EVALUATION OF A SUBSURFACE FLOW WETLAND PROCESSING SEWAGE FROM THE SEVILLETA LTER* FIELD STATION

By

Eleonora H. Trotter
Principal Investigator
Department of Biology
The University of New Mexico

Bruce Thomson
Principal Investigator
Department of Civil Engineering
The University of New Mexico

Ross Coleman
Co-Principal Investigator
Hydra Aquatic Ecology
Tijeras, New Mexico

TECHNICAL COMPLETION REPORT

Account Number 1423948

June 1994

New Mexico Water Resources Research Institute
in cooperation with

The Department of Biology
and
The Department of Civil Engineering
The University of New Mexico

The research on which this report is based was financed in part by the U.S.Department of the Interior, Geological Survey, through the New Mexico Water Resources Institute and by the Chino Mines Company Grant Fund.

* The Sevilleta Long Term Ecological Research site is one of 18 in North America, Puerto Rico, and Antarctica funded by the National Science Foundation.

DISCLAIMER

The purpose of Water Resources Research Institute technical reports is to provide a timely outlet for research results obtained on projects supported in whole or in part by the Institute. Through these reports, we are promoting the free exchange of information and ideas and hope to stimulate thoughtful discussion and actions that may lead to resolution of water problems. The WRRI, through peer review of draft reports, attempts to substantiate the accuracy of information contained in its reports, but the views expressed are those of the author(s) and do not necessarily reflect those of the WRRI or its reviewers. Contents of this publication do not necessarily reflect the views and policies of the U.S. Department of the Interior, nor does mention of trade names or commercial products constitute their endorsement by the United States government.

ACKNOWLEDGEMENT

We thank the Campbell Family who donated their 225,000 acre ranch to the Nature Conservancy to be used strictly for ecological research. We thank the U.S. Fish and Wildlife Agency which administers this land for permission to construct a wetland to filter sewage from a new field research station, and the National Science Foundation for permission to add the constructed wetland to the research field-station which it funded as part of the Sevilleta Long Term Ecological Research Site. The Sevilleta LTER is part of an 18-site long-term ecological research network in North America, Puerto Rico and Antarctica. We thank the New Mexico Environment Department and Sandoval County for granting a permit to construct this experimental subsurface flow wetland, and the University of New Mexico (UNM) for permission to add the constructed wetland to their field station's septic tanks and drain field. Engineer Jeff Mortinson added our plans to the field-station drawings.

Students at UNM helped with plumbing, collecting wetland plants from La Joya State Game Refuge and Bosque Del Apache National Wildlife Refuge, planting the three cells of the wetland, and collecting and analyzing data. As an undergraduate, Ms. Fiona Jordan assisted us in the preparation of the wetland cells and data collection. She is now a graduate student in ecological microbiology at UNM's Department of Biology. Mr. Keet D'Arms, a junior at UNM, assisted in construction, data collection, laboratory analysis, and computer data entry between as an entering freshmen at UNM.

Thanks also to Mr. John Craig for nitrogen analysis and to Mr. John DeWitt for sampling in October of 1992 and periodically checking water levels in the wetland cells.

Dr. Trotter thanks her colleagues Mr. Coleman, and Dr. Thomson, WRRI staff responsible for administering this grant, and Ms. Ann Powell, Office of Research Administration at UNM. Dr. Thomson provided Dr. Trotter the use of his laboratory and many supplies gratis, and served on this project without compensation from its inception through the preparation of this report. The authors thank Catherine Ortega Klett for a thorough editorial review and three anonymous technical reviewers whose comments and questions improved the quality of this report substantially. A final great thanks to Ms. Anne Rice for making this report photo-ready; she edited with wisdom and style.

ABSTRACT

A wetland was constructed in the fall, 1991 to evaluate the performance of a three-cell subsurface-flow constructed wetland containing various species of emergent aquatic plants for treating domestic wastewater. These were: 1) a multiculture, 2) a reed monoculture, and 3) a bulrush monoculture. Wetland cells were fed by two septic tanks of the Sevilleta Long Term Ecological Research Field Station near Socorro, New Mexico. Biochemical oxygen demand, total and fecal coliform bacteria, total Kjeldahl Nitrogen, NH_3, and NO_3^- were measured. Wastewater from the septic tank and from the wetland cells was discharged to the ground through a conventional absorption field divided in half. The wetland cell system was constructed to allow sample collection from septic tank wastewater entering, midway, and at the end of each cell. Water samples also were collected from the septic and wetland drainfields. Water quality from the wetlands was substantially better than in the drainfield receiving water from the septic tank directly. In May 1992 and 1993 the field station population increased from three or four people to 25 for summer research. Following startup of the wetland, effluent water quality rapidly improved. However, at the beginning of each research season effluent quality dropped, then subsequently improved as each cell acclimated to the increased hydraulic and organic loadings. Based on ranked data, the multiculture performed best of the three cells, which may be the result of a variety of plant-microbial associations in this channel opposed to a more limited plant-microbial association in the two monocultures.

Key Words: Subsurface-flow constructed wetland, sewage treatment, biochemical oxygen demand, fecal coliform, total coliform, nitrogen, aquatic ecosystems, microbial/plant interactions, marsh plants, multiculture, *Phragmites*, *Scirpus*, *Typha*, reed, bulrush, cattail.

TABLE OF CONTENTS

LIST OF FIGURES

FIGURE **PAGE**

LIST OF TABLES

INTRODUCTION

The Problem

Groundwater and surface-water contamination has become a critical problem in the southwestern United States partially due to rapid development, particularly in rural areas not served by wastewater collection and treatment facilities (Grisham et al. 1991). Along the Rio Grande basin of central New Mexico both groundwater and surface-water resources have been contaminated by inappropriate on-site wastewater treatment and disposal systems. Local and regional contamination results from excessive discharges to groundwater, failing absorption fields due to poorly designed and operated treatment systems and inappropriate soil hydraulic characteristics. Fecal coliform have been found commonly in drinking water wells contaminated by septic tank-septic drainfield effluents. Additional groundwater quality problems associated with on-site treatment and disposal systems are either high concentrations of nitrate (NO_3^-) in highly aerobic subsurface environments, or high concentrations of ammonia, iron, manganese, and sulfides produced under organically overloaded subsurface systems with anaerobic conditions. These latter constituents are not regulated drinking-water parameters, but are considered pollutants because they cause aesthetic problems associated with taste, odor, and staining of laundry and plumbing fixtures.

In the next decade, ground water contamination is likely to increase. Those people native to in the Southwest along with newcomers from other parts of the country where water is abundant, often are unfamiliar with the beauty and economy of xeriscaping with native plants. Many make excessive use of pesticides and herbicides without recognizing their profound effects on water quality. With rapidly growing populations, cities like Albuquerque encourage industrial development without taking into account the industry's effect on the area's water supply and water quality. At the same time, there is growing concern for preserving the right to water quantity and water quality. As an example,

Albuquerque recently negotiated with the Pueblo of Isleta over water quality standards in the Rio Grande. The standards proposed by the Pueblo would require effluent standards from the Southside Water Reclamation Plant that are, in several cases more stringent than drinking water standards. Before negotiations, it was estimated that a $250 million sewage plant expansion, resulting in an increase in residential water and wastewater costs of $10 per household per month might be required (Norm Gaume, City of Albuquerque Engineering Department, personal communication, March 6, 1994), if EPA's draft permit based on the Isleta standards were to be enforced. The City considered the use of constructed wetlands as one alternative treatment process to meet potential discharge requirements.

