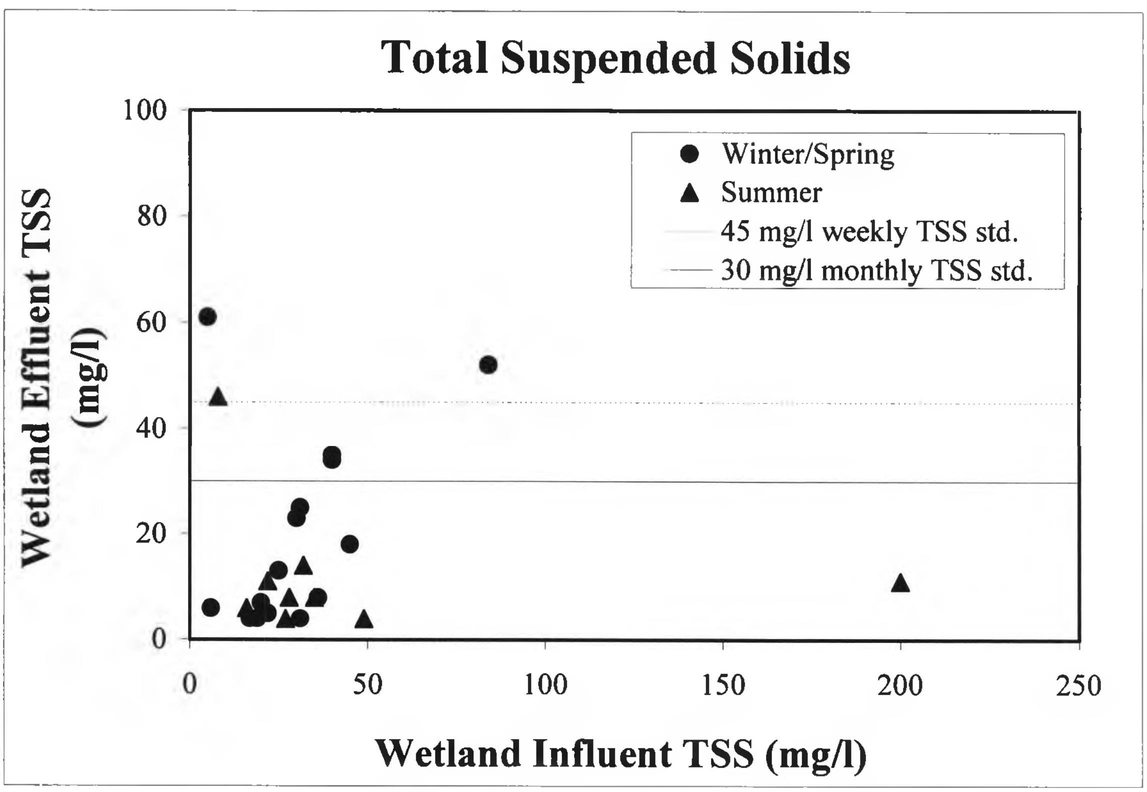


Figure 6-5: Secondary Treatment Performance Assessment for TSS

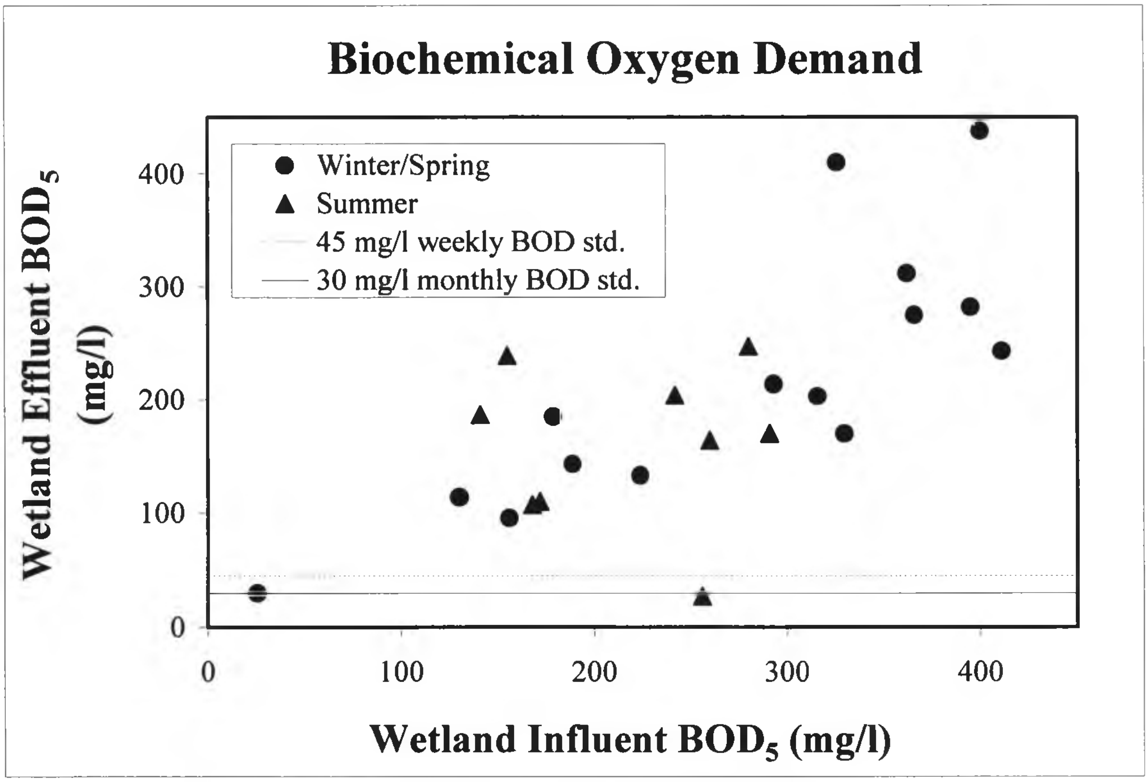


Figure 6-6: Secondary Treatment Performance Assessment for BOD_5

6.4 Comparison of Observed Results to Design Models

This section presents an assessment of how well the observed results fit various design models provided in the literature. The models evaluated include a water temperature to air temperature correlation, hydraulic loading correlations, water balance and evapotranspiration models, and BOD and TSS removal models.

6.4.1 Temperature

The water temperature measured at the wetland outlet follows the same trend as average daily air temperature as illustrated in Figure 6-7. There is a strong correlation between water temperature at the wetland outlet and average daily air temperature as displayed in Figure 6-8. The temperature data presented in this plot that was used to develop the regression relationship contained all of the monitoring data corresponding to air and water temperatures above 0°C (14 monitoring events). When the air temperature was continually below 0°C, an ice layer formed on top of the water within the wetland outlet tank and the water temperature beneath it was maintained slightly above 0°C. Statistically, the linear regression developed specifically to fit these data does not represent a significantly different model than the model presented as Equation 2-17 ($\alpha = 0.1$). Only data from the warmer period were modeled since there are temperature limits for the model specifying that air and water temperatures should be greater than 0°C.

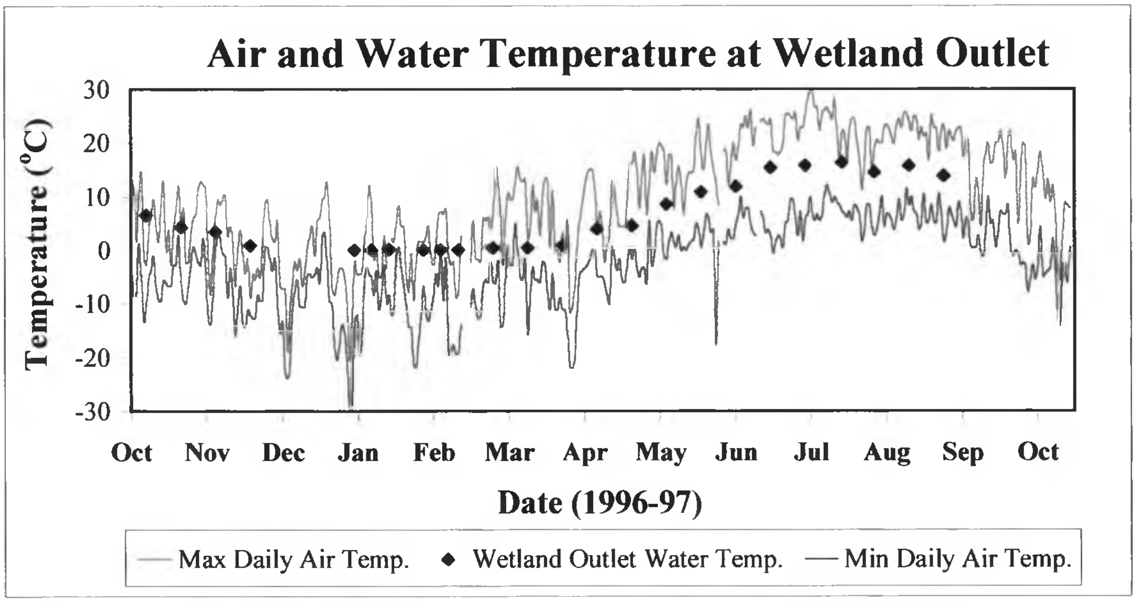


Figure 6-7: Air and Water Temperature at the Wetland Outlet

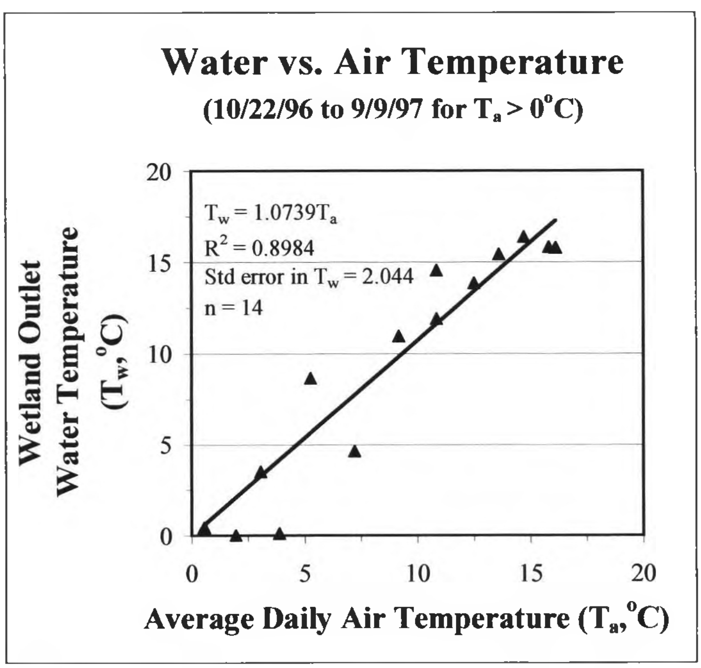


Figure 6-8: Water vs. Air Temperature Regression

A more accurate model of the relationship between air temperature and water temperature could be developed by considering the influence of the following factors: the average air temperature corresponding to the hydraulic retention time, and the presence of snow, gravel and plant material to insulate the wetland. However, the simplicity of this model makes it useful for analyzing design scenarios for which climatic data are available. The reaction rates for various processes, such as nitrification, are dependent on water temperature.

6.4.2 Hydraulic Loading

Hydraulic loading correlations were performed using the flow estimates from the upflow filter dosing counter, exclusively, in order to provide a consistent basis for hydraulic loading over the monitoring period. Typically, the use of an average of inflow and outflow is recommended within the literature to account for precipitation gains and ET losses within the wetland. However, since incomplete flow data were available for wetland outflow, it was decided that the inflow data would provide the most reasonable basis of analysis. Regression analysis of percent removal for each of the monitored wastewater variables vs. HRT or HLR did not provide strong correlations ($R^2 < 0.5$).

6.4.3 Water Balance

A water balance consists of reviewing the inputs (influent and precipitation) and the outputs (ET and outflow) to the wetland to ensure that they are approximately equal (See Figure 2-2). When precipitation is less than ET, there is a net concentrating effect on the contaminants within the wetland; and when ET is less than precipitation, there is a net diluting effect on the contaminants within the wetland. The removal efficiencies presented in Section 5 only consider the inflow and outflow concentrations. In order to obtain a more accurate assessment of treatment performance on a mass basis, the influence of ET and precipitation on the hydraulic loading was considered.

The problem encountered in performing a water balance on this wetland system is the uncertainty associated with the flow data. This is described in detail in Section 5.2.1. A water balance was conducted for the months of July through September 1997, corresponding to the period in which a meter was in place downstream of the wetland outlet. During this period, daily readings of the cumulative flow were read from the meter downstream of the wetland outlet and from the upflow filter dosing counter upstream of the wetland inlet.

The precipitation volume was estimated using the daily precipitation data for Allenspark and the surface area of the wetland. Surface run-on and runoff during precipitation events were neglected since there is a berm around the wetland. An estimate of ET volume was obtained using the class A pan evaporation (EP) rates for Estes Park, Colorado (Table 6-5).

Table 6-5: Estes Park Class A Pan Evaporation ***(Source: Colorado Climate Center)***

Month	Pan Evaporation (in/month)
May	5.91
June	7.51
July	7.46
August	6.37
September	5.25
October	4.49

A monthly water balance of the constructed wetland for July 8 – September 30, 1997 is presented in Table 6-6. The ET estimation included within this table is based on the relationship of 0.7 *EP (typically used to estimate ET for FWS wetlands, see Section 2.4.2). The total ET estimated for this period using this relationship (17.00 m^3) is closer to the calculated difference between wetland inputs and effluent (14.19 m^3) than total ET estimates calculated by Equation 2-3 (22.29 m^3) and Equation 2-4 (1.65 m^3). Error within the water balance may be attributed to (in order of declining likelihood) flow measurement errors, ET estimation errors, precipitation estimation errors, and seepage from the bentonite liner bed of the SF wetland. The estimated concentrating ratio for each contaminant due to ET is estimated as approximately 10%; however, this concentrating ratio is compensated by the diluting effect attributable to precipitation (~6%).