New Mexico's rural population is growing. These rural areas often have no wastewater collection and treatment and rely upon on-site wastewater treatment and disposal methods. Currently no water quality standards exist for discharge of residential wastewater to groundwater of less than 2,000 gpd (gallons per day), in New Mexico. Some areas within the rapidly growing east mountain area near Albuquerque are unsuitable for conventional treatment and disposal systems because of inadequate soil conditions for proper use of absorption fields. For example in some areas, soil thinly coats a limestone substrate either forcing the water back to the surface or through rock fractures into groundwater. People living in rural settings or small older communities often cannot afford sewers or a full sewage treatment plant. They are then faced with the possibility of polluting their drinking water. Therefore it is important to test simple, comparatively low-cost, low-maintenance alternative sewage treatment methods in New Mexico (Brewer 1991). Constructed wetlands offer such a method for urban, suburban, and rural settings in New Mexico.

Study Objectives

This study evaluated the performance of a subsurface flow constructed wetland or SFS wetland (Metcalf and Eddy 1991) for on-site wastewater treatment and disposal in central New Mexico and compared this method with a conventional septic tank and absorption field system. A subsurface flow constructed wetland is a lined wetland filled with gravel in which emergent marsh plants rooted in the gravel substrate provide improved wastewater treatment (Cooper 1993). Settled wastewater from a septic tank or other pretreatment process, passes under a gravel surface and is purified by the microbial community living around the roots of the wetland plants as well as on rock surfaces underwater. The plants' root systems provide oxygen and a surface to which the microorganisms can attach themselves and microbes convert nutrients such as nitrogen into a form plants take up and use to grow (Armstrong 1964, 1978). The gravel also provides substrate for microbial attachment. Up to ten percent removal of nutrients may also be provided through uptake of nitrogen and phosphorous by wetland plants (Wetzel 1993).

This wastewater-treatment method offers a comparatively inexpensive, low-maintenance method of wastewater purification which depends on the natural ability of marsh plants and their microbial associates to clean water (Brix 1987, 1993a, b; Conley et al. 1991). Certain plant-microbial associations have been shown to purify water of non-domestic pollutants as well (Shutes et al. 1993). The combination of anaerobic/aerobic environments in wetlands as well as physical adsorption to marsh soils and plant uptake has been used successfully to clean up for mine tailings (Smith et al. 1988). Finally, it may be possible to tailor the plant/microbial associations in constructed wetlands. Some microorganisms, for example, contain enzymes for the breakdown of specific compounds (Hatano et al. 1993). It may even be possible to inoculate wetland with pre-acclimated microorganisms with the capacity to breakdown constituents in a particular wastewater.

BACKGROUND

The Theory of Constructed Wetlands and Review of Recent Literature

Since their inception in the 1970s the use of constructed wetlands for municipal, small community, individual business and residential sewage treatment has grown exponentially (Bastian 1990; Gearheart 1990; Hammer 1989; Moshiri 1993; Wilhelm et al. 1990; Wolverton and McDonald 1979).

There are two general types of constructed wetlands used to treat wastewater: free water surface (FWS) and subsurface flow (SFS) systems (Hammer 1989; Moshiri 1993; U.S. EPA 1988, U.S. EPA 1993). Both require that the wastewater receive primary treatment to remove settleable solids. Free water surface wetlands (FWS) contain open water out of which grow emergent aquatic plants such as cattail, reed, and bulrush. These plants are rooted in soil at the bottom of the wetland. A FWS wetland requires a larger surface area than the SFS wetland and is best suited for areas where there is controlled access to prevent human exposure to pathogens. The SFS wetland has no open water. Instead, emergent plants are rooted in a gravel bed through which wastewater flows several inches below the gravel surface. It eliminates odors and protects animals and people from exposure to pathogens. Wildlife are also attracted to the marsh plants growing in this constructed wetland for food and cover. Both types of wetlands are built as a cell or group of cells, in parallel or in series. These channels are dug in the earth and lined with impervious material such as several forms of plastic such as PVC (polyvinylchloride), HDPE (high density polyethylene), polypropylene, or clay.

The functioning of either type of constructed wetland is based on the symbiotic relationship which has evolved between aquatic plants and the microbial community (bacteria, actinomycetes, and fungi) living with these plants in natural marshes (Gunnison and Barko 1989; Hatano et al. 1993; McKee et al. 1989). Marsh plants like cattail (*Typha*), bulrush (*Scirpus*) and reed (*Phragmites*) are

rooted in anaerobic soil at the bottom of a marsh. The plants have evolved air spaces in their leaves, stems, and roots which provide a pathway for oxygen absorbed through stomates (openings) in leaves. Oxygen is drawn down through the plant following an oxygen gradient created by growing and dividing fine plant root cells (Armstrong 1978). Root cells leak oxygen into the area immediately around the roots called the "rhizosphere" (Brix 1987). This area contains oxygen as the roots grow and extend into the anaerobic marsh soil. The rhizosphere also is inhabited by a microbial community (Gunnison and Barko 1989) which uses the plant roots as substrate and the oxygen the roots give off to convert and incorporate some nitrogen and other nutrients from the water for their growth as well as the growth of their plant hosts (Hatano et al. 1993). Nitrogen is removed from the system mainly through nitrification and denitrification by microorganisms (Brix 1993a, b). Microbial activity also may convert metals to insoluble forms that precipitate in the gravel matrix of a constructed wetland (Wolverton 1987).

In natural marsh soils, substances are removed through filtration, sorption, precipitation and sedimentation into void spaces in the soils (Brix 1987; Reed et al. 1988; Reed and Crites 1984). If the marsh's soil is fine, there is low hydraulic conductivity (water moves through slowly), and if it is coarse, there is high hydraulic conductivity (water moves through rapidly). Plants exude various compounds including sugars which are useful to their microbial associates. Around the plant roots is an oxygenated zone surrounded by an anoxic zone. Conversion of nitrogen in ammonia (NH_3) to nitrogen in nitrate (NO_3^-), and subsequently to nitrogen gas (N_2), through nitrification and denitrification reactions, occurs at the border between the oxygenated rhizosphere and the surrounding anoxic substrate in which aquatic plants are rooted (Armstrong 1978; Dahm et al. 1987). Pathogenic organisms in waste-water are removed through dieoff from unfavorable environmental conditions, sorption and filtration in soils, predation by microorganisms, and in a FWS wetland exposure to ultraviolet light (Reed et al. 1988).

Understanding of the plant-microbial relationship in a natural marsh is necessary to design their working relationship in a constructed wetland (Trotter et al. 1990; Wetzel 1993). Important design considerations include 1) the porosity of the substrate which determines the speed with which the water moves through the plant root zone (hydraulic conductivity) and the potential for plugging of this zone, and 2) the relationship between the depth of the constructed wetland and the rooting depth of emergent plants. Generally, a gavel substrate with mean diameters of two to four inches in a constructed wetland is reported (Brix 1987).

The three most commonly used emergent plants—cattail, reed, and bulrush in SFS wetlands are often planted as a monoculture in a single cell. Each of these plants can have a different rooting depth: 12 inches for cattail, 18 inches for reed, and 24 inches for bulrush reported by Stengel (1993) which suggests that their use together may provide more conversion of pollutants to nutrients for the plants and microbial community if their roots are occupying different levels of the wetland. Table 1 shows the range of removal rates for SFS wetlands in the United States and Europe (Conley et al. 1991).

Table 1. Reported removal rates of pollutants from water in subsurface flow wetlands.

1)	Biochemical oxygen demand	64-96%
2)	Total Nitrogen	24-61%
3)	Ammonia	57-94%

Nitrogen removal through volatilization, filtration of particulate nitrogen, and plant uptake were not considered significant by Gersberg (1986). However, Reedy and DeBusk (1987) reported a substantial amount of nitrogen was removed by plants and suggested a plant harvesting regime in a SFS wetland which increased removal of nitrogen (floating plant systems are harvested regularly; Hammer 1989). These systems are considered easy to maintain and not as expensive to install as a conventional sewage treatment system at the small-community scale (Choate et al. 1993; Green and Upton 1993; Steiner and Combs 1993; Steiner et al. 1993).

Such simple sewage treatment systems are desirable in the rapidly growing Southwest, but since water is a scarce resource here, it is necessary to evaluate the trade-offs in using such a system. For example, the SFS wetland is encouraged in Bernalillo County because it minimizes exposure of people and animals to pathogens which may be present in the wastewater. Of equal importance in the arid Southwest, the SFS system loses less water through evapotranspiration than would a FWS wetland and is less likely to freeze in cold climatic zones in New Mexico (Levkin et al. 1993).

Special Considerations for Using Constructed Wetlands in New Mexico

Two related environmental factors are important to consider in the functioning of constructed wetlands in New Mexico: temperature and water loss.

Most constructed wetlands are found in the southern third of the country because the climate is usually warm enough for a long growing season (Reed 1990). Although there are constructed wetlands in Alaska, Minnesota, South Dakota, and Michigan (Dornbush 1993), they are more complicated to build and operate where due to freezing temperatures over an extended period of the year. In the Southwest, constructed wetlands are operating successfully at high elevations such as the Mogollon Rim at Show Low, Arizona (7,000 ft; Wilhelm et al. 1990), in Santa Fe (7,500 ft) and Albuquerque at 5,000 ft (Andrews 1990; Ogden 1990), and in the Manzano Mountains near

Albuquerque at 7,750 ft (Coleman 1994). During the winter, thermal storage by soil mass, warmer effluent from underground septic tanks, and snow and mulch cover prevent freezing (Coleman 1994).

Constructed wetlands also can operate where it is hot and dry. An SFS wetland is operating in Mesquite, Nevada (Levkin et al. 1993). There is a FWS wetland in Abiqui, New Mexico, at Ghost Ranch (Coleman 1994) and the Village of Los Ranchos de Albuquerque has a subsurface flow wetland serving its village hall (Coleman 1994). More than 30 constructed wetlands, nest serving private residences have been identified in the Bernalillo County area of Central New Mexico (Martin 1994).

Plants in both FWS and SFS wetlands lose water through evapotranspiration as they metabolize and grow, but less opportunity to freeze and less evaporation from the surface of a SFS wetland are two important considerations for their use in the mountains and colder parts of New Mexico, as well as in the dry, hot lowland areas of the state. Both the FWS and SFS wetlands have been permitted by the New Mexico Environment Department.

EXPERIMENTAL PROGRAM

Design of the Sevilleta Subsurface Flow Constructed Wetland

Description of Sevilleta Field Station and Occupancy

The Sevilleta Long-Term Ecological Research Site Field Station is on the Sevilleta National Wildlife Refuge north of Socorro, New Mexico (Figure 1). This research station has a highly variable occupancy. Between September and March the LTER field station coordinator lives at the field station while research scientists, LTER staff members, visitors and occasional groups visit the station periodically. From late spring through fall considerable research activity occurs with the residences and field laboratory filled to capacity. Approximately 25 people lived at the station from May 18-August 30, 1992, and 25 people in June 1993.

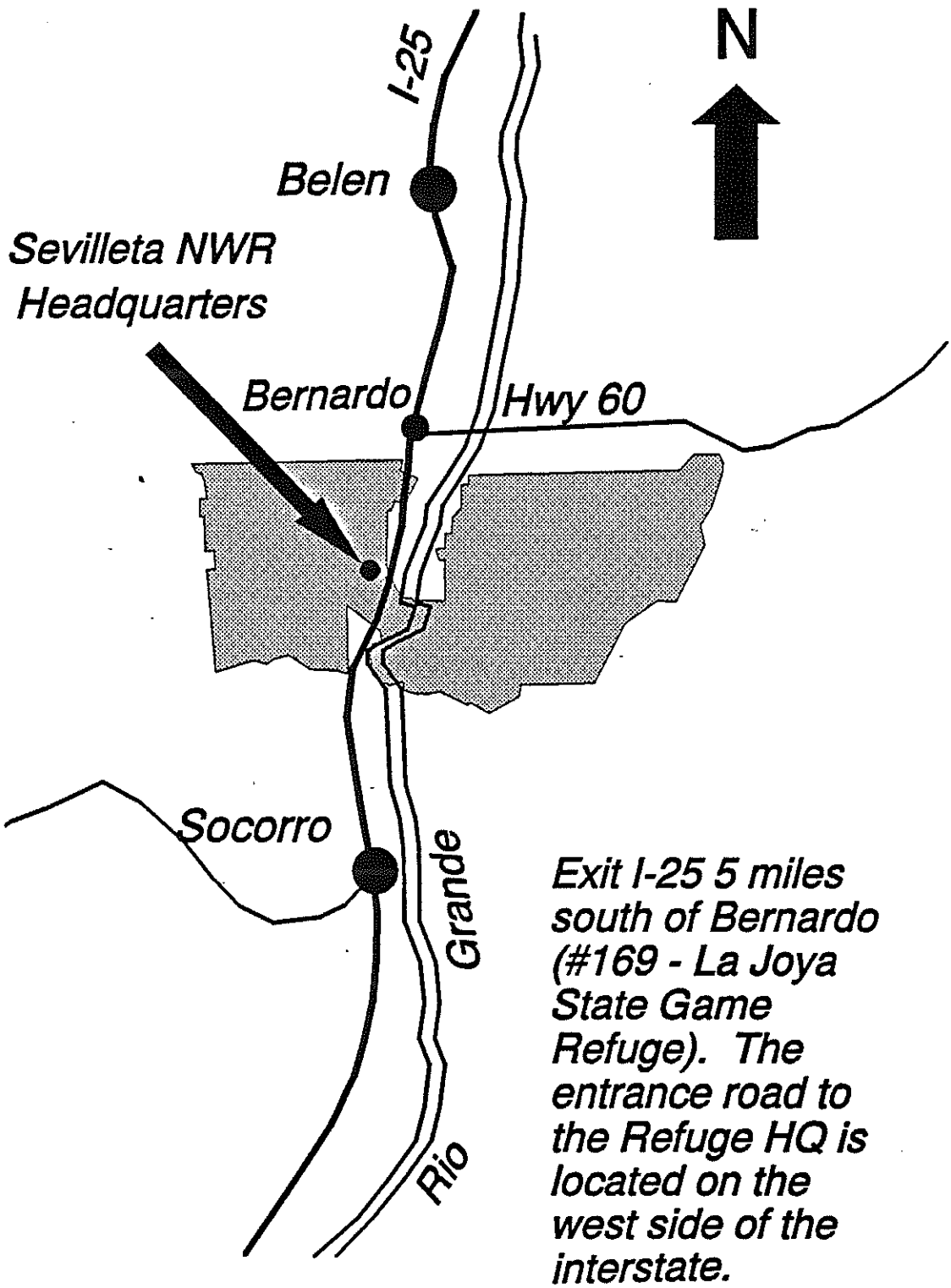

Figure 1. The Sevilleta National Wildlife Refuge north of Socorro and Sevilleta Long-Term Ecological Research Field Station