Table 6-6: Highlands Wetland Water Balance (7/8/97 - 9/30/97)

Month[1]	Wetland influent (m^3)	Precipitation (m^3)	Total inputs (m^3)	Wetland effluent (m^3)	Difference[2] (inputs - effluent) (m^3)	ET estimate 0.7* EP (m^3)
July-97	70.19	2.10	72.28	73.40	-1.12	5.49
August-97	54.09	4.43	58.53	46.86	11.67	6.31
September-97	38.67	3.43	42.10	38.46	3.64	5.20
				Total	14.19	17.00

Notes:
1) July -97 only represents 7/8/97 through 7/31/97; the other months are complete.
2) Difference (inputs - effluent) is assumed to account for ET, seepage, and measurement error.
3) Heavy rainfall in late July/early August 1997 may have contributed surface runoff to the wetland inputs.
(During 7/29-7/31/97, with 1+ in. rainfall, the wetland effluent was 10.9 m^3 > wetland influent and precipitation.)

6.4.4 BOD and TSS Removal

There are two approaches applied in the literature for modeling removal efficiency. The first approach consists of using the first order kinetic model (Equation 2-7) with its associated temperature-dependent rate constant (Equation 2-8 for BOD removal). The second approach for modeling removal consists of a regression relationship derived from the North American Data Base of wetlands (Equation 2-15 for BOD removal and Equation 2-16 for TSS removal), which does not include a temperature correction factor. The kinetic modeling approach is based on influent concentration, temperature, and hydraulic residence time; whereas, the regression modeling approach is based on influent concentration and hydraulic loading rate.

The following figures display a comparison of the observed BOD_5 and TSS concentrations with those predicted by the kinetic and regression models presented in Section 2.4. Note that the models do not fit the observed data and predict that the wetland treatment performance should have been much higher. In fact, using the Sign Test (described in section 4.2.2.1), a null hypothesis that there was not a difference between the observed and predicted removal efficiencies was rejected easily in favor of an alternative hypothesis that the observed removal efficiencies were significantly lower than the predicted removal efficiencies for all of the TSS and BOD models ($\alpha = 0.01$). The regression models appear to be a closer fit than the kinetic models, although the predicted concentrations are significantly different from the observed data for both models. The kinetic model may be overly dependent on HRT because it appears that HRTs greater than 10 days have a diminishing effect on removal efficiency. Although this kinetic model is widely published and seemingly accepted, Kadlec and Knight (1996) report it does not model BOD removal efficiency accurately for HRTs greater than 18 hours.

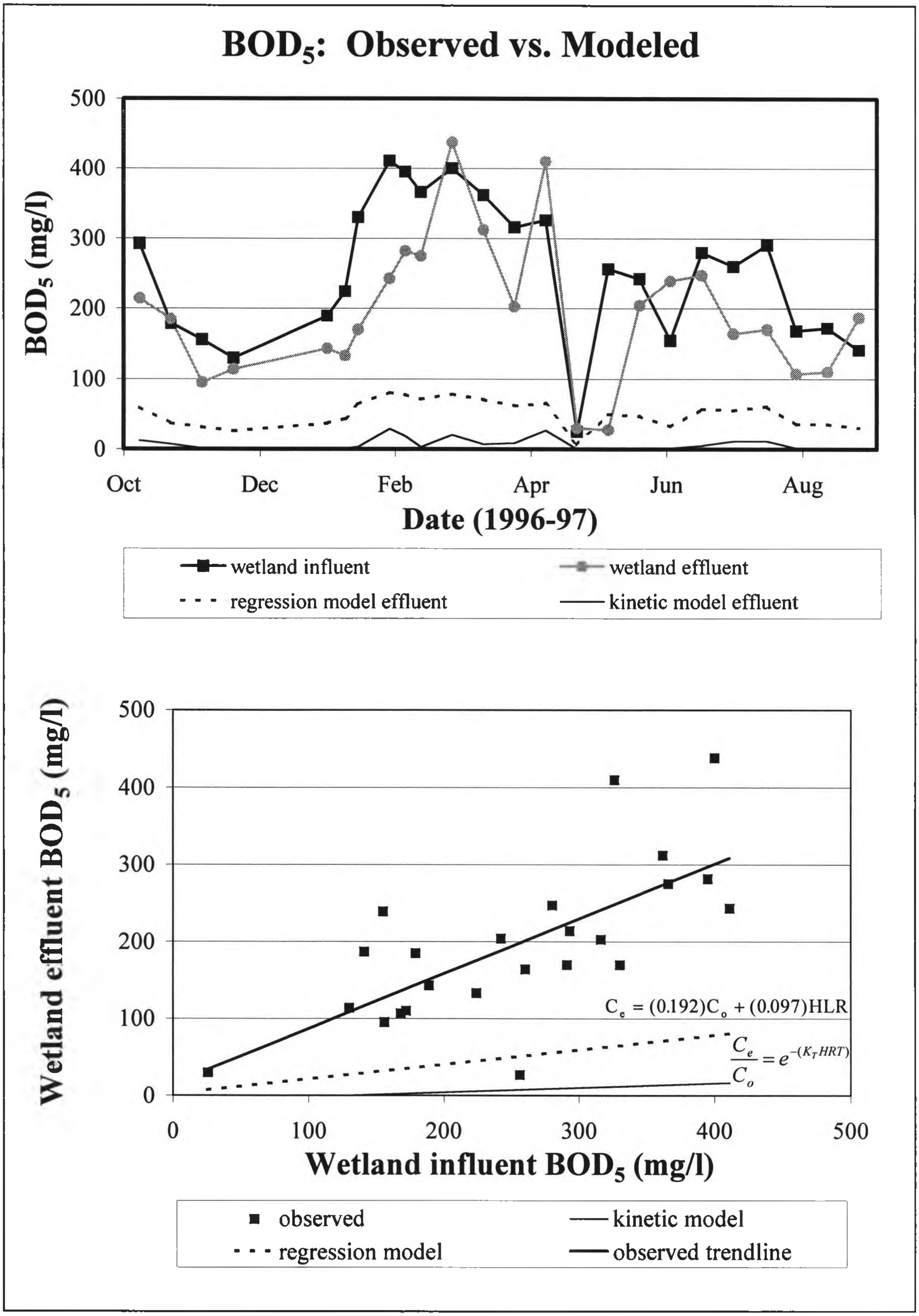


Figure 6-9: BOD_5: Observed vs. Modeled

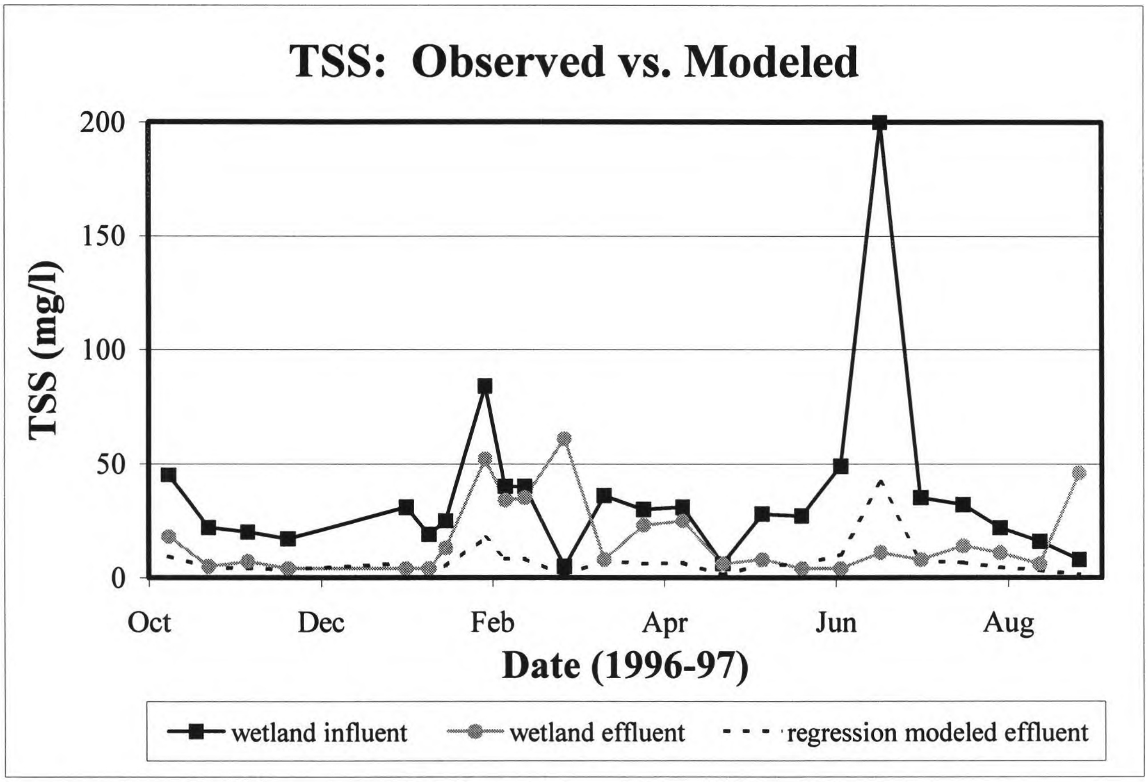


Figure 6-10: TSS: Observed vs. Modeled

6.4.5 Nitrogen Removal

The removal of nitrogen is expected to improve with system maturity. Nitrifiers are often slow to establish a large microbial community, and nitrifier growth is highly dependent on warm temperatures (optimal 25 to 35°C). Since this wetland was recently constructed and the water temperature has averaged approximately 4°C for the first half of the monitoring period, nitrifiers have not yet had the opportunity to establish themselves. Reed *et al.* (1995) state that the potential for nitrogen removal may take several years to develop in a wetland system, since it may require several growing seasons for plants, root systems, soils, and benthic materials to equilibrate. A series of photographs is shown in Figure 6-2, which illustrates the progression of the wetland through the seasons of the monitoring period. Only at the end of the monitoring period, during the summer months, were the plants really given the opportunity to flourish and contribute biological treatment.

The observed pH during this monitoring period (5.8 to 7.0) was less than the optimal pH range for nitrifiers. There is a narrow optimal range between pH of 7.5 and 8.6 for the growth and activity of nitrifiers but systems acclimated to lower pH conditions have nitrified successfully (Metcalf & Eddy, 1991). A large quantity of alkalinity is consumed for the oxidation of ammonia.

SF wetlands have the potential to remove nitrogen. However, this potential may take several growing seasons of operation to develop and requires the presence of specific environmental conditions. Thompson *et al.* (1996a and 1996b) report nitrogen removal efficiencies of less than 40% in a study of 15 wetlands in New Mexico with less than four years operation.

7. Summary, Conclusions, and Recommendations

7.1 Summary

A unique, constructed subsurface flow (SF) wetland study for domestic wastewater treatment was carried out at Highlands Presbyterian Camp located near Allenspark, Colorado. This site is located in a cold climate region at an elevation of 2530 m (8300 ft). A pilot SF wetland system with a 1.9 m^3/d (500 gpd) capacity was constructed in the late summer of 1996. This passive treatment system features an innovative treatment train located in between a standard septic tank and leachfield. The septic tank effluent flows sequentially through an upflow anaerobic filter with a dosing siphon, a vertical flow aerobic filter, a constructed SF wetland, and another automatic siphon dosing chamber to dose a subsurface disposal field (see Figure 3-4 for a profile diagram of the system).

The purpose of this study was to document and evaluate the first-year performance of the Highlands constructed wetland system and assess the scientific understanding of design methodologies for SF constructed wetlands within cold climate regions. To help accomplish this purpose, a year-long study of the pilot constructed wetland system was conducted with the following four objectives to evaluate the system's treatment performance and design:

1) Describe the contribution of each unit to the overall wastewater treatment provided by the system,
2) Quantify the seasonal variation of pollutant removal efficiencies through the system,
3) Compare the system's treatment performance to secondary treatment standards, and
4) Compare the observed results to those predicted by existing design models.

The water quality monitoring of this site consisted of approximately biweekly monitoring from October 1996 through September 1997 of physical, chemical, and biological variables at sampling ports located up and down gradient of each major system unit. The monitored variables included flow, water temperature, pH, total dissolved solids (TDS), specific conductance, dissolved oxygen (DO), oxidation-reduction potential (ORP), 5-day biochemical oxygen demand (BOD_5), total suspended solids (TSS), total organic carbon (TOC), ammonia/ammonium (NH_3/NH_4^+), nitrites/nitrates (NO_2^-/NO_3^-), total phosphorus (TP), and fecal coliforms (FC).

This system was successful in achieving reductions of BOD_5, TSS, TOC, TP, and FC during its first year of operation (see Table 5-1). The median removal efficiencies for the monitoring period were 53% for BOD_5, 84% for TSS, 40% for TOC, 23% for TP, and 92.1% for FC. However, the system's removal efficiencies were generally less than those presented in the literature for more established systems. Essentially, during this start-up period, the constructed wetland was functioning as a physical filter, and its performance is expected to improve with maturation of the plant and microbial communities.

Each treatment unit monitored (upflow anaerobic filter, vertical flow filter, and constructed wetland) contributed to the overall treatment performance (see Table 6-4). The positioning of the upflow aerobic filter as the first filter and the relatively long detention time of the constructed wetland may explain why these treatment units contributed more to the overall treatment performance than the vertical flow filter.

Seasonally, the removal efficiencies of some monitored variables differed significantly whereas others did not appear to be affected. The removal efficiencies for TSS, TP, and FC were more consistent and of higher magnitude in the warmer months than in the colder months. The removal efficiency for NH_3/NH_4^+-N was negative in the colder months (indicating an increase through the system) and positive in the warmer months. In contrast, the removal efficiency of BOD_5 is characterized by a year-round median of 53% and its removal efficiency did not appear different seasonally. There was a significant difference between winter/spring and summer removal efficiencies for ammonia/ammonium, TOC, and FC; however, there was not a significant difference between seasonal removal efficiencies for BOD_5, TSS and TP. The seasonal removal efficiencies are displayed in Figure 6-3. The lower hydraulic wastewater loading during the winter months due to lower attendance levels at the Camp provided a longer hydraulic residence time and helped to compensate for the reduced treatment capability of the constructed wetland at colder temperatures.