Water Use and Expected Flows

Design flows for the field station were based on expected use of the five residences with three bedrooms each. Normal full capacity is 25 persons. At 75 gallons per person per day, a design flow of approximately 1,875 gpd (gallons per day) was established. Occasionally more than 25 people used the facility simultaneously. Wetland cells were designed to handle the entire flow if necessary, but experimental procedures initially called for the flow to be split evenly between the wetland channels and the standard drainfield which serves the septic tank directly.

Description of the Septic System, Wetland Channels, and Divided Drainfield

Figure 2 is the general layout of the wastewater system at the Sevilleta station. The system consists of two fiber-glass septic tanks in series: 1,000 gallons and 2,000 gallons. Effluent from the septic tanks flows into a splitter box which divides flow between the constructed wetland and the drainfield (the normal mode of operation). The standard drainfield is divided in half, and the movement of water in these two sections is separated by two additional splitter boxes. This setting can be changed depending on the station's future needs. Half the entire drainfield receives flow directly from the septic tank and is referred to as the "septic drainfield." The other half of the drainfield receives the entire flow from the three wetland cells and is referred to as the "wetland drainfield." The splitter boxes within the drainfield allow opening of the drainfield completely to either the septic tank or wetland effluent. This option was not used during the experimental period.

The drainfield consists of three 100-foot-long channels 3 feet wide and approximately 4 feet deep. A one-foot layer of 3/4" to 2" river gravel was placed in the bottom of the trenches below and around the 4" perforated drainfield pipe. The gravel was covered with rosin paper and backfilled with soil. One-inch PVC tubes were placed vertically into each of six plastic tubs filled with the drainfield gravel into which water from the perforated drain pipes could seep. These PVC tubes reached above grade and were fitted with removable caps for sampling.

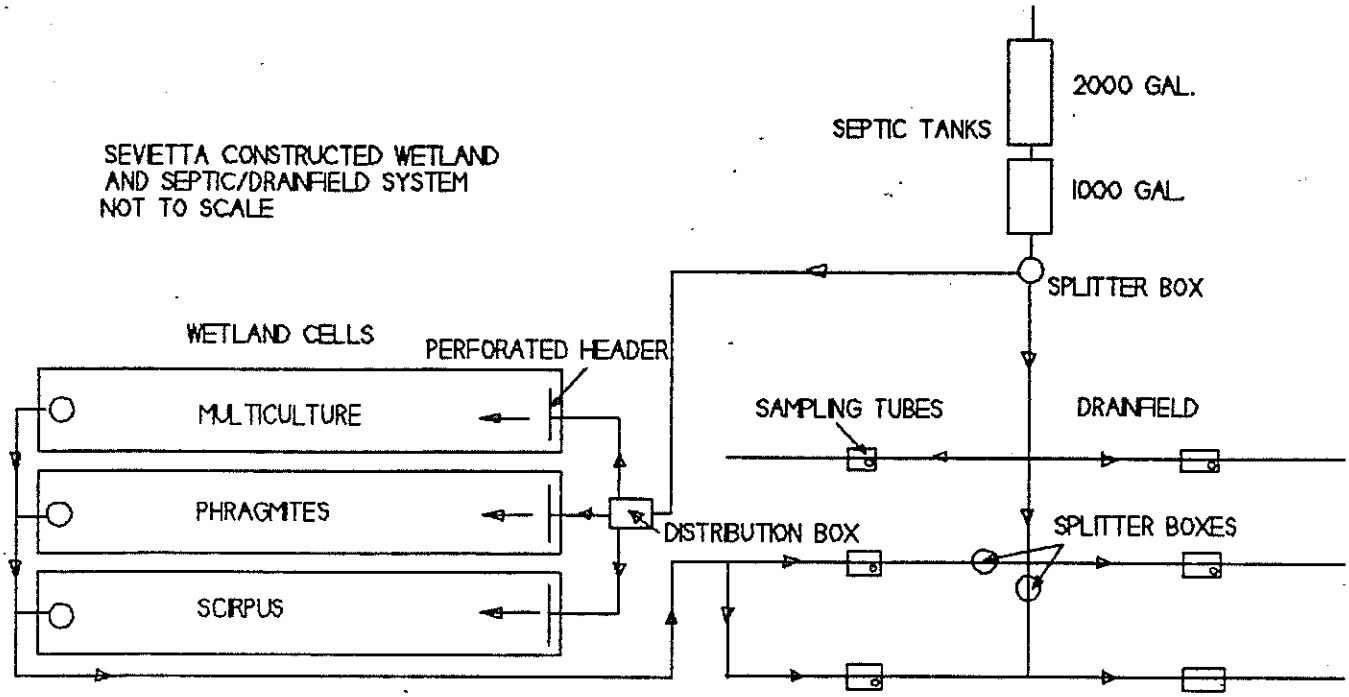

Figure 2. The general layout of the wastewater system at the Sevilleta Long-Term Ecological Research Field Station

Construction of Sevilleta Subsurface Flow Constructed Wetland

Design of the Cells

The SFS wetland design was based on the use of hydraulic loading (Metcalf and Eddie 1991). Hydraulic residence time (HRT) was estimated at 4.5 days under maximum flow conditions (i.e., full occupancy of the research station) and nine days when the flow was split between the constructed wetland and drainfield. The porosity of the gravel media was estimated at 33%, and the total volume of each cell was 132 cubic yards. The overall hydraulic surface loading was 1.05 gal/d-ft^2 and each cell was two feet deep on average.

Three parallel wetland cells were excavated adjacent to the drainfield. The cells are each 50 feet long and 11 feet wide (length to width ratio of approximately 5:1). Cell depths range from 22" at the inlet end to 28" at the outlet end creating a 1% slope at the bottom. Cells are lined with 30 mil PVC and filled with river gravel and cobble ranging from 1/2" to 8" diameter. The mean river gravel size was 3/4" to 3" diameter. The inlet header was constructed of 4" perforated pipe (SDR 35) with 4-8" cobbles placed around the header before backfilling with gravel.

Slide valves were used initially to split flows evenly between channels. After operating the system from September 1991 through June of 1992, it was found that trickle flows from the septic tank were very difficult to split using slide valves. A Tuftite brand distribution box with speed levelers was installed and found to be very effective in evenly splitting trickle flows amongst cells (Figure 3).

The outlet structure was fabricated with a perforated 12" PVC section placed vertically over an adjustable 4" PVC pipe and capped. The cap was not glued to allow sampling access. PVC liner exposed along the freeboard (above the gravel substrate) was rip-rapped with cobble for ultraviolet light protection.

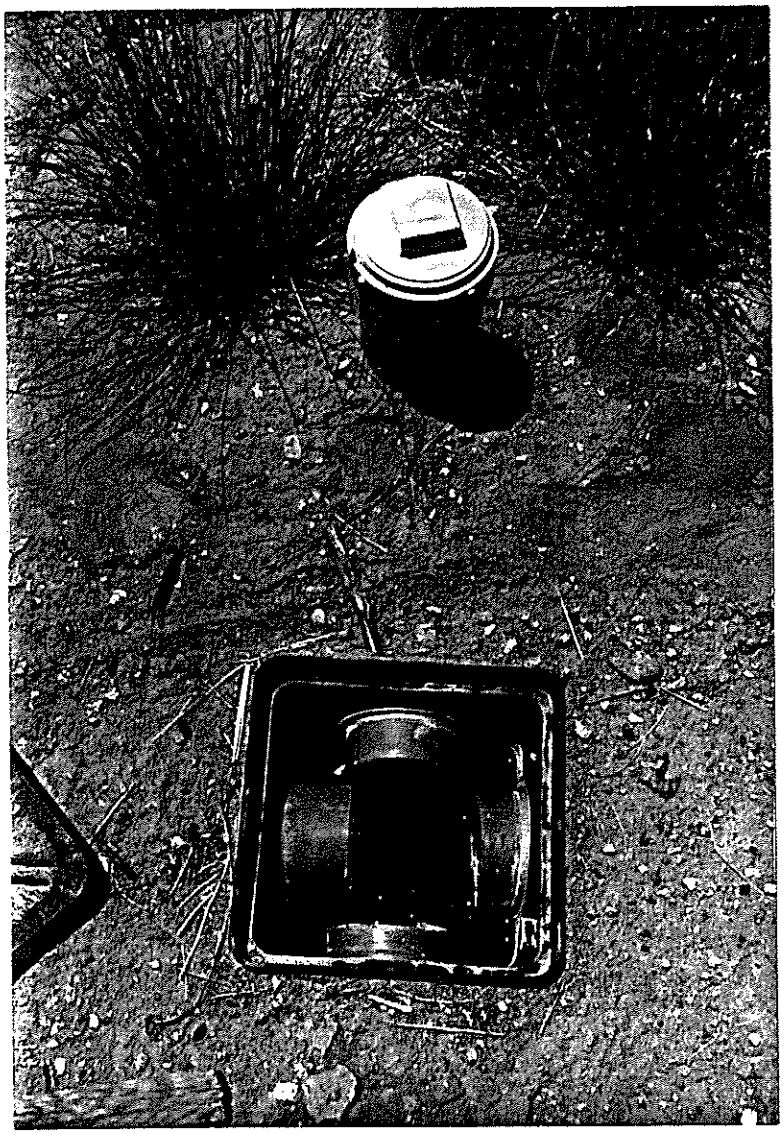

Figure 3. A Tuftite ® distribution box with speed levelers

Wetland Plant Selection and Planting Scheme

Bosque del Apache Wildlife Preserve and La Jolla State Game Refuge gave permission for harvesting plants from these areas for planting in the Sevilleta Constructed Wetland. Plants were identified using Flora of New Mexico (Martin and Hutchens 1980). Cell 1, the furthest west, was planted as a multiculture of four dominant species: 1) *Typha latifolia* (cattail), 2) *Phragmites communus* (common reed), 3) *Scirpus acutus* (hardstem bulrush) 4) *Scirpus olneyi* (Olney bulrush). *Anemopsis californicus* (yerba manza) and other small marsh plants were included and left in the multiculture because they represented less than five percent of the area planted. Plants were approximately 18" apart, the same species in ten foot bands across the width of the cell. Cell 2, the middle cell, was planted as a monoculture of *Phragmites communis*, and Cell 3, the furthest east, was planted as a monoculture of *Scirpus acutus*. These plants were also approximately one foot apart. All plants were transplanted the same day they were dug from local marshes in September 1991. Plants were not mulched or fertilized. Water from the field station septic tank was released into the three wetland cells immediately after planting during the fall and winter months when the field station coordinator was living at the station and researchers visited the station sporadically. Water levels were held at the gravel surface for four weeks to allow initial root development, and subsequently dropped to two inches below the gravel surface for normal operation. Transplanting success measured the following spring was 95%. Plants near the inlet were shorter than those in the remainder of the wetland. Undesirable grasses grew in the bulrush monoculture channel and the first planting of bulrushes did not thrive. It was replanted in early spring 1992.

Construction Costs for Wetland Cells and Associated Plumbing

Total costs are shown in Figure 4. Construction costs were kept low through the use of student and volunteer labor. A local gravel supplier provided the main substrate gravel. While this gravel contained a significant fraction of larger sizes than desired, the cost savings over bringing in gravel

SUPPLIER	ITEM	COST
Lemitar Sand & Gravel	River Gravel	$1,150.00
Snow Company	PVC Liner	1,562.50
Roy McAdams	Bobcat Work	332.50
Pip Brown	Bulldozer	1,600.00
Perry Supply	Plumbing Supplies	42.56
Samons	Plumbing Supplies	38.46
Southwest Pipe	Plumbing Supplies	615.04
Builders Square	Shade Screen	64.15
Walmart	Plastic Tubs	37.88
Student Construction	Labor	290.00
Ross Coleman	Construction Fee	2,000.00
	TOTAL	$7,733.09

Figure 4. Construction costs of the Sevilleta Subsurface Flow Wetland consisting of three cells

from Albuquerque was substantial. The overall cost for construction of the three channels and plumbing was approximately $4.25/square foot.

Research Questions

Effluent was sampled from the septic tank, the middle and end of each of the three wetlands, and the two halves of the drainfield to answer the following questions:

1. Which plant/microbial combination was most effective in wastewater treatment, the multiculture or one of the two monocultures?
2. Which of the two monocultures improved water quality best?
3. Was there a seasonal difference in water quality between the multiculture and monocultures?
4. Was there a seasonal difference in water quality between monocultures?
5. What was the difference in water quality halfway through the wetland compared with at the end of the wetland?
6. Was there a difference in water quality in the septic drainfield compared with the wetland drainfield?
7. What was the response to shock loading when the population of researchers increased?

Field Data Collection Program

Samples were collected twice monthly in the morning and taken back to the environmental engineering laboratory at the University of New Mexico. One liter of water was collected at each position (Figure 2):

1. before entry to the wetland channels—the bottom of the splitter box at the septic tank's outlet before the water ran either to the wetland or to the septic drainfield ($n = 1$).
2. wetland channels—in the middle of each channel from a vertical 4" perforated PVC sample pipe with half inch holes drilled in it along its length which allowed the sampling of wastewater flowing through in the gravel ($n = 3$); the exit pipe of each of the wetland drainfields ($n = 3$).

3. the drainfields—3 sampling tubes installed in gravel-filled tubs below the three 100-foot long standard drainfield pipes so that the septic drainfield and the wetland drainfield were sampled in three positions each. In the drainfield, the pipe closest to the septic tank was fed by the septic tank only (sample positions 1 and 2); the middle pipe was divided in half so that one side receives water from the wetland (sample position 3) and the other side from the septic tank (sample position 4). The third pipe received water from the wetland only (sample positions 5 and 6). Water from the end of the wetlands flows through a 4" PVC pipe to connect with the drainfield serving the wetland.