The effluent from the system did not meet secondary treatment standards consistently. The system operated at secondary treatment standards for pH ($6<pH<9$), but failed to meet secondary treatment standards for TSS and BOD_5 (<30 mg/l for 30-day average and <45 mg/l for 7-day average). The treatment system operated near secondary treatment standards for TSS with an average TSS effluent concentration of 17 mg/l; however, three monitoring events exceeded the TSS standards (see Figure 6-5). The system only met the BOD_5 standard for two monitoring events; otherwise, the BOD_5 effluent concentration was consistently >100 mg/l (see Figure 6-6). However, the influent wastewater was consistently at least twice typical domestic wastewater strength.

In addition, the observed removal efficiencies of BOD_5 and TSS for the SF constructed wetland were significantly lower than those predicted by first-order kinetic models and regression models from the literature (see Figures 6.9 and 6.10).

The results and analysis of the first year of performance of the Highlands Camp treatment system offer potential but are insufficient, at this time, to allow recommendation of a constructed wetland treatment system for the camp's proposed expansion. Further monitoring and analysis is required before the treatment performance potential of this system can be properly and completely evaluated. The development of full wetland treatment potential is expected to take several growing seasons.

The use of constructed wetland systems for wastewater treatment is an emerging technology, and monitoring efforts of operating constructed wetland systems contribute toward the advancement of the scientific knowledge for future applications. Based on the results of this study, several recommendations are provided that address the importance of allowing an adequate start-up period, the need to develop more advanced design models to predict treatment performance, monitoring program adaptations to allow for a more in-depth analysis of nitrogen removal, methods to interpret treatment performance when loading is widely variable, operational strategies for cold weather, and issues requiring further research.

7.2 CONCLUSIONS REGARDING EACH OBJECTIVE

1) <u>Contribution of each unit to the overall wastewater treatment provided by the system.</u>

- The septic tank appeared to be functioning adequately with sludge depths of less than 20 cm (8 in.) in each compartment and concentrations of measured variables (BOD_5, TSS, VSS, NH_3/NH_4^+-N, NO_2^-/NO_3^--N, and TP) within or below the typical range characterizing septage.
- The upflow anaerobic filter was effective in removal of BOD_5, TSS, TOC, TP, and FC and on average, contributed 25 to 57% of the overall system removal of these variables.
- The vertical flow filter contributed over 30% of the system's removal of BOD_5, TOC, and TP. However, this filter did not appear to aerate the wastewater flowing through as was intended for enhancing nitrification within the wetland.

- The SF wetland was responsible for contributing approximately one-third to the overall reduction of BOD_5, TSS, TOC, TP, and FC.

2) Seasonal variation of pollutant removal efficiencies through the system.

- Winter/spring removal rates for TSS, TP, and FC were more widely variable while the summer removal rates were more consistent and of a higher magnitude.
- NH_3/NH_4^+-N concentrations tended to increase by 17 to 51% through the system during the winter/spring and decrease by 7 to 26% through the system during the summer.
- There was a significant difference ($\alpha = 0.1$) between winter/spring and summer removal efficiencies for ammonia/ammonium, TOC, and FC; however, there was not a significant difference between seasonal removal efficiencies for BOD_5, TSS, and TP.

3) Treatment performance of system compared to secondary treatment standards.

- The wetland treatment system operated at secondary treatment standards for pH ($6<pH<9$).
- The wetland treatment system operated near secondary treatment standards for TSS (TSS < 30 mg/l for 30-day average, and TSS < 45 for 7-day average). The TSS concentration averaged 17 mg/l for all of the sampling events. However, there were three events with wetland effluent TSS concentrations in exceedence of the standard (*i.e.*, between 45 and 61 mg/l).
- The system only met the BOD_5 standard (BOD_5 < 30 mg/l for 30-day average, and BOD_5 < 45 for 7-day average) for two of the monitoring events, corresponding with significant dilution due to inflow and infiltration into the system. The BOD_5 concentration of the wetland effluent was consistently >100 mg/l. However, the BOD_5 concentration of the septic tank effluent was consistently at least twice the concentration of typical septic tank effluent.

4) Observed results compared to those predicted by existing design models.

- The water temperature at the wetland outlet was closely correlated to the average daily air temperature for the monitoring data corresponding to air and water temperatures above 0°C. When the air temperature was continually below 0°C, the water temperature at the wetland outlet was slightly above 0°C underneath an ice layer.
- ET is estimated to concentrate the pollutants within the SF wetland during the summer months of July through September by ~10%, and precipitation is estimated to dilute the

pollutants by ~6%. Therefore, removals based on a mass balance approach are actually ~4% higher than those based directly on comparison of influent and effluent concentrations.

- The observed treatment performance of this wetland was significantly lower than performance predicted by existing models for BOD removal at the hydraulic loading rates and temperatures observed. The literature indicates that with system maturation the BOD removal rate should improve.
- The observed performance for TSS removal also was significantly lower than the predicted treatment performance.

In summary, the Highlands Camp treatment system was successful in reducing BOD_5, TSS, TOC, TP, and FC; however, the reductions of BOD_5 and TSS were not sufficient to consistently meet secondary treatment standards and were significantly lower than model predictions. The winter/spring removal efficiencies were significantly different from summer removal efficiencies for NH_3/NH_4^+-N, TOC, and FC, but not significantly different for BOD_5, TSS, and TP. The results and analysis of the first year of performance of the Highlands Camp treatment system offer potential but are insufficient, at this time, to allow recommendation of a wetland treatment system for the camp's proposed expansion. The conditions characterizing start-up (sparse vegetation and lack of aerobic environments for microbial communities) are suspected to be a greater limitation to this system's treatment potential than the presence of cold climate and high altitude conditions. Further monitoring and analysis is required before the treatment performance potential of this system can be properly and completely evaluated.

7.3 Recommendations

The use of constructed wetland systems for wastewater treatment is an emerging technology, and there is much yet to be learned about how they function from a scientific perspective. As the scientific understanding of this technology develops, this knowledge can be applied to improve the design, operation, and performance of constructed wetland systems. Monitoring efforts of operating constructed wetland systems contribute toward the advancement of the scientific knowledge for future applications. Based on the results of this study, several recommendations are provided that address the importance of allowing an adequate start-up period, the need to develop more advanced design models to predict treatment performance, monitoring program adaptations to allow for a more in-depth analysis of nitrogen removal, methods to interpret treatment performance when loading is widely variable, operational strategies for cold weather, and issues requiring further research.

It is recommended that the plans for monitoring, operation, and regulation of constructed wetland systems allow for an appropriate start-up period. Three years is typically necessary for start-up to allow maturation of the plants and stabilization of processes. As the plant and microbial communities develop, the biological processes greatly enhance overall treatment performance. Monitoring programs of at least 3-5 years are recommended in order to accurately assess treatment performance and not dismiss the potential of the technology before the system is mature. In addition, with a longer-term study, it would be possible to evaluate treatment trends related to seasonality and maturation of the system, treatment potential for nitrogen removal, and value of harvesting plant biomass. Regulatory flexibility or conservative operation is required during the start-up period.

There is a need to develop more advanced design models that are more accurate for predicting treatment performance. The commonly used BOD and TSS removal models did not fit the observed data for this system, presumably due to the system's immaturity and possibly deficiency of the existing models. Since there is a discrepancy between start-up performance and the performance of a mature system, it would be beneficial to develop a model that would predict performance as a function of system maturity. Ultimately, due to the complexity of wetland systems, it would be valuable to develop a computer-based, mechanistic model in which design variables (*e.g.*, HRT, medium gradation, depth, plant species and density, daily air temperatures, and wastewater characteristics) could be input and treatment performance ranges would be output.

Nitrogen removal processes could be more fully evaluated by making several adaptations to the monitoring program. First, it is important to monitor each of the primary species of nitrogen (organic nitrogen, ammonia nitrogen, and nitrite/nitrate), thereby allowing an analysis of the nitrogen mass balance, and determination of rates for ammonification, nitrification, denitrification, and nitrogen uptake by plants. Organic nitrogen was not analyzed as part of this study, which prevented such analysis. Second, the extent of nitrogen treatment within the leachfield could be analyzed by extracting samples from lysimeter installations. In addition, continuous measurement of redox potential, alkalinity and dissolved oxygen, using probes with data loggers positioned within each monitoring port for the study duration, would be helpful in assessing whether and when suitable conditions existed for nitrification. Calibration of equipment should be checked periodically to ensure the collection of accurate data. Although such adaptations to the monitoring program would require additional funding, time and resources, the additional knowledge gained of nitrogen removal processes would be valuable.

It is recommended that a method be developed for more accurately analyzing treatment performance in situations involving widely variable loading. In operational constructed wetland systems, such as Highlands, organic and hydraulic loading are not controlled variables. The variability and pulses of flows and pollutant concentrations cause difficulties in interpreting treatment performance. For example, if monitoring were to take place following a high concentration pulse by a time period approximately equivalent to the hydraulic residence time of the wetland, it is possible that the wetland outlet concentrations would exceed the contemporaneous measurement of wetland inlet concentrations (as is suspected to have occurred for the March 11, 1997 sampling date). The actual extent of treatment for such cases is unknown based on data commonly collected. While, it is acknowledged that the use of accurate flow measurement equipment is crucial to the analysis of performance, hydraulic loading pulses do not necessarily coincide with organic loading pulses.

Regarding the operation of the Highland Camp wetland specifically during cold weather, several recommendations are provided to improve winter performance. The wetland water level lower was lowered during the colder months to provide more insulation. However, during periods of minimal use (*e.g.,* December 1996) the water level could be lowered even further. Excessively large HRTs (*i.e.,* >15 days) did not appear to improve performance but instead allowed greater temperature reductions and freezing. When large events occur during the winter, flows should be split between the wetland treatment train and the older leachfields instead of being diverted solely through the wetland treatment train. To prevent problems associated with freezing, the insulation of each tank could be improved. A mulch layer over the wetland, which would not blow away, could help insulate the wetland.

More research needs to be performed to analyze water losses due to ET within a SF constructed wetland. When ET is greater than precipitation inputs, there is a net concentrating of wetland pollutants that may lead to underestimation of treatment performance. In addition, there may be important implications for water right laws related to ET water losses. In a monitoring program specifically designed to quantify ET, more elaborate flow measurement instrumentation and on-site precipitation gages would be required.

Generally, several issues deserve further research to advance the understanding of constructed wetlands and these include: (1) determining the role of plants in providing oxygen to the root zone for use by autotrophic microbes such as nitrifiers, (2) developing models to more accurately predict treatment performance under various conditions (*e.g.*, cold climate, start-up, and variable loading), (3) developing design and operational strategies to optimize initial performance and shorten the start-up period required to reach design potential, (4) evaluating the benefits/drawbacks of using various local plant species as compared to those typically studied (reeds, cattails, *etc.*), and (5) evaluating the effectiveness of various strategies to increase sequential nitrification/denitrification (*e.g.*, recirculating a proportion of the effluent within the wetland and designing separate treatment units for nitrification and denitrification).

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APPENDICES

Appendix A: Abbreviations and Definitions

Appendix B: Weather Data

Appendix C: Field Data

Appendix D: Lab Data

APPENDIX A: ABBREVIATIONS AND DEFINITIONS

Abbreviations

BOD_5	5-day biochemical oxygen demand
CDPHE	Colorado Department of Public Health and Environment
CFR	Code of Federal Regulations
COD	chemical oxygen demand
DO	dissolved oxygen
ET	evapotranspiration
EP	pan evaporation
FC	fecal coliforms
FWS	free-water-surface (wetlands)
gpd	gallons per day
HLR	hydraulic loading rate
HRT	hydraulic residence time
ISDS	individual sewage disposal system
MGD	million gallons per day
MPN	most probable number
NH_3/NH_4^+	ammonia/ammonium
NO_2^-/NO_3^-	nitrites/nitrates
O & M	operation and maintenance
ORP	oxidation-reduction potential
PE	population equivalent
PFU	plaque forming units (viruses)
PL	public law
ROL	radial oxygen loss (plants)
SF	subsurface flow (wetlands)
SS	settleable solids

TDS	total dissolved solids
TKN	total kjeldahl nitrogen
TOC	total organic carbon
TC	total coliforms
TN	total nitrogen
TP	total phosphorus
TSS	total suspended solids
USEPA	United States Environmental Protection Agency
USC	United States Code
VSB	vegetated submerged beds
VSS	volatile suspended solids

Definitions

Definitions are provided below, in alphabetic order, for words and phrases commonly used in this thesis. These definitions are intended solely for the context of this thesis.

Biochemical Oxygen Demand (BOD) is an indicator of wastewater strength in terms of the quantity of biodegradable organic matter. BOD_5 is a standard 5-day test, which measures the quantity of dissolved oxygen required to meet the metabolic needs of aerobic microorganisms in the biochemical oxidation of organic matter (Metcalf & Eddy, 1991). The effluent BOD_5 concentration is typically regulated in wastewater discharge permits.

Cold Climate is a broad classification, which includes the Highlands Camp wetland site. More specifically, this site is situated in a "cold temperate climate," according to the Köppen-Geiger-Pohl classification (Wittgren and Mæhlum, 1997), which specifies that the mean air temperature of the coldest month is below -3°C (26.6°F) and that the mean air temperature of the warmest month is above 10°C (50°F).

Fecal Coliforms (FC) are an indicator for waterborne pathogens of fecal origin. Wastewater management professionals commonly use FC as an indicator of pathogens in wastewater effluent, whereas total coliforms (measure of coliform of both fecal and nonfecal origin) are typically used for drinking water. FC are a subgroup of total coliforms and provide stronger evidence of the presence of fecal pathogens (AWWA, 1990). Operationally, FC are defined as all of the aerobic and facultatively anaerobic, gram-negative, nonspore-forming, rod-shaped bacteria that ferment lactose with gas formation within 48 hours at 43 to 44.5 °C (AWWA, 1990).