The total number of sample pipes for the septic tank effluent, wetland channels and drainfields was 13, although periodically some in the drainfield had no water in them and no samples were taken.

A plastic sampling tube from an erlenmeyer flask was lowered into the sampling port, water was drawn into the erlenmeyer with a hand-operated vacuum pump and then poured into a 1-liter plastic sampling bottle, capped immediately, and put on ice to minimize the amount of oxygen added to the sample and to slow biological processes. Water samples were taken half way between the water surface and the bottom of the sampling tubes in the three wetland channels and the two drainfields.

Laboratory Analysis

All tests were performed according to Standard Methods for the Examination of Water and Wastewater, 18th edition, 1993.

BOD_5 (5-Day Biochemical Oxygen Demand)

BOD_5 analysis was set up the day of sampling. Two of four 300 mL incubation jars containing incubation medium were filled with either 20 or 50 mLs of each water sample and read with an oxygen probe for oxygen content. The jars were filled to 300 mLs after the probe was removed and

sealed for a 5-day incubation period at 20°C. At the end of five days the water was read again for oxygen content and the difference was attributed to the presence or absence of organisms requiring oxygen.

Fecal Coliform Bacteria

Four incubation plates were prepared for each sampling point. Two 100 mL replicates (10 mLs sample + 90 mLs distilled water) were pulled through a filter pad which was then placed on the incubation plate containing 1.5% agar, M-FC broth and 1% rosolic acid. The two other incubation plates were prepared using 1 mL sample + 99 mLs distilled water. Plates were sealed from air and incubated under water at 44.5°C for 24 hours. Colonies produced by fecal coliform bacteria of M-FC medium were various shades of blue. Pale yellow colonies were atypical *E. coli*. Non-fecal coliform colonies were gray to cream-colored.

Total Coliform Bacteria

LES Endo agar was added to dishes onto which the membrane was placed after water had been filtered through it. Plates (n = 4) were sealed and incubated in the dark in an electric incubator at 35°C for 24 hours and then colonies were counted. Pink to dark red colonies are coliform colonies with a shiny metallic surface. The shiny area may vary in size from a small pinhead to complete coverage of the colony surface. Shiny colonies were total coliform colonies.

Nitrogen (Total Kjeldahl Nitrogen, Ammonia, and Nitrate)

Mr. John Craig of the Long-Term Ecological Research Center, at the Department of Biology, UNM, analyzed water samples from five collection dates in 1992, and from two collection dates in 1993 for Total Kjeldahl Nitrogen. Samples were also assayed on a Technicon Autoanalyzer II for ammonia (Industrial Method # 98-70W, 1973) and nitrate (Industrial Method #100-70W, 1973). Water samples were preserved by adding 1 mL/100 mL of 100 ppm phenyl mercuric acetate (PMA), which inhibits microbial activity to prevent nitrogen uptake, and were refrigerated until tests could be

run. This is standard procedure for preparing nitrogen analyses for Total Kjeldahl Nitrogen or water analysis on the Technicon Autoanalyzer II.

RESULTS OF THE FIELD SAMPLING PROGRAM

The results of the field sampling program are shown in Tables 2-4 and are presented graphically at the end of this section in Figures 5-23. There were five principal water quality characteristics that were measured during this study:

1) five-day biochemical oxygen demand (BOD_5)—Figures 5-9,
2) ammonia/ammonium nitrogen (NH_3)—Figures 10-13,
3) total Kjeldahl Nitrogen (TKN)—Figures 14-17,
4) total coliform bacteria—Figures 18-20, and
5) fecal coliform bacteria—Figures 21-23.

It should be noted that none of these parameters are regulated for discharges from on-site wastewater treatment systems to the soil through absorption field systems. However, they are each important measures of wastewater quality and are commonly regulated for wastewater discharges to surface waters (Metcalf and Eddy 1991).

Biochemical Oxygen Demand

BOD_5 is a measure of the organic content in a wastewater and is of primary concern in surface water discharges as organics can result in oxygen depletion of the receiving water. In systems discharging to groundwater BOD_5 is of secondary importance, and of concern only in that it also is an indication of how well the water has been treated prior to discharge. In areas with a high density of on-site wastewater treatment and disposal systems, a high organic loading of the soil may cause

oxygen depletion of the subsurface environment resulting in high iron ($Fe2^+$), manganese ($Mn2^+$) and sulfide (HS^-) concentrations causing taste and odor problems in the underlying groundwater.

The performance of the three wetland cells with respect to BOD_5 is summarized in Figures 5-9. After initial start up (two-three people present) and the adjustment of the entire system to the arrival of the summer research staff on May 18, 1992 (25 people), the effluent from each of the cells was very high quality. A summary of the averages of the last four sample collection events is presented as Table 2.

Table 2. Average concentration of BOD_5 during the last four sample collections

Sample Location	**BOD_5 (mg/L)**	**BOD_5 Removal (%)**
Septic Tank Effluent	82.3	—
Multiculture Channel		
Mid-point	56.5	31.3
Effluent	11.0	86.6
Phragmites Channel		
Mid-point	28.3	65.6
Effluent	11.8	85.7
Scirpus Channel		
Mid-point	66.0	19.8
Effluent	26.3	68.0

Nitrogen

The principle concern associated with high concentrations of NH_3 and TKN are that they may become oxidized to nitrate (NO_3^-) which is a regulated drinking water contaminant as well as a regulated groundwater constituent in many states, including New Mexico. Total Kjeldahl Nitrogen is a measure of both NH_3 and organic nitrogenous compounds (e.g., proteins, urea, nucleic acids). In the subsurface environment TKN rapidly hydrolyses to NH_3 which may then be microbially oxidized to NO_3- as shown by the following reactions (Chapelle 1993):

$$2NH_4^+ + 3O_2 \quad \textit{Nitrosomonas} \rightarrow \quad 2NO^- + 4H^+ + 2H_20 \tag{1}$$

$$2NO_2^- + O_2 \quad \textit{Nitrobacter} \rightarrow \quad 2NO_3^- \tag{2}$$

The overall stoichiometry of the nitrification reaction is:

$$NH_4^+ + 2O_2 \quad \textit{Nitrifying Organism} \rightarrow \quad NO_3^+ + 2H^+ + H_2O \tag{3}$$

The groundwater standard for NO_3^- in New Mexico is 10 mg NO_3^-—N/L which corresponds to the state and federal drinking water standards (NM Environment Department Groundwater Standards 1989).

It is interesting to note that groundwater systems which are subject to high loadings of BOD_5 often quickly become anaerobic which prevents the nitrification reactions. A very good example of this phenomenon is found in the Albuquerque basin. Regions of the basin with high densities of on-site wastewater treatment and disposal systems and shallow groundwater generally have foul tasting water resulting from high concentrations of Fe^+, Mn_2^+, and HS^-, and these areas also have no measurable NO_3^-. Areas with oxidizing subsurface conditions have high NO_3^- and negligible concentrations of the constituents which cause taste and odor problems. (CH2M-Hill 1990, Heggen et al. 1979; Thomson and McQuillan 1983; Gallaher and McQuillan 1986).