Free-Water-Surface (FWS) Constructed Wetland consists of a bed of emergent aquatic vegetation in shallow water (~0.4 m) exposed to the atmosphere, a layer of soil for rooting media, a liner to protect the groundwater, and appropriate inlet and outlet structures (Reed *et al.*, 1995).

Harvesting consists of removal of biomass (*e.g.*, plant clippings) to ensure permanent removal of nutrients or wastewater contaminants from the treatment system.

Hydraulic Short-Circuiting occurs when flow is routed quickly through the system by channelization and prevented from interfacing with the reactive media for the theoretical residence time. Problems of hydraulic short-circuiting indicate the likely presence of large dead zones where water is stagnant.

Nitrogen occurs in several forms that are of interest in waters and wastewaters; these include: nitrate, nitrite, ammonia, and organic nitrogen. Ammonia nitrogen can be toxic to fish in very small concentrations and the oxidation of ammonia/ammonium (NH_3/NH_4^+) in the receiving stream can depress the oxygen level. Another concern is a high level of nitrates in groundwater (<10 mg/l NO_3^--N is the drinking water standard). High nitrates in drinking water can cause methemoglobinemia, also known as "blue baby syndrome" (Stednick, 1991). Nitrogen is an essential nutrient for many photosynthetic autotrophs and in some cases has been identified as a growth-limiting nutrient (*Standard*, 1992).

The oxidation and reduction of nitrogen species is biologically mediated. Nitrogen within septic tank effluent is primarily in the form of organic nitrogen and ammonia nitrogen. Total Kjeldahl Nitrogen (TKN) is the analytical measurement of ammonia and organic nitrogen. Bacterial decomposition of complex organic matter mineralizes organic nitrogen to ammonia nitrogen. The balance between ammonia and ammonium is dependent on pH and temperature. At a pH of 7 and temperature of 25°C, un-ionized ammonia consists of < 1 % of the total ammonia nitrogen present; as the pH and temperature increase, the ratio of NH_3/NH_4^+ increases (Kadlec and Knight, 1996). The oxidation of NH_3/NH_4^+ to nitrite (NO_2^-), and then to nitrate (NO_3^-) is referred to as nitrification and is mediated by microbes known as nitrifiers in the presence of oxygen. The nitrate can then be immobilized into living organic matter by photosynthetic plants or reduced to nitrogen gas and nitrous oxide by heterotrophs in an anaerobic process known as denitrification.

pH is "a measure representing the negative base-ten logarithm of the hydrogen-ion activity of a solution, in moles per liter" ($pH = -\log \{H^+\}$) (USGS, 1998). The pH controls speciation of many geochemicals, influences dissolution and precipitation, and determines whether the water will support aquatic life (McCutcheon, 1993). The pH is reported on a scale that most commonly ranges from 0 to 14 and that is directly related to the ratio of hydrogen ion activity $\{H^+\}$ and hydroxyl ion activity $\{OH^-\}$ at a given temperature. A solution is considered acidic if $\{H^+\} > \{OH^-\}$ (pH less than 7 at 25°C); a solution is considered basic, or alkaline, when $\{OH^-\} > \{H^+\}$. Carbon dioxide (CO_2)-free water at 25°C is considered neutral because $\{H^+\} = \{OH^-\}$ (USGS, 1998).

Phosphorus occurs in natural waters as phosphates, which are classified as orthophosphates, condensed phosphates (pyro-, meta-, and polyphosphates), and organically bound phosphates (*Standard*, 1992). Phosphate ions in solution are generally in low concentrations due to plant uptake, complexation with other solutes, adsorption to metal oxides, and precipitation (Stednick, 1991). Like nitrogen, phosphorus is an essential nutrient and in some cases a growth-limiting nutrient (*Standard*, 1992). Effluent concentrations of total phosphorus (TP) may be regulated to control eutrophication impacts to surface water quality.

Redox Potential (Eh), or electric potential, is "a measure of the equilibrium potential, relative to the standard hydrogen electrode, developed at the interface between a noble metal electrode and an aqueous solution containing electroactive redox species" (USGS, 1998). Redox reactions involve the transfer of electrons. Oxidation is a process in which a molecule or ion loses electrons. Reduction is a process by which electrons are gained. When Eh > 300 mV, conditions are termed aerobic because dissolved oxygen is available. When Eh < -100 mV, conditions are termed anaerobic because there is no dissolved oxygen (Kadlec and Knight, 1996). The reactivities and mobilities of important elements in biological systems (*e.g.*, Fe, S, N, and C) are strongly dependent on redox conditions (*Standard*, 1992). Oxidation-reduction potential (ORP) measurements are not fundamental indicators of a specific chemical environment, but rather of qualitative use. "The voltage reading produced by an ORP cell is a reflection of many reactions – it is a 'mixed potential' and its value is difficult if not impossible to interpret in any fundamental chemical terms" (Snoeyink and Jenkins, 1980).

Specific Conductance, also called electric conductivity, is a function of the total quantity of ionized materials in an aqueous solution and a convenient measure of the salt content of wastewaters. Specific conductance is defined as the reciprocal of resistance between two platinum electrodes 1 cm apart and each with a surface area of 1 cm^2, reported at a temperature of 25°C in units of micromhos per centimeter (µmhos/cm) (Kadlec and Knight, 1996). 1.0 µmho/cm = 0.1 mS/m (millisiemen per meter).

Subsurface Flow (SF) Constructed Wetlands, as opposed to free-water-surface (FWS) wetlands, consist of a planted, 2 - 2 ½ ft. deep, porous media bed with the water level maintained below the media surface. Subsurface flow wetlands have been described as vegetated submerged beds (VSB), microbial rock reed filters, gravel marsh, root-zone, reed bed, rock/plant filter, and gravel-based emergent macrophyte systems. There is some confusion in the literature when subsurface flow wetlands are abbreviated as SSF wetlands and free-water-surface wetlands are designated as surface flow (SF) wetlands. In this thesis, SF wetlands refer to subsurface flow wetlands exclusively.

Total Dissolved Solids (TDS) is a measure of the total quantity of dissolved solids in a water sample and typically measured by filtration followed by sample evaporation. TDS is reported in units of mg/l, and is proportional to specific conductance (Kadlec and Knight, 1996).

Total Organic Carbon (TOC) and **Chemical Oxygen Demand (COD)** each represent a measure of biodegradable and non-biodegradable organic material. A site-specific correlation can be developed between TOC and BOD_5 or COD. By establishing a correlation, it may be possible to discontinue BOD_5 tests, since these are both expensive and time-consuming (Metcalf & Eddy, 1991).

Total Suspended Solids (TSS) is a measure of the inorganic and organic particles. Wastewater typically contains large quantities of suspended material that is mostly organic in nature (Metcalf & Eddy, 1991). The concentration of TSS throughout a treatment process typically parallels that of BOD_5. The TSS concentration of wastewater effluent is regulated.

Wetlands are land areas that are wet during part or all of the year, which support highly productive ecosystems that are valued for their ability to improve water quality. "Wetlands are wet long enough to alter soil properties because of the chemical, physical, and biological changes that occur during flooding, and to exclude plant species that cannot grow in wet soils" (Kadlec and Knight, 1996).

APPENDIX B: WEATHER DATA

Table B - 1: Monthly Historic Record for Allenspark Weather

Summary of Monthly Climatic Data for Allenspark, Colorado for years 1944-1992
Weather Station No. 05-0185-04 (Allenspark 1NW)
Latitude: 40° 32', Longitude: 105° 32', Elevation 8320 ft.
(Note: years of data record varies from 29 to 44 years)

Month	Air Temperature (°F)								
	Mean Minimum			Mean Average			Mean Maximum		
	Min.	Avg.	Max.	Min.	Avg.	Max.	Min.	Avg.	Max.
Jan	4.1	13.9	23.4	15.2	24.3	32.2	26.3	34.4	49.1
Feb	7.4	15.3	23.3	17.5	25.9	37.6	27.3	36.5	53.0
Mar	5.7	17.7	27.8	18.2	29.1	36.9	30.7	40.5	47.8
Apr	13.2	24.3	32.2	30.4	36.9	44.0	41.9	49.4	56.3
May	24.4	32.4	40.3	40.3	45.8	50.1	52.8	59.1	65.7
Jun	35.2	39.5	44.3	49.1	54.3	61.3	62.1	69.2	79.7
Jul	39.3	44.7	49.0	57.1	60.1	64.5	70.8	75.5	80.3
Aug	39.3	43.5	46.7	55.3	58.2	61.2	68.8	72.9	76.4
Sep	30.6	37.2	42.2	44.4	51.7	56.3	55.7	66.2	72.9
Oct	20.4	29.6	36.3	33.4	42.9	52.3	43.6	56.1	68.2
Nov	14.3	21.0	33.3	24.7	31.9	41.8	33.6	42.8	53.2
Dec	5.2	16.2	25.8	18.5	26.5	38.6	27.1	36.4	52.5
Annual	24.3	28.0	30.8	38.0	40.5	44.4	50.1	53.0	59.1

Month	Precipitation (in.)			Snowfall (in.)		
	Min.	Avg.	Max.	Min.	Avg.	Max.
Jan	0.03	1.14	4.32	0.3	20.4	73.0
Feb	0.03	0.98	3.04	1.0	18.2	37.0
Mar	0.16	1.78	4.66	4.0	27.4	66.0
Apr	0.22	2.24	7.26	0.0	25.7	78.0
May	0.05	2.67	8.95	0.0	9.9	55.0
Jun	0.12	2.25	8.26	0.0	1.5	16.0
Jul	0.05	2.33	7.20	0.0	0.0	0.0
Aug	0.13	2.20	9.96	0.0	0.0	0.0
Sep	0.05	1.47	4.49	0.0	2.2	17.0
Oct	0.12	1.35	4.03	0.0	10.8	81.0
Nov	0.07	1.32	4.70	0.0	18.8	64.0
Dec	0.00	1.13	3.64	0.0	18.0	63.0
Annual	12.03	20.91	28.80	103.9	155.5	250.5

Source of Data: Colorado Climate Center, Fort Collins, CO

Table B - 2: Allenspark Weather for October, 1996

Weather Station No. 05-0185-04 (Allenspark 1NW)
Latitude: 40° 32', Longitude: 105° 32', Elevation 8320 ft.

Date	Air Temperature				Precipitation	Snow	Snow on ground
	Maximum		Minimum				
	(°F)	(°C)	(°F)	(°C)	(in.)	(in.)	(in.)
10/01/96	65	18	36	2	0	0	0
10/02/96	66	19	30	-1	0	0	0
10/03/96	52	11	36	2	0	0	0
10/04/96	64	18	32	0	0.23	0	0
10/05/96	56	13	32	0	0.02	0	0
10/06/96	62	17	44	7	0	0	0
10/07/96	65	18	33	1	0	0	0
10/08/96	58	14	37	3	0	0	0
10/09/96	54	12	28	-2	0	0	0
10/10/96	60	16	28	-2	0	0	0
10/11/96	68	20	44	7	0	0	0
10/12/96	70	21	39	4	0	0	0
10/13/96	66	19	36	2	0	0	0
10/14/96	66	19	37	3	0	0	0
10/15/96	58	14	28	-2	0	0	0
10/16/96	57	14	28	-2	0	0	0
10/17/96	52	11	17	-8	0.14	0.3	0
10/18/96	35	2	17	-8	Trace	Trace	0
10/19/96	51	11	34	1	0	0	0
10/20/96	58	14	23	-5	0.09	0.9	0
10/21/96	30	-1	8	-13	0	0	0
10/22/96	27	-3	14	-10	Trace	Trace	0
10/23/96	39	4	23	-5	0	0	0
10/24/96	44	7	25	-4	Trace	Trace	0
10/25/96	49	9	30	-1	0	0	0
10/26/96	40	4	20	-7	0.03	1.7	1
10/27/96	35	2	15	-9	0	0	0
10/28/96	48	9	15	-9	0	0	0
10/29/96	55	13	22	-6	0.08	1.2	1
10/30/96	32	0	21	-6	0.04	0.6	1
10/31/96	39	4	20	-7	0	0	0

Source of Data: Colorado Climate Center, Fort Collins, CO

Table B - 3: Allenspark Weather for November, 1996

Weather Station No. 05-0185-04 (Allenspark 1NW)
Latitude: 40° 32', Longitude: 105° 32', Elevation 8320 ft.

Date	Air Temperature				Precipitation	Snow	Snow on ground
	Maximum		Minimum				
	(°F)	(°C)	(°F)	(°C)	(in.)	(in.)	(in.)
11/01/96	27	-3	20	-7	0.1	2	1
11/02/96	39	4	27	-3	0	0	0
11/03/96	46	8	27	-3	0	0	0
11/04/96	54	12	37	3	0.06	0.6	0
11/05/96	41	5	21	-6	0	0	0
11/06/96	46	8	15	-9	0.05	0.9	0
11/07/96	28	-2	14	-10	Trace	Trace	0
11/08/96	28	-2	19	-7	Trace	Trace	0
11/09/96	37	3	26	-3	0	0	0
11/10/96	43	6	33	1	0	0	0
11/11/96	44	7	31	-1	0	0	0
11/12/96	53	12	28	-2	0	0	0
11/13/96	55	13	27	-3	0	0	0
11/14/96	54	12	36	2	0	0	0
11/15/96	53	12	25	-4	0.14	2.8	2
11/16/96	27	-3	9	-13	0.44	7.8	8
11/17/96	17	-8	7	-14	0.07	1.6	8
11/18/96	32	0	17	-8	0.18	2	8
11/19/96	43	6	32	0	0.11	1.1	5
11/20/96	49	9	39	4	0	0	3
11/21/96	47	8	36	2	0	0	1
11/22/96	49	9	31	-1	0	0	1
11/23/96	51	11	30	-1	Trace	0.2	0
11/24/96	37	3	16	-9	0.02	0.3	0
11/25/96	40	4	26	-3	0	0	0
11/26/96	36	2	18	-8	0.05	1	1
11/27/96	20	-7	3	-16	0.41	5.8	6
11/28/96	32	0	13	-11	0	0	5
11/29/96	39	4	20	-7	0	0	4
11/30/96	31	-1	7	-14	0.23	3.3	9

Source of Data: Colorado Climate Center, Fort Collins, CO

Table B - 4: Allenspark Weather for December, 1996

Weather Station No. 05-0185-04 (Allenspark 1NW)
Latitude: 40° 32', Longitude: 105° 32', Elevation 8320 ft.

Date	Air Temperature				Precipitation	Snow	Snow on ground
	Maximum		Minimum				
	(°F)	(°C)	(°F)	(°C)	(in.)	(in.)	(in.)
12/01/96	24	-4	6	-14	0	0	5
12/02/96	29	-2	12	-11	0.15	1.7	5
12/03/96	16	-9	10	-12	0	0	4
12/04/96	24	-4	9	-13	0.03	0.5	3
12/05/96	22	-6	9	-13	Trace	Trace	1
12/06/96	26	-3	17	-8	0.32	3.2	5
12/07/96	23	-5	15	-9	0.21	1.7	6
12/08/96	34	1	15	-9	Trace	Trace	5
12/09/96	47	8	33	1	0	0	5
12/10/96	49	9	33	1	0	0	4
12/11/96	41	5	29	-2	0.06	0.7	4
12/12/96	36	2	25	-4	0.2	2.2	6
12/13/96	35	2	29	-2	0.08	0.9	6
12/14/96	42	6	14	-10	0	0	5
12/15/96	20	-7	4	-16	0	0	5
12/16/96	19	-7	8	-13	0.07	1.4	5
12/17/96	19	-7	-9	-23	0.18	3.6	6
12/18/96	-2	-19	-11	-24	0	0	5
12/19/96	11	-12	-7	-22	0	0	4
12/20/96	20	-7	11	-12	Trace	Trace	4
12/21/96	28	-2	18	-8	0.11	2.2	5
12/22/96	25	-4	22	-6	0.2	3	7
12/23/96	29	-2	13	-11	0.05	0.9	6
12/24/96	20	-7	13	-11	0.11	2.2	7
12/25/96	25	-4	13	-11	Trace	Trace	5
12/26/96	33	1	24	-4	0.04	0.4	5
12/27/96	37	3	24	-4	Trace	Trace	3
12/28/96	40	4	23	-5	0.13	1.3	5
12/29/96	30	-1	24	-4	Trace	Trace	4
12/30/96	42	6	26	-3	0	0	3
12/31/96	43	6	21	-6	0	0	3

Source of Data: Colorado Climate Center, Fort Collins, CO

Table B - 5: Allenspark Weather for January, 1997

Weather Station No. 05-0185-04 (Allenspark 1NW)
Latitude: 40° 32', Longitude: 105° 32', Elevation 8320 ft.

Date	Air Temperature				Precipitation	Snow	Snow on ground
	Maximum		Minimum				
	(°F)	(°C)	(°F)	(°C)	(in.)	(in.)	(in.)
01/01/97	49	9	37	3	0	0	2
01/02/97	50	10	38	3	0	0	2
01/03/97	55	13	28	-2	0	0	1
01/04/97	44	7	15	-9	0.06	0.8	1
01/05/97	20	-7	14	-10	Trace	Trace	1
01/06/97	17	-8	0	-18	0.13	1.8	3
01/07/97	21	-6	-5	-21	0	0	3
01/08/97	26	-3	1	-17	0.02	0.2	3
01/09/97	26	-3	7	-14	0.01	0.1	3
01/10/97	23	-5	4	-16	0.15	3.2	5
01/11/97	14	-10	-6	-21	0.18	2.7	7
01/12/97	-5	-21	-21	-29	0.85	9.7	15
01/13/97	9	-13	-20	-29	0.07	1	14
01/14/97	28	-2	8	-13	0	0	15
01/15/97	24	-4	10	-12	0	0	10
01/16/97	24	-4	-3	-19	0.03	0.9	11
01/17/97	24	-4	1	-17	0	0	10
01/18/97	33	1	18	-8	0	0	8
01/19/97	41	5	26	-3	0	0	7
01/20/97	54	12	24	-4	0	0	7
01/21/97	48	9	23	-5	0	0	0
01/22/97	29	-2	17	-8	0	0	0
01/23/97	32	0	25	-4	Trace	Trace	0
01/24/97	23	-5	12	-11	0	0	0
01/25/97	23	-5	17	-8	Trace	Trace	0
01/26/97	37	3	27	-3	0.45	4.5	N/A
01/27/97	26	-3	14	-10	0.15	2.5	N/A
01/28/97	N/A	N/A	17	-8	Trace	Trace	10
01/29/97	36	2	10	-12	Trace	Trace	9
01/30/97	35	2	12	-11	0	0	9
01/31/97	41	5	30	-1	0	0	8

Source of Data: Colorado Climate Center, Fort Collins, CO

Table B - 6: Allenspark Weather for February, 1997

Weather Station No. 05-0185-04 (Allenspark 1NW)
Latitude: 40° 32', Longitude: 105° 32', Elevation 8320 ft.

Date	Air Temperature				Precipitation	Snow	Snow on ground
	Maximum		Minimum				
	(°F)	(°C)	(°F)	(°C)	(in.)	(in.)	(in.)
02/01/97	47	8	33	1	0	0	8
02/02/97	40	4	26	-3	0	0	7
02/03/97	40	4	20	-7	0.06	0.9	9
02/04/97	23	-5	13	-11	0	0	8
02/05/97	18	-8	6	-14	0.06	1.8	10
02/06/97	31	-1	6	-14	0.01	0.6	9
02/07/97	15	-9	-7	-22	0.07	2.2	12
02/08/97	29	-2	-7	-22	0	0	11
02/09/97	35	2	2	-17	0	0	10
02/10/97	35	2	10	-12	0	0	9
02/11/97	35	2	20	-7	0	0	9
02/12/97	37	3	10	-12	0.13	2.2	11
02/13/97	40	4	8	-13	0.05	1	10
02/14/97	30	-1	12	-11	0	0	9
02/15/97	27	-3	16	-9	0.04	0.6	9
02/16/97	33	1	24	-4	Trace	Trace	9
02/17/97	44	7	20	-7	0	0	8
02/18/97	45	7	33	1	0	0	8
02/19/97	44	7	15	-9	Trace	Trace	8
02/20/97	46	8	29	-2	0	0	8
02/21/97	30	-1	-3	-19	0.27	5.2	13
02/22/97	27	-3	-2	-19	Trace	Trace	12
02/23/97	28	-2	0	-18	0.17	3.7	14
02/24/97	16	-9	-3	-19	0.04	0.9	13
02/25/97	19	-7	-2	-19	0	0	12
02/26/97	37	3	7	-14	0.07	2.5	14
02/27/97	N/A	N/A	N/A	N/A	N/A	N/A	N/A
02/28/97	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Source of Data: Colorado Climate Center, Fort Collins, CO

Table B - 7: Allenspark Weather for March, 1997

Weather Station No. 05-0185-04 (Allenspark 1NW)
Latitude: 40° 32', Longitude: 105° 32', Elevation 8320 ft.

Date	Air Temperature				Precipitation	Snow	Snow on ground
	Maximum		Minimum				
	(°F)	(°C)	(°F)	(°C)	(in.)	(in.)	(in.)
03/01/97	N/A	N/A	N/A	N/A	0.24	4.8	17
03/02/97	28	-2	13	-11	0	0	16
03/03/97	42	6	19	-7	0.02	0.4	14
03/04/97	29	-2	13	-11	0.09	1	14
03/05/97	29	-2	9	-13	Trace	Trace	13
03/06/97	28	-2	10	-12	0	0	12
03/07/97	43	6	20	-7	0	0	12
03/08/97	42	6	22	-6	0	0	11
03/09/97	43	6	21	-6	0.1	1.5	12
03/10/97	39	4	28	-2	0	0	11
03/11/97	45	7	21	-6	0	0	10
03/12/97	60	16	21	-6	0	0	9
03/13/97	54	12	28	-2	0	0	9
03/14/97	45	7	6	-14	0.14	3.1	11
03/15/97	27	-3	7	-14	0.17	3.2	14
03/16/97	43	6	22	-6	Trace	Trace	10
03/17/97	51	11	33	1	0	0	9
03/18/97	49	9	27	-3	Trace	Trace	8
03/19/97	49	9	27	-3	0	0	8
03/20/97	55	13	41	5	0	0	7
03/21/97	60	16	31	-1	0	0	6
03/22/97	56	13	23	-5	0	0	5
03/23/97	55	13	22	-6	0	0	3
03/24/97	56	13	29	-2	Trace	Trace	2
03/25/97	36	2	3	-16	0.25	3.7	5
03/26/97	40	4	17	-8	0	0	3
03/27/97	54	12	26	-3	0	0	1
03/28/97	45	7	22	-6	Trace	Trace	0
03/29/97	49	9	22	-6	0.11	2.4	2
03/30/97	37	3	21	-6	0	0	0
03/31/97	50	10	28	-2	0	0	0

Source of Data: Colorado Climate Center, Fort Collins, CO

Table B - 8: Allenspark Weather for April, 1997

Weather Station No. 05-0185-04 (Allenspark 1NW)
Latitude: 40° 32', Longitude: 105° 32', Elevation 8320 ft.

Date	Air Temperature				Precipitation	Snow	Snow on ground
	Maximum		Minimum				
	(°F)	(°C)	(°F)	(°C)	(in.)	(in.)	(in.)
04/01/97	56	13	27	-3	0.01	0.4	0
04/02/97	56	13	18	-8	0.76	10.2	10
04/03/97	33	1	12	-11	0.07	1.1	8
04/04/97	52	11	24	-4	0	0	3
04/05/97	32	0	12	-11	Trace	Trace	2
04/06/97	32	0	12	-11	Trace	Trace	2
04/07/97	28	-2	16	-9	0	0	1
04/08/97	38	3	12	-11	0.01	0.2	1
04/09/97	31	-1	12	-11	0.11	2.5	4
04/10/97	42	6	4	-16	0.19	2.6	5
04/11/97	11	-12	-6	-21	0.32	3.5	8
04/12/97	13	-11	-8	-22	0.11	1.7	9
04/13/97	20	-7	-4	-20	0.07	1.2	9
04/14/97	34	1	13	-11	0	0	6
04/15/97	42	6	24	-4	Trace	0	4
04/16/97	47	8	25	-4	0.03	0.6	4
04/17/97	53	12	26	-3	0	0	0
04/18/97	58	14	27	-3	0	0	0
04/19/97	59	15	29	-2	0	0	0
04/20/97	59	15	32	0	0	0	0
04/21/97	53	12	32	0	0.48	Trace	0
04/22/97	38	3	23	-5	Trace	Trace	0
04/23/97	45	7	23	-5	0.07	1.2	0
04/24/97	39	4	23	-5	1.58	17.1	17
04/25/97	28	-2	21	-6	1.73	18.4	30
04/26/97	34	1	17	-8	0.16	2.3	28
04/27/97	37	3	14	-10	0.15	2.3	25
04/28/97	55	13	33	1	0	0	19
04/29/97	53	12	30	-1	0.18	0	15
04/30/97	44	7	25	-4	0.33	1.3	15

Source of Data: Colorado Climate Center, Fort Collins, CO

Table B - 9: Allenspark Weather for May, 1997

Weather Station No. 05-0185-04 (Allenspark 1NW)
Latitude: 40° 32', Longitude: 105° 32', Elevation 8320 ft.

Date	Air Temperature				Precipitation	Snow	Snow on ground
	Maximum		Minimum				
	(°F)	(°C)	(°F)	(°C)	(in.)	(in.)	(in.)
05/01/97	40	4	29	-2	0.01	0.2	11
05/02/97	40	4	22	-6	Trace	Trace	9
05/03/97	40	4	21	-6	0.02	Trace	9
05/04/97	48	9	26	-3	0	0	6
05/05/97	61	16	33	1	0	0	2
05/06/97	61	16	29	-2	0	0	1
05/07/97	65	18	33	1	Trace	0	0
05/08/97	59	15	26	-3	0	0	0
05/09/97	46	8	23	-5	0	0	0
05/10/97	56	13	26	-3	0	0	0
05/11/97	64	18	26	-3	0	0	0
05/12/97	44	7	21	-6	0.21	1.7	1
05/13/97	55	13	42	6	0	0	0
05/14/97	65	18	27	-3	0	0	0
05/15/97	58	14	30	-1	0.13	0	0
05/16/97	64	18	40	4	0.03	0	0
05/17/97	68	20	42	6	0	0	0
05/18/97	67	19	40	4	Trace	0	0
05/19/97	65	18	30	-1	0.19	0.5	0
05/20/97	54	12	29	-2	0	0	0
05/21/97	64	18	35	2	Trace	0	0
05/22/97	64	18	38	3	0.35	0	0
05/23/97	46	8	35	2	0.35	0	0
05/24/97	55	13	33	1	Trace	0	0
05/25/97	60	16	37	3	0.24	0	0
05/26/97	55	13	32	0	0.02	Trace	0
05/27/97	44	7	33	1	0.02	Trace	0
05/28/97	54	12	32	0	0.1	0	0
05/29/97	58	14	34	1	0.17	0	0
05/30/97	58	14	35	2	0.25	0	0
05/31/97	59	15	36	2	0.03	0	0

Source of Data: Colorado Climate Center, Fort Collins, CO

Table B - 10: Allenspark Weather for June, 1997

Weather Station No. 05-0185-04 (Allenspark 1NW)
Latitude: 40° 32', Longitude: 105° 32', Elevation 8320 ft.