The NH_3 and TKN nitrogen data are presented in Table 3 and Figures 10-13, and Table 4 and Figures 14-17, respectively. Samples collected at each of the sampling points throughout the wastewater treatment and disposal system were also analyzed for nitrate (NO_3^-), however, none of the concentrations was greater than 1.0 mg N/L as NO_3^-, hence this data is not plotted. Fewer samples were analyzed for nitrogen species than for other parameters due to the increased cost. Thus, the

Table 3. Average ammonia (NH_3) concentrations and percent removal.

SAMPLE LOCATION	AVERAGE NH_3 (MG/L)	% REMOVAL OF NH_3
Septic Tank Effluent	47.1	—
Multiculture Cell		
Midpoint	23.6	50.0
Effluent	15.6	66.9
Phragmites Cell		
Midpoint	33.1	29.7
Effluent	22.6	52.0
Scirpus Cell		
Midpoint	40.2	14.6
Effluent	29.7	37.0

Table 4. Average Total Kjeldahl Nitrogen (TKN) concentrations and percent removal.

SAMPLE LOCATION	AVERAGE TKN (MG/L)	% REMOVAL TKN
Septic Tank Effluent	62.1	—
Multiculture Cell		
Midpoint	35.0	43.8
Effluent	17.1	72.5
Phragmites Cell		
Midpoint	47.6	23.4
Effluent	29.1	53.2
Scirpus Cell		
Midpoint	53.8	13.4
Effluent	33.7	45.8

transient phenomenon seen for BOD_5 are not apparent for nitrogen concentrations since these analyses weren't collected during initial start-up conditions. The average nitrogen data for the last four sampling events are summarized in Table 3. As with the BOD_5 data, the NH_3 and TKN analyses clearly show that the three wetlands are capable of substantially reducing the wastewater's nitrogen content. In contrast to the BOD_5 removal, there is significantly better NH_3 removal in the multiculture wetland than the other two. There are two possible explanations for this removal. The first is nitrification where NH_3 is oxidized to nitrate (NO_3^-) as shown by the following reaction:

$$NH_3 + 2O_2 \rightarrow H^+ + NO_3^- + H_2O \quad (4)$$

Virtually no NO_3^- was detected in any of the water samples. However, the absence of these constituents does not necessarily mean that nitrification is not occurring. It is speculated that nitrification does in fact occur in aerobic microenvironments adjacent to the plant roots. The bulk of the wetland though contains high concentrations of organic compounds and is anoxic and anaerobic. Therefore, rapid reduction of NO_3^- occurs through the denitrification process. The second nitrogen removal mechanism is uptake by wetland vegetation with subsequent incorporation into plant tissue. Due to the vegetation's heavy growth in each of the three wetland cells, this is also believed to be a nitrogen removal mechanism, at least for this study's duration. As the wetlands mature, unless the plants are regularly harvested, nitrogen from plant detrital material may contribute to the wastewater, thus reducing the effectiveness of the process for nitrogen removal.

Total and Fecal Coliform Bacteria

Coliform organisms are gram negative rod-shaped bacteria commonly assumed to be of intestinal origin used as indicators of fecal contamination of water. Both total coliform and fecal coliform organisms were analyzed in this study, the principal distinction being that the latter organisms are assumed to be present in mammalian hosts whereas total coliform bacteria may be

present in non-mammals as well. There is no state or federal standards for this parameter. Instead they are established based on classification of the receiving water which is determined by its use. Coliform concentrations in permitted discharges can vary from 0 orgs/100 mL to 100 orgs/100 mL depending on the NPDES permit requirements.

Two features common to all data are worth noting. First, it is clear that there was an initial acclimation process for each wetland cell during which time a heterotrophic microbial population and the wetland plants became established. This occurred for less than one month so that by the first of April 1992, all wetland cells were performing well. During this time the research station had only three occupants, therefore the on-site wastewater disposal system was lightly loaded. A second and much larger transient occurred on May 18, 1992, with the influx of summer students, bringing the total population to 25 people. This is particularly noticeable as a spike in the BOD_5 data for the three wetland cells. The second feature common to all data is the high degree of variability. This reflects several factors including variations in actual water quality due to transient flow and the wastewater's water quality characteristics at the site, sample variability associated with collecting grab samples from a wastewater treatment and disposal system, and variations inherent in laboratory analyses. To the extent possible statistical analyses are incorporated in this report, however, the constraints imposed by a relatively small data set coupled with a high degree of variability limit the confidence intervals that can be placed on the conclusions.

The analyses results for total and fecal coliform organisms are shown in Figures 18-23. Total coliform organisms are gram negative bacteria capable of producing hydrogen gas by fermentation. The coliform bacteria include the genera Escherichia and Aerobacter, which complicates interpretation of the results because both groups include species capable of growing in the soil. Thus, the presence of coliform organisms does not always indicate contamination by human waste. Counts of fecal coliform organisms were also performed. These organisms are incubated at an elevated temperature

(44.5°C) and are believed to be more closely correlated with human wastes. Because these organisms may be present in water at widely varying concentrations, the data is presented graphically using a logarithmic scale. To construct this plot, all measured concentrations of 0 organisms/100 mL were reported as 1 organism/100 mL (the logarithm of 0 is negative infinity). Note also that the highest measurable concentration in this study was 25,000 organisms/100 mL.

Field sampling results show that all three wetlands are capable of providing a high degree of BOD_5 removal. For reference, the national criteria for discharge of treated wastewater to surface waters is 30 mg/L, which is based upon application of secondary biological treatment processes. The data presented here show that the three wetland systems built for this study are capable of meeting secondary treatment standards.

Of equal importance are the sampling results collected at the mid-point of each wetland cell. These demonstrate two features. The first is that the wetlands were each able to respond to the stress resulting from an approximate five-fold increase in the flow on May 18, 1992. While the effluent quality remains high, the BOD_5 values at each of the mid-point locations quickly rose to values approaching the influent concentration. As each wetland adjusted to the increased loading through increased growth of microbial populations as well as growth of the macrophytes, the mid-point BOD_5 concentrations dropped. The second point illustrated by the BOD_5 data is the dependence of performance on time in the wetland. This is shown graphically in Figure 8 which is a plot of average BOD_5 concentration versus distance traveled along each wetland. As there are only three sampling points (beginning, middle and end), it is not possible to determine a quantitative relationship between BOD_5 concentration and residence time of wastewater in the wetland, but it is clear that removal of organic constituents in the wetland cells improves with time.

Given the large scatter in the data and the fact that this sampling period reflects start-up conditions during which both the microbial and emergent plant populations were becoming

established, it is not possible to make a statistically defensible conclusion as to which of the three wetland systems exhibited the best performance. Furthermore, it is not believed to be justified to fit the data to a previously published performance model or equation.