Date	Air Temperature				Precipitation	Snow	Snow on ground
	Maximum		Minimum				
	(°F)	(°C)	(°F)	(°C)	(in.)	(in.)	(in.)
06/01/97	71	22	41	5	0	0	0
06/02/97	76	24	39	4	0	0	0
06/03/97	64	18	33	1	0	0	0
06/04/97	59	15	38	3	0	0	0
06/05/97	68	20	44	7	0	0	0
06/06/97	74	23	43	6	0	0	0
06/07/97	65	18	38	3	0.76	0	0
06/08/97	59	15	39	4	0.42	0	0
06/09/97	55	13	0	-18	0.40	0	0
06/10/97	47	8	35	2	0.32	0	0
06/11/97	N/A	N/A	N/A	N/A	N/A	N/A	N/A
06/12/97	65	18	35	2	0	0	0
06/13/97	66	19	34	1	0.44	0	0
06/14/97	54	12	39	4	0.19	0	0
06/15/97	61	16	36	2	0.02	0	0
06/16/97	68	20	36	2	0	0	0
06/17/97	62	17	41	5	0.43	0	0
06/18/97	67	19	44	7	0	0	0
06/19/97	74	23	50	10	0.06	0	0
06/20/97	73	23	43	6	0	0	0
06/21/97	77	25	46	8	0.01	0	0
06/22/97	73	23	46	8	0	0	0
06/23/97	79	26	41	5	0.10	0	0
06/24/97	67	19	38	3	0.01	0	0
06/25/97	73	23	37	3	0	0	0
06/26/97	N/A	N/A	N/A	N/A	0	0	0
06/27/97	75	24	45	7	0	0	0
06/28/97	76	24	43	6	0.01	0	0
06/29/97	75	24	38	3	0	0	0
06/30/97	74	23	39	4	0	0	0

Source of Data: Colorado Climate Center, Fort Collins, CO

Table B - 11: Allenspark Weather for July, 1997

Weather Station No. 05-0185-04 (Allenspark 1NW)
Latitude: 40° 32', Longitude: 105° 32', Elevation 8320 ft.

Date	Air Temperature				Precipitation	Snow	Snow on ground
	Maximum		Minimum				
	(°F)	(°C)	(°F)	(°C)	(in.)	(in.)	(in.)
07/01/97	76	24	37	3	0	0	0
07/02/97	65	18	31	-1	0	0	0
07/03/97	65	18	35	2	0	0	0
07/04/97	64	18	37	3	0	0	0
07/05/97	65	18	36	2	0	0	0
07/06/97	67	19	33	1	Trace	0	0
07/07/97	77	25	41	5	0	0	0
07/08/97	78	26	42	6	0	0	0
07/09/97	77	25	49	9	0	0	0
07/10/97	76	24	49	9	Trace	0	0
07/11/97	78	26	43	6	0.01	0	0
07/12/97	69	21	37	3	0.13	0	0
07/13/97	73	23	45	7	0	0	0
07/14/97	73	23	35	2	0	0	0
07/15/97	78	26	43	6	0	0	0
07/16/97	83	28	44	7	0	0	0
07/17/97	85	29	50	10	0	0	0
07/18/97	85	29	44	7	0	0	0
07/19/97	80	27	42	6	Trace	0	0
07/20/97	80	27	44	7	0.12	0	0
07/21/97	72	22	42	6	0.02	0	0
07/22/97	78	26	44	7	0.05	0	0
07/23/97	79	26	51	11	0	0	0
07/24/97	80	27	54	12	0.03	0	0
07/25/97	78	26	51	11	0	0	0
07/26/97	76	24	48	9	0	0	0
07/27/97	83	28	50	10	0.05	0	0
07/28/97	71	22	48	9	0.02	0	0
07/29/97	63	17	47	8	0.18	0	0
07/30/97	72	22	45	7	0.22	0	0
07/31/97	71	22	44	7	0.65	0	0

Source of Data: Colorado Climate Center, Fort Collins, CO

Table B - 12: Allenspark Weather for August, 1997

Weather Station No. 05-0185-04 (Allenspark 1NW)
Latitude: 40° 32', Longitude: 105° 32', Elevation 8320 ft.

Date	Air Temperature				Precipitation	Snow	Snow on ground
	Maximum		Minimum				
	(°F)	(°C)	(°F)	(°C)	(in.)	(in.)	(in.)
08/01/97	62	17	43	6	0.35	0	0
08/02/97	72	22	45	7	0.05	0	0
08/03/97	76	24	42	6	0	0	0
08/04/97	76	24	47	8	0.01	0	0
08/05/97	69	21	46	8	0.14	0	0
08/06/97	63	17	44	7	0.49	0	0
08/07/97	52	11	35	2	0.23	0	0
08/08/97	61	16	39	4	0	0	0
08/09/97	73	23	47	8	0	0	0
08/10/97	73	23	47	8	0.81	0	0
08/11/97	59	15	40	4	0.18	0	0
08/12/97	66	19	37	3	0.02	0	0
08/13/97	69	21	39	4	0.07	0	0
08/14/97	68	20	44	7	0.07	0	0
08/15/97	68	20	50	10	Trace	0	0
08/16/97	73	23	40	4	0	0	0
08/17/97	74	23	44	7	0.02	0	0
08/18/97	73	23	44	7	0	0	0
08/19/97	70	21	42	6	0.22	0	0
08/20/97	68	20	39	4	0.15	0	0
08/21/97	74	23	43	6	0	0	0
08/22/97	76	24	49	9	0	0	0
08/23/97	73	23	42	6	0.01	0	0
08/24/97	78	26	44	7	Trace	0	0
08/25/97	78	26	53	12	0	0	0
08/26/97	75	24	47	8	0.03	0	0
08/27/97	72	22	50	10	0	0	0
08/28/97	77	25	45	7	0.21	0	0
08/29/97	76	24	44	7	0.03	0	0
08/30/97	69	21	39	4	0	0	0
08/31/97	73	23	41	5	0.04	0	0

Source of Data: Colorado Climate Center, Fort Collins, CO

Table B - 13: Allenspark Weather for September, 1997

Weather Station No. 05-0185-04 (Allenspark 1NW)
Latitude: 40° 32', Longitude: 105° 32', Elevation 8320 ft.

Date	Air Temperature				Precipitation	Snow	Snow on ground
	Maximum		Minimum				
	(°F)	(°C)	(°F)	(°C)	(in.)	(in.)	(in.)
09/01/97	70	21	51	11	Trace	0	0
09/02/97	71	22	41	5	0.1	0	0
09/03/97	62	17	42	6	0.02	0	0
09/04/97	77	25	47	8	0.01	0	0
09/05/97	73	23	42	6	Trace	0	0
09/06/97	73	23	41	5	0	0	0
09/07/97	65	18	51	11	0	0	0
09/08/97	72	22	44	7	0	0	0
09/09/97	74	23	35	2	0	0	0
09/10/97	66	19	38	3	0.11	0	0
09/11/97	72	22	46	8	0	0	0
09/12/97	70	21	44	7	0.07	0	0
09/13/97	69	21	42	6	Trace	0	0
09/14/97	72	22	40	4	0.05	0	0
09/15/97	73	23	48	9	Trace	0	0
09/16/97	73	23	45	7	0.02	0	0
09/17/97	63	17	36	2	0	0	0
09/18/97	69	21	43	6	0.03	0	0
09/19/97	69	21	41	5	0.13	0	0
09/20/97	43	6	33	1	1.13	0	0
09/21/97	42	6	33	1	0.1	0	0
09/22/97	56	13	33	1	0.08	0	0
09/23/97	52	11	37	3	0.19	0	0
09/24/97	40	4	31	-1	0.34	0	0
09/25/97	60	16	30	-1	Trace	0	0
09/26/97	65	18	39	4	0	0	0
09/27/97	68	20	50	10	0.04	0	0
09/28/97	61	16	41	5	0	0	0
09/29/97	62	17	42	6	0	0	0
09/30/97	68	20	33	1	0	0	0

Source of Data: Colorado Climate Center, Fort Collins, CO

Table B - 14: Allenspark Monthly Weather Summary for Monitoring Period

Weather Station No. 05-0185-04 (Allenspark 1NW)
Latitude: 40° 32', Longitude: 105° 32', Elevation 8320 ft.

Month	Temperature (°F)		Temperature (°C)		Precipitation (in)	Snow (in)
	Mean Max.	Mean Min.	Mean Max.	Mean Min.		
Oct-96	52.3	27.5	11.3	-2.5	0.63	4.7
Nov-96	39.9	23.0	4.4	-5.0	1.86	29.4
Dec-96	28.6	15.3	-1.9	-9.3	1.95	25.9
Jan-97	30.2	12.3	-1.0	-11.0	2.11	27.4
Feb-97	32.7	11.0	0.4	-11.7	0.97	21.6
Mar-97	44.6	21.1	7.0	-6.1	1.13	20.1
Apr-97	40.7	18.3	4.9	-7.6	6.36	66.6
May-97	56.0	31.5	13.4	-0.3	2.13	2.4
Jun-97	67.8	38.6	19.9	3.7	3.17	0.0
Jul-97	74.7	43.3	23.7	6.3	1.48	0.0
Aug-97	70.5	43.6	21.4	6.4	3.13	0.0
Sep-97	65.0	40.6	18.3	4.8	2.43	0.0

Source of Data: Colorado Climate Center, Fort Collins, CO

APPENDIX C: FIELD DATA

Table C - 1: Water Temperature

Water Quality Variable: Water Temperature (^{o} C)

Sampling Date	Monitoring Port			
	septic tank outlet (HI-02)	upflow filter outlet (HI-03)	wetland inlet (HI-04)	wetland outlet (HI-05)
10/22/96	10.88	11.29	8.24	N/A
11/5/96	7.76	7.78	6.04	4.36
11/19/96	6.74	6.71	5.72	3.52
12/3/96	5.24	5.29	N/A	0.89
1/14/97	2.13	0.75	1.38	0.08
1/21/97	3.17	1.69	1.33	0.01
1/28/97	3.53	2.64	1.38	0.23
2/11/97	4.53	3.70	1.49	0.01
2/18/97	5.34	4.06	2.00	0.13
2/25/97	3.36	2.17	1.52	0.13
3/11/97	3.62	3.45	1.43	0.44
3/25/97	5.64	5.24	2.28	0.41
4/8/97	5.13	5.03	4.29	0.88
4/22/97	6.22	6.53	5.57	3.99
5/6/97	3.78	3.91	3.88	4.63
5/20/97	8.98	8.68	8.04	8.66
6/3/97	12.00	11.11	10.41	10.95
6/17/97	14.33	13.56	11.78	11.90
7/1/97	17.33	16.31	15.26	15.43
7/15/97	18.81	17.57	16.67	15.82
7/30/97	N/A	18.98	18.58	16.38
8/12/97	16.30	16.00	14.34	14.56
8/26/97	16.34	16.00	14.86	15.78
9/9/97	15.66	15.68	14.15	13.83

Table C - 2: pH

Water Quality Variable: pH (standard units)

Sampling Date	Monitoring Port			
	septic tank outlet (HI-02)	upflow filter outlet (HI-03)	wetland inlet (HI-04)	wetland outlet (HI-05)
10/22/96	6.36	6.36	6.72	N/A
11/5/96	6.26	6.60	6.43	6.60
11/19/96	6.09	6.33	7.61	6.80
12/3/96	6.00	6.11	N/A	6.58
1/14/97	6.18	6.30	6.28	6.52
1/21/97	6.22	6.25	6.43	6.74
1/28/97	6.45	6.37	6.41	6.71
2/11/97	6.11	6.23	6.53	6.99
2/18/97	6.00	6.24	6.42	6.94
2/25/97	6.27	6.65	6.49	6.82
3/11/97	6.53	6.50	6.63	6.71
3/25/97	6.21	6.28	6.56	6.71
4/8/97	6.18	6.28	6.50	6.97
4/22/97	6.27	6.21	6.37	6.60
5/6/97	6.53	6.52	6.59	6.87
5/20/97	5.86	5.81	6.07	7.01
6/3/97	6.21	6.31	6.38	6.64
6/17/97	6.62	6.44	6.84	6.63
7/1/97	5.80	5.87	6.45	6.63
7/15/97	6.22	6.33	6.63	6.59
7/30/97	N/A	6.28	6.34	6.50
8/12/97	6.22	6.25	6.56	6.66
8/26/97	6.27	6.23	6.38	6.60
9/9/97	6.23	6.21	6.34	6.53

Table C - 3: Specific Conductance

Water Quality Variable: Specific Conductance (mS/cm)

Sampling Date	Monitoring Port			
	septic tank outlet (HI-02)	upflow filter outlet (HI-03)	wetland inlet (HI-04)	wetland outlet (HI-05)
10/22/96	0.94	0.89	0.90	N/A
11/5/96	0.88	0.91	0.94	1.04
11/19/96	0.77	0.78	0.92	1.00
12/3/96	0.78	0.80	N/A	1.05
1/14/97	0.80	0.81	0.86	1.09
1/21/97	0.75	0.78	0.84	1.00
1/28/97	0.79	0.75	0.78	0.99
2/11/97	0.75	0.75	0.78	0.96
2/18/97	0.78	0.79	0.81	0.96
2/25/97	0.83	0.81	0.86	1.00
3/11/97	0.77	0.74	0.76	0.86
3/25/97	0.61	0.61	0.68	0.75
4/8/97	0.63	0.66	0.35	0.71
4/22/97	0.41	0.44	0.49	0.76
5/6/97	0.19	0.11	0.12	0.19
5/20/97	0.46	0.45	0.47	0.23
6/3/17	0.41	0.45	0.50	0.64
6/17/97	0.63	0.64	0.65	0.68
7/1/97	0.47	0.50	0.53	0.66
7/15/97	0.54	0.61	0.62	0.73
7/30/97	N/A	0.65	0.65	0.69
8/12/97	0.52	0.52	0.52	0.67
8/26/97	0.58	0.53	0.51	0.61
9/9/97	0.59	0.56	0.54	0.62

Table C - 4: Total Dissolved Solids (TDS)

Water Quality Variable: Total Dissolved Solids (mg/l)

Sampling Date	Monitoring Port			
	septic tank outlet (HI-02)	upflow filter outlet (HI-03)	wetland inlet (HI-04)	wetland outlet (HI-05)
10/22/96	601	571	578	N/A
11/5/96	562	579	602	668
11/19/96	490	500	591	641
12/3/96	502	511	N/A	672
1/14/97	513	521	549	700
1/21/97	477	496	540	637
1/28/97	508	479	498	635
2/11/97	479	478	497	614
2/18/97	499	508	520	616
2/25/97	528	520	551	641
3/11/97	496	475	486	553
3/25/97	388	392	433	479
4/8/97	406	421	226	455
4/22/97	261	284	314	489
5/6/97	120	70	79	120
5/20/97	295	289	301	148
6/3/17	265	285	321	408
6/17/97	401	412	417	437
7/1/97	303	320	337	422
7/15/97	344	390	396	469
7/30/97	N/A	415	417	439
8/12/97	333	331	333	428
8/26/97	374	341	326	391
9/9/97	378	356	345	399

Table C - 5: Dissolved Oxygen (DO)

Water Quality Variable: Dissolved Oxygen (mg/L)

Sampling Date	Monitoring Port			
	septic tank outlet (HI-02)	upflow filter outlet (HI-03)	wetland inlet (HI-04)	wetland outlet (HI-05)
10/22/96	0.00	0.00	0.00	N/A
11/5/96	0.00	0.00	0.00	0.00
11/19/96	4.07	4.18	5.41	5.76
12/3/96	0.00	0.00	N/A	0.00
1/14/97	10.34	10.42	10.73	8.64
1/21/97	4.14	5.13	4.15	4.44
1/28/97	10.69	10.66	10.68	11.56
2/11/97	4.02	4.68	4.57	5.31
2/18/97	8.63	8.69	8.57	9.89
2/25/97	4.94	5.08	5.31	6.20
3/11/97	4.33	4.84	5.39	6.00
3/25/97	8.32	9.07	10.25	11.22
4/8/97	3.83	4.15	6.95	5.52
4/22/97	4.75	5.12	5.27	5.96
5/6/97	7.59	5.86	7.89	5.82
5/20/97	4.96	5.85	5.46	4.37
6/3/17	2.22	3.21	3.33	2.54
6/17/97	0.65	1.02	0.26	0.00
7/1/97	4.00	4.47	5.15	4.60
7/15/97	3.17	3.63	4.84	4.70
7/30/97	N/A	3.32	4.22	4.16
8/12/97	4.40	4.31	4.81	4.89
8/26/97	3.64	4.02	4.06	4.54
9/9/97	3.91	3.86	4.28	4.56

Table C - 6: Oxidation-Reduction Potential (ORP)

Water Quality Variable: Oxidation-Reduction Potential (mV)

Sampling Date	Monitoring Port			
	septic tank outlet (HI-02)	upflow filter outlet (HI-03)	wetland inlet (HI-04)	wetland outlet (HI-05)
10/22/97	-81.67	-70.00	50.33	N/A
11/5/97	-71.33	-64.33	-26.67	-37.00
11/19/97	-55.67	-68.33	13.33	-49.33
12/3/97	-99.00	-88.00	N/A	39.33
1/14/97	-125.00	-105.33	-115.00	-131.67
1/21/97	-129.00	-124.00	-115.00	-126.67
1/28/97	-126.00	-123.00	-93.67	-115.33
2/11/97	-102.33	-61.00	-55.33	-108.00
2/18/97	-39.67	-31.33	-6.00	-52.33
2/25/97	-34.00	-35.00	-33.67	-57.00
3/11/97	-27.33	-6.33	11.33	-24.67
3/25/96	-69.33	-76.00	-30.00	-68.00
4/8/97	-25.67	-39.00	35.67	14.00
4/22/97	-29.33	-35.00	3.33	-71.67
5/6/97	70.67	155.33	108.00	-26.00
5/20/97	-67.67	-42.33	-30.33	-54.00
6/3/17	-67.00	-77.33	-14.33	-107.67
6/17/97	-97.67	-100.67	27.00	-90.67
7/1/97	-63.00	-68.00	5.67	-88.33
7/15/97	-74.67	-80.67	26.33	-120.33
7/30/97	N/A	-102.00	-43.33	-123.00
8/12/97	-67.67	-63.67	-5.67	-121.00
8/26/97	-87.33	-77.00	-62.67	-101.67
9/9/97	-93.00	-81.67	-59.00	-124.00

Table C - 7: Flow (Table 1 of 3)

Date	Upper Dosing Tank			
	Dose #	average gal/dose	cum flow (gal)	avg flow (gpd)
10/1/96	180	205		
11/1/96	252	200	14591	471
11/5/96	259	200	15991	350
11/19/96	277	199	19578	256
12/1/96	283	198	20768	99
12/3/96	284	198	20967	99
1/1/97	292	198	22550	55
1/14/97	300	197	24129	121
1/22/97	306	197	25311	148
1/28/97	312	196	26491	197
2/1/97	313	196	26687	49
2/11/97	327	195	29429	274
2/18/97	335	195	30990	223
2/25/97	336	195	31185	28
2/28/97	338	195	31574	130
3/11/97	352	194	34293	247
3/25/97	366	193	36999	193
3/31/97	372	192	38155	193
4/8/97	382	192	40077	240
4/22/97	409	190	45231	368
4/30/97	427	189	48641	426
5/6/97	429	189	49019	63
5/20/97	440	188	51091	148
5/31/97	446	188	52218	102
6/3/97	450	187	52968	250
6/16/97	481	185	58744	444
6/17/97	482	185	58929	185
6/18/97	487	185	59855	925
6/19/97	489	185	60225	370
6/20/97	490	185	60409	185
6/21/97	493	185	60963	554
6/22/97	495	184	61332	369
6/23/97	496	184	61517	184
6/24/97	499	184	62069	553
6/25/97	504	184	62989	920
6/26/97	507	184	63541	551
6/27/97	509	183	63908	367
6/28/97	514	183	64824	917
6/29/97	518	183	65557	732
6/30/97	519	183	65739	183
7/1/97	523	183	66470	731
7/2/97	526	182	67018	547
7/3/97	528	182	67382	365
7/4/97	530	182	67747	364
7/5/97	532	182	68111	364
7/6/97	534	182	68475	364

Date	Lower Dosing Tank			
	Dose #	gal/dose	cum flow (gal)	avg flow (gpd)
10/1/96	180	126		
11/1/96	294	126	14364	463
11/5/96	300	126	15120	189
11/19/96	322	126	17892	198
12/1/96	325	126	18270	32
12/3/96	325	126	18270	0
1/1/97	325	126	18270	0
1/14/97	329	126	18774	39
1/22/97	330	126	18900	16
1/28/97	336	126	19656	126
2/1/97	336	126	19656	0
2/11/97	344	126	20664	101
2/18/97	348	126	21168	72
2/25/97	348	126	21168	0
2/28/97	348	126	21168	0
3/11/97	371	126	24066	263
3/25/97	375	126	24570	36
3/31/97	375	126	24570	0

Table C - 8: Flow (Table 2 of 3)

Date	Upper Dosing Tank			
	Dose #	average gal/dose	cum flow (gal)	avg flow (gpd)
7/7/97	537	182	69020	545
7/8/97	540	181	69565	545
7/9/97	543	181	70109	544
7/10/97	547	181	70833	725
7/11/97	551	181	71557	724
7/12/97	556	180	72460	903
7/13/97	559	180	73001	541
7/14/97	563	180	73721	720
7/15/97	568	180	74620	899
7/16/97	574	179	75697	1077
7/17/97	579	179	76592	895
7/18/97	583	179	77308	715
7/19/97	588	178	78200	892
7/20/97	592	178	78913	713
7/21/97	595	178	79447	534
7/22/97	600	178	80335	889
7/23/97	604	177	81045	710
7/24/97	609	177	81931	886
7/25/97	613	177	82638	707
7/26/97	618	176	83521	883
7/27/97	621	176	84049	529
7/28/97	625	176	84754	704
7/29/97	631	176	85808	1054
7/30/97	636	175	86685	877
7/31/97	641	175	87560	875
8/1/97	645	175	88259	699
8/2/97	652	174	89479	1221
8/3/97	653	174	89654	174
8/4/97	655	174	90002	348
8/5/97	658	174	90523	522
8/6/97	662	173	91218	695
8/7/97	665	173	91738	520
8/8/97	669	173	92431	693
8/9/97	672	173	92949	519
8/10/97	674	173	93295	346

Date	Meter below wetland	
	reading (gal)	avg flow (gpd)
7/7/97	1323920	
7/8/97	1324280	360
7/9/97	1324750	470
7/10/97	1325270	520
7/11/97	1325790	520
7/12/97	1326470	680
7/13/97	1327120	650
7/14/97	1327980	860
7/15/97	1328780	800
7/16/97	1329930	1150
7/17/97	1331120	1190
7/18/97	1332120	1000
7/19/97	1333040	920
7/20/97	1333460	420
7/21/97	1333920	460
7/22/97	1334620	700
7/23/97	1335210	590
7/24/97	1335930	720
7/25/97	1336510	580
7/26/97	1337080	570
7/27/97	1337600	520
7/28/97	1339230	1630
7/29/97	1339470	240
7/30/97	1341280	1810
7/31/97	1343310	2030
8/1/97	1344160	850
8/2/97	1345870	1710
8/3/97	1346740	870
8/4/97	1347020	280
8/5/97	1347510	490
8/6/97	1348110	600
8/7/97	1349030	920
8/8/97	1349390	360
8/9/97	1349730	340
8/10/97	1350360	630

Table C - 9 : Flow (Table 3 of 3)

Date	Upper Dosing Tank			
	Dose #	average gal/dose	cum flow (gal)	avg flow (gpd)
8/11/97	675	173	93468	173
8/12/97	677	173	93813	345
8/13/97	679	172	94158	345
8/14/97	679	172	94158	0
8/15/97	680	172	94330	172
8/16/97	682	172	94675	345
8/17/97	688	172	95707	1032
8/18/97	692	172	96393	687
8/19/97	697	171	97250	857
8/20/97	701	171	97934	684
8/21/97	703	171	98276	342
8/22/97	704	171	98447	171
8/23/97	706	171	98788	341
8/24/97	711	170	99641	852
8/25/97	713	170	99981	340
8/26/97	714	170	100151	170
8/28/97	716	170	100491	170
8/31/97	724	169	101849	453
9/1/97	730	169	102864	1015
9/4/97	733	169	103371	169
9/7/97	746	168	105561	730
9/8/97	750	168	106232	672
9/9/97	751	168	106400	168
9/30/97	785	165	112063	270
7/22/98	1098	145	160650	165

Date	Meter below wetland	
	reading (gal)	avg flow (gpd)
8/11/97	1350360	0
8/12/97	1350560	200
8/13/97	1350650	90
8/14/97	1350650	0
8/15/97	1350650	0
8/16/97	1350730	80
8/17/97	1351630	900
8/18/97	1352120	490
8/19/97	1352790	670
8/20/97	1353240	450
8/21/97	1353510	270
8/22/97	1353520	10
8/23/97	1353670	150
8/24/97	1354260	590
8/25/97	1354470	210
8/26/97	1354590	120
8/28/97	1354610	10
8/31/97	1355690	360
9/1/97	1356620	930
9/4/97	1357120	167
9/7/97	1358770	550
9/8/97	1359480	710
9/9/97	1359570	90
9/30/97	1365850	299
7/22/98	3565.1	new meter

APPENDIX D: LAB DATA

Table D - 1: Biochemical Oxygen Demand (BOD_5)

Water Quality Variable: BOD_5 (mg/l)

Sampling Date	Monitoring Port: septic tank outlet (HI-02)	upflow filter outlet (HI-03)	wetland inlet (HI-04)	wetland outlet (HI-05)	Comments
10/22/96	457	309	293	214	G/GA: low bias
11/5/96	282	200	179	185	G/GA: low bias,BOD_6
11/19/96	285	182	156	95.4	
12/3/96	269	200	130	114	
1/14/97	425	265	189	143	high blanks: 10% positive bias
1/22/97	393	316	224	133	BOD_6, high blanks: 5% positive bias, HI-04 dup (222 mg/l)
1/28/97	447	392	330	170	
2/11/97	569	487	411	243	BOD_6
2/18/97	608	481	395	282	
2/25/97	551	407	366	275	High blanks: < 1% positive bias
3/11/97	363	338	400	438	
3/25/97	481	394	362	312	High blanks: < 5% positive bias
4/8/97	431	N/A	316	203	Improper dilutions made for HI-03
4/22/97	350	355	326	410	HI-05 dup (418 mg/l)
5/6/97	30.8	27.1	25.4	30	1 high blank
5/20/97	>300	356	256	27.2	For HI-2 and HI-5: Sample depleted at all dilutions, reported minimum.
6/3/97	270	257	242	204	HI-05 dup (193 mg/l)
6/17/97	314	328	155	239	High blanks: < 30% positive bias
7/1/97	459	373	280	247	HI-03 dup (357 mg/l)
7/15/97	348	309	260	164	Low G/GA: no bias.
7/30/97	351	317	291	170	HI-04 dup (289 mg/l)
8/12/97	310	226	168	107	HI-03 dup (211 mg/l), Low G/GA: no bias.
8/26/97	354	276	172	110	BOD_6
9/9/97	301	246	141	187	High blanks due to low temp (19.2 vs. 20 C), lab splits w/in <7%

Notes:

1. G/GA: Glucose/Glutamic acid check
2. BOD_6: 6-day incubation vs. 5-day standard
   (lab testing indicates an expected positive bias of < 5%)
3. High dilution water blanks (>0.2 mg/l standard)
4. Standard to report results for dilutions with depletion < 2 mg/l

(Samples analyzed by the EPA Region VIII Lab in Lakewood, CO)

Table D - 2: Total Suspended Solids (TSS)

Water Quality Variable: TSS (mg/l)

Sampling Date	Monitoring Port septic tank outlet (HI-02)	upflow filter outlet (HI-03)	wetland inlet (HI-04)	wetland outlet (HI-05)	Comments
10/22/96	190	36	45	18	lab split w/in < 5%
11/5/96	95	19	22	5	lab splits w/in < 13%
11/19/96	66	20	20	7	lab split w/in < 6%
12/3/96	69	28	17	<4	lab split w/in <12%
1/14/97	186	48	31	4	lab split w/in < 3%
1/22/97	61	34	19	<4	HI-04 dup (23 mg/l), lab split w/in < 7%
1/28/97	37	28	25	13	lab split w/in < 5%
2/11/97	86	108	84	52	lab split w/in < 1%
2/18/97	69	46	40	34	lab split w/in < 18%
2/25/97	61	38	40	35	lab split w/in < 9%
3/11/97	27	33	5	61	lab split w/in < 7%
3/25/97	54	36	36	8	lab split w/in <12%
4/8/97	60	44	30	23	lab split w/in <15%
4/22/97	42	41	31	25	HI-05 dup (27 mg/l), lab split w/in <5%
5/6/97	6	9	6	6	lab split w/in < 5%
5/20/97	78	42	28	8	lab split w/in < 9%
6/3/97	27	18	27	< 4	HI-05 dup (4 mg/l), lab split w/in < 15%
6/17/97	71	64	49	4	
7/1/97	65	61	200	11	HI-03 dup (66 mg/l), lab split w/in <19%
7/15/97	51	38	35	8	lab split w/in < 7%
7/30/97	47	29	32	14	HI-04 dup (31 mg/l), lab split w/in < 16%
8/12/97	39	21	22	11	HI-03 dup (42 mg/l), lab split w/in <14%
8/26/97	38	25	16	6	lab split w/in < 12%
9/9/97	65	56	8	46	lab split w/in < 9%

(Samples analyzed by the EPA Region VIII Lab in Lakewood, CO)

Table D - 3: Total Organic Carbon (TOC)

Water Quality Variable: TOC (mg/l)

Sampling Date	Monitoring Port: septic tank outlet (HI-02)	upflow filter outlet (HI-03)	wetland inlet (HI-04)	wetland outlet (HI-05)	Comments
10/22/96	130	143	144	101	high blank: <10% bias, HI-05 dup (106 mg/l)
11/5/96	118	113	108	103	high blank: <10% bias, lab split w/in <6%
11/19/96	150	114	103	78.2	high blank: <10% bias, HI-04 dup (104 mg/l), lab splits w/in <5%
12/3/96	156	128	88.1	95.2	high blank: <10% bias
1/14/97	132	123	102	86.6	high blank: <10% bias, lab split w/in <2%
1/22/97	163	150	112	87.5	high blank: <10% bias
1/28/97	163	155	148	94.1	high blank: <10% bias, lab split w/in <5%
2/11/97	229	216	181	130	lab split w/in <2%
2/18/97	309	272	226	152	HI-04 dup (222 mg/l), lab split w/in <2%
2/25/97	267	221	199	163	lab split w/in 3%
3/11/97	196	190	214	236	lab split w/in <2%
3/25/97	227	207	179	151	lab split w/in 3%
4/8/97	234	216	182	120	HI-03 dup (215 mg/l), lab split w/in <6%
4/22/97	145	154	142	172	lab split w/in <3%
5/6/97	25.5	23.7	23.2	25.0	lab split w/in <3%
5/20/97	210	170	141	30.4	lab split w/in <3%
6/3/97	142	139	134	113	
6/17/97	159	154	138	117	lab split w/in <1%
7/1/97	207	171	133	112	lab split w/in <4%
7/15/97	175	170	142	102	HI-03 dup (165 mg/l)
7/30/97	191	180	167	108	lab split w/in <5%
8/12/97	180	134	102	78	
8/26/97	177	148	97.5	72	HI-02 dup (173 mg/l), lab split w/in <1%
9/9/97	134	129	66.1	91	HI-05 dup (63.3 mg/l)

(Samples analyzed by the EPA Region VIII Lab in Lakewood, CO)

Table D - 4: Ammonia/Ammonium (NH_3/NH_4^+-N)

***Water Quality Variable:** NH_3/NH_4-N (mg/l)*

Sampling Date	Monitoring Port: septic tank outlet (HI-02)	upflow filter outlet (HI-03)	wetland inlet (HI-04)	wetland outlet (HI-05)	Comments
10/22/96	61.7	57.6	58	52.1	HI-05 dup (51.7 mg/l)
11/5/96	59.9	62.1	61.9	53.6	
11/19/96	46.5	45.4	52.2	52.5	HI-04 dup (52.7 mg/l)
12/3/96	40.2	45.3	45.7	56.3	
1/14/97	35.4	36.5	36.3	53.3	lab split w/in <1%
1/22/97	28.8	30.6	34.4	46.4	
1/28/97	32	31.6	32.3	48.3	lab split w/in <2%
2/11/97	34.6	35.3	37.8	43	lab split w/in <1%
2/18/97	33.7	38.5	38.4	42.2	HI-04 dup (37.4 mg/l), lab split w/in <3%
2/25/97	35.6	34.8	37.1	39.8	lab split w/in <2%
3/11/97	40.2	44.2	46.3	48.4	
3/25/97	24.2	34.0	33.6	36.7	
4/8/97	22.4	25.8	30.6	29.8	HI-03 dup (26.5 mg/l)
4/22/97	15.0	17.5	18.7	29.2	
5/6/97	0.76	0.77	1.06	4.37	
5/20/97	19.9	21.8	19.5	5.94	lab split w/in <7%
6/3/97	22.9	25.4	29.4	21.4	lab split w/in <5%
6/17/97	48.1	51.4	47.5	35.4	
7/1/97	26.5	25.2	25.6	28.3	lab split w/in <1%
7/15/97	51.4	60.3	61.4	40.7	HI-03 dup (58.5 mg/l), lab split w/in <1%
7/30/97	63.8	65.7	63.0	42.5	
8/12/97	39.6	67.6	41.4	50.5	
8/26/97	55.8	52.8	39.6	47.8	HI-02 dup (53.5 mg/l)
9/9/97	58.5	51.1	40.9	51.0	HI-05 dup (40.6 mg/l)

(Samples analyzed by the EPA Region VIII Lab in Lakewood, CO)

Table D - 5: Nitrite/Nitrate (NO_2^-/NO_3^-)

Water Quality Variable: NO_3/NO_2-N (mg/l)

Sampling Date	Monitoring Port				Comments
	septic tank outlet (HI-02)	upflow filter outlet (HI-03)	wetland inlet (HI-04)	wetland outlet (HI-05)	
10/22/96	< 0.05	< 0.05	< 0.05	< 0.05	HI-05 dup (same)
11/5/96	< 0.05	< 0.05	< 0.05	< 0.05	
11/19/96	<0.05	< 0.05	< 0.05	< 0.05	HI-04 dup (same)
12/3/96	<0.05	<0.05	<0.05	<0.05	
1/14/97	<0.05	<0.05	<0.05	<0.05	
1/22/97	<0.05	<0.05	<0.05	<0.05	
1/28/97	<0.05	<0.05	<0.05	<0.05	
2/11/97	<0.05	<0.05	<0.05	<0.05	
2/18/97	<0.05	<0.05	<0.05	<0.05	HI-04 dup (same)
2/25/97	<0.05	<0.05	<0.05	<0.05	
3/11/97	<0.05	<0.05	<0.05	<0.05	
3/25/97	<0.05	<0.05	<0.05	<0.05	
4/8/97	<0.05	<0.05	<0.05	<0.05	HI-03 dup (same)
4/22/97	<0.05	<0.05	<0.05	<0.05	
5/6/97	1.86	0.37	0.15	<0.05	
5/20/97	<0.05	<0.05	<0.05	<0.05	
6/3/97	<0.05	<0.05	<0.05	<0.05	
6/17/97	<0.05	<0.05	<0.05	<0.05	
7/1/97	<0.05	<0.05	0.14	<0.05	
7/15/97	<0.05	<0.05	0.33	<0.05	HI-03 dup (same)
7/30/97	<0.05	<0.05	<0.05	<0.05	
8/12/97	<0.05	0.12	0.05	<0.05	
8/26/97	<0.05	<0.05	<0.05	<0.05	HI-02 dup (same)
9/9/97	<0.05	<0.05	<0.05	<0.05	HI-05 dup (same)

(Samples analyzed by the EPA Region VIII Lab in Lakewood, CO)

Table D - 6: Total Phosphorus (TP)

Water Quality Variable: Total Phosphorus (mg/l)

Sampling Date	Monitoring Port				Comments
	septic tank outlet (HI-02)	upflow filter outlet (HI-03)	wetland inlet (HI-04)	wetland outlet (HI-05)	
10/22/96	8.55	8.18	8.01	8.31	HI-05 dup (8.51 mg/l)
11/5/96	7.74	7.2	7.17	7.61	
11/19/96	5.57	5.17	5.23	6.24	High spike recovery, HI-04 dup (4.98 mg/l)
12/3/96	5.07	4.68	2.94	5.92	High spike recovery
1/14/97	5.63	3.59	3.13	4.33	
1/22/97	5.12	4.41	3.21	3.18	
1/28/97	5.46	4.89	4.35	2.98	lab split w/in 1%
2/11/97	7.2	6.06	4.48	3.15	
2/18/97	7.78	6.29	5.23	3.77	HI-04 dup (5.10 mg/l), lab split w/in <8%
2/25/97	6.68	5.39	4.80	3.79	lab split w/in <5%
3/11/97	5.46	6.01	6.71	6.85	
3/25/97	6.93	6.30	6.07	5.44	
4/8/97	7.5	6.98	6.09	4.81	HI-03 dup (7.07 mg/l)
4/22/97	3.02	3.34	3.23	3.56	
5/6/97	0.28	0.24	0.26	0.47	
5/20/97	5.65	4.41	3.78	0.5	lab split w/in <2%
6/3/97	5.67	5.49	5.73	4.28	lab split w/in 3%
6/17/97	7.45	7.00	6.48	5.87	
7/1/97	6.17	5.83	5.31	4.62	lab split w/in <1%
7/15/97	6.60	6.34	5.52	5.36	HI-03 dup (6.15 mg/l), lab split w/in <2%
7/30/97	8.01	7.65	7.18	6.20	lab split w/in <3%
8/12/97	7.18	5.75	5.54	5.35	lab split w/in <1%
8/26/97	6.07	5.63	5.22	4.11	HI-02 dup (6.19 mg/l), lab split w/in <3%
9/9/97	6.99	6.51	5.06	6.15	HI-05 dup (5.07 mg/l)

Notes:

1. High spike recovery due to spike value being less than 10% of sample value. Acceptable blank spike indicates spiking technique and spike concentration are acceptable.

(Samples analyzed by the EPA Region VIII Lab in Lakewood, CO)

Table D - 7: Fecal Coliforms (FC)

Water Quality Variable: Fecal Coliform (#/100 ml) [1]

Sampling Date	Monitoring Port				Comments[2]
	septic tank outlet (HI-02)	upflow filter outlet (HI-03)	wetland inlet (HI-04)	wetland outlet (HI-05)	
10/22/96	320,000	26,000	680,000	180,000	EPA, lab split w/in <8% (limit is 20%)
11/5/96	N/A	N/A	N/A	N/A	EPA: FC not analyzed, holding period > 9 hrs
11/19/96	23,000	280,000	11,000	1,700	EPA
12/3/96	455,000	140,000	70,000	350	Agro-Enviro
1/14/97	9,000	7,500	6,700	3,600	EPA, lab split w/in <6% (limit is 20%)
1/28/97	300,000	350,000	420,000	5,500	EPA, lab split w/in <9% (limit is 20%)
2/11/97	190,000	85,000	112,000	81,000	EPA
2/18/97	41,000	52,000	66,000	260,000	EPA: HI-05 field dup: FC = 90,000/100 ml
3/25/97	655,000	250,000	43,200	13,500	Agro-Enviro
4/8/97	275,000	485,000	93,500	24,000	Agro-Enviro
5/6/97	8,000	5,300	11,000	1,500	CSU Env. Quality
6/3/97	440,000	260,000	<10,000	280,000	CSU Env. Quality
6/17/97	1,100,000	270,000	180,000	2,000	CSU Env. Quality
7/1/97	600,000	550,000	5,000	140	CSU Env. Quality
7/15/97	1,800,000	1,400,000	1,100,000	40,000	CSU Env. Quality
7/30/97	1,200,000	400,000	500,000	100,000	CSU Env. Quality
8/12/97	120,000	100,000	50,000	<10,000	CSU Env. Quality
8/26/97	460,000	130,000	220,000	10,000	CSU Env. Quality
9/9/97	520,000	330,000	440,000	8,000	CSU Env. Quality

Notes:

1. Values reported for fecal coliforms are not absolute numbers; Standard (1992) provides equations for calculating 95% confidence limits.
2. Samples analyzed by either the EPA Region VIII Lab, Agro-Enviro Consultants, or the CSU Environmental Quality Lab with EPA Region VIII funding as noted.

Table D - 8: Septic Tank Sludge

Sampling Date: 5/20/97

Monitoring Variable (mg/l)	Sludge			Comments
	Septic Tank Compartment			
	1st (HI-1a)	2nd (HI-1b)	3rd (HI-1c)	
BOD_5	10200	5150	1350	DO depletion < 2 mg/l for HI-1b and HI-1c at all dilutions. Value estimated.
TSS	12830	19700	6150	lab split w/in < 3%
VSS	11500	13300	4200	lab split w/in < 2%
NH_3/NH_4^+-N	34.1	67.7	38.8	
NO_2^-/NO_3^--N	0.2	0.21	< 0.05	
TP	26.9	228	68.6	lab split w/in < 1%

(Samples analyzed by the EPA Region VIII Lab in Lakewood, CO)