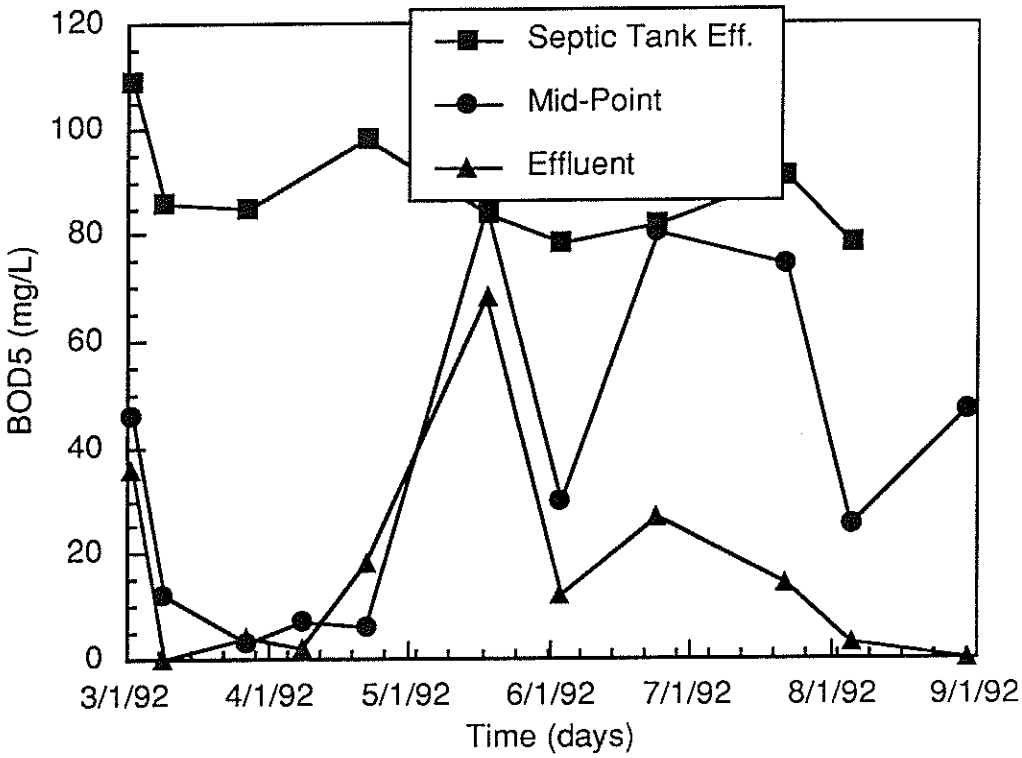

Figure 5. BOD_5 data for the Multiculture cell.

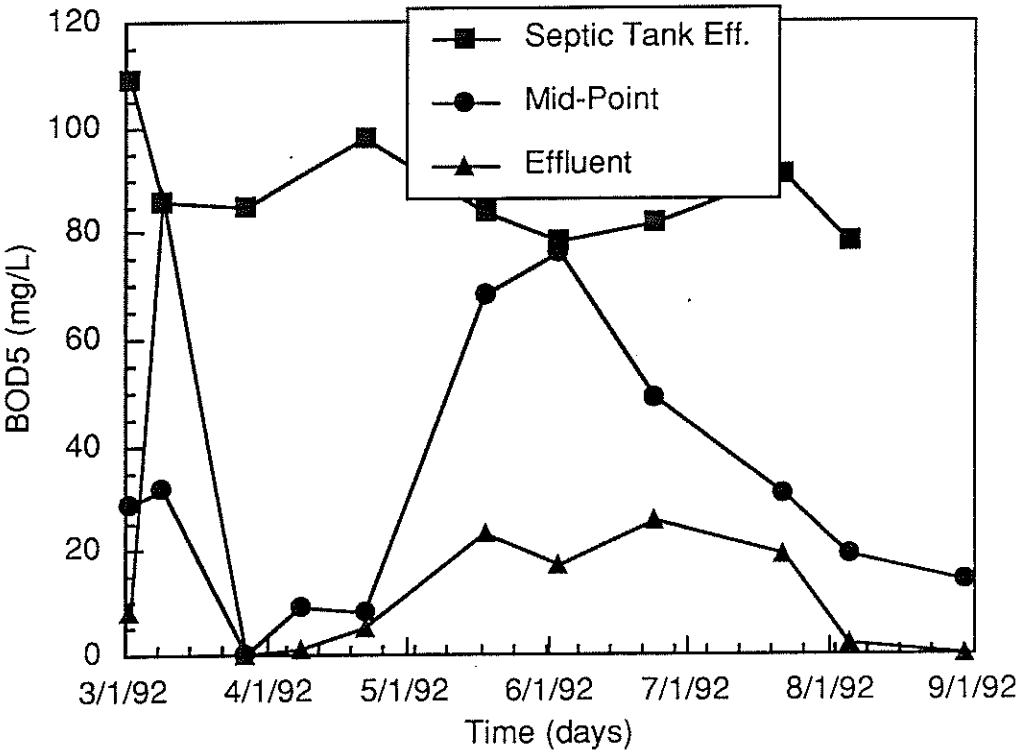

Figure 6. BOD_5 data for the Phragmites cell.

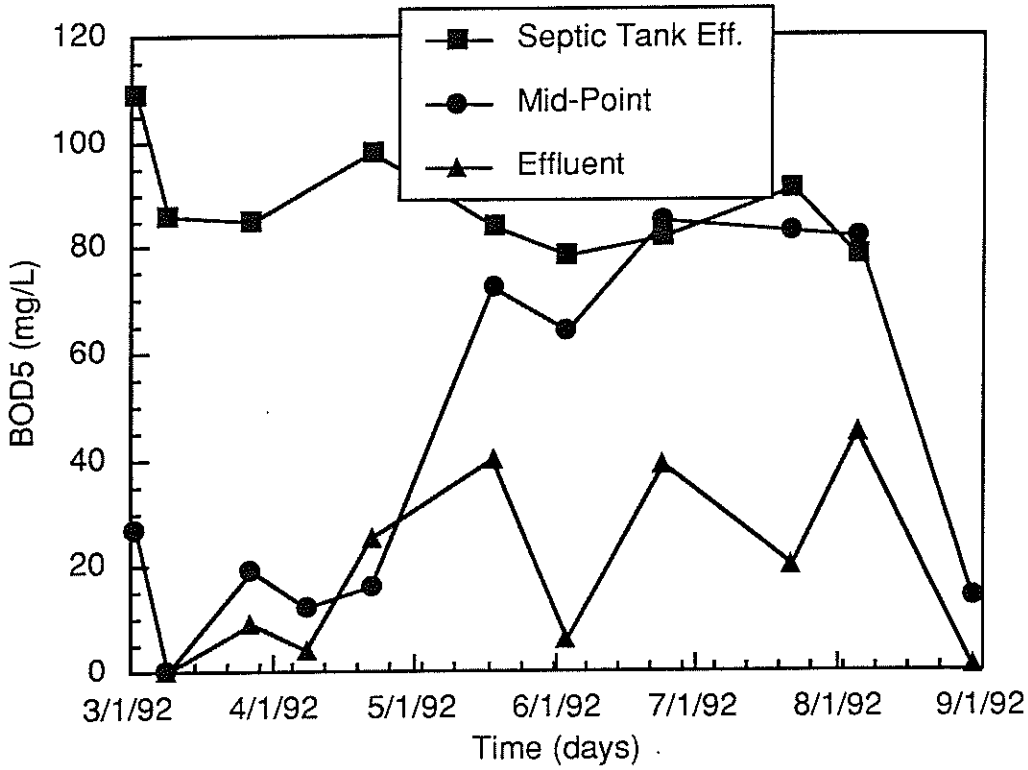

Figure 7. BOD_5 data for the Scirpus cell.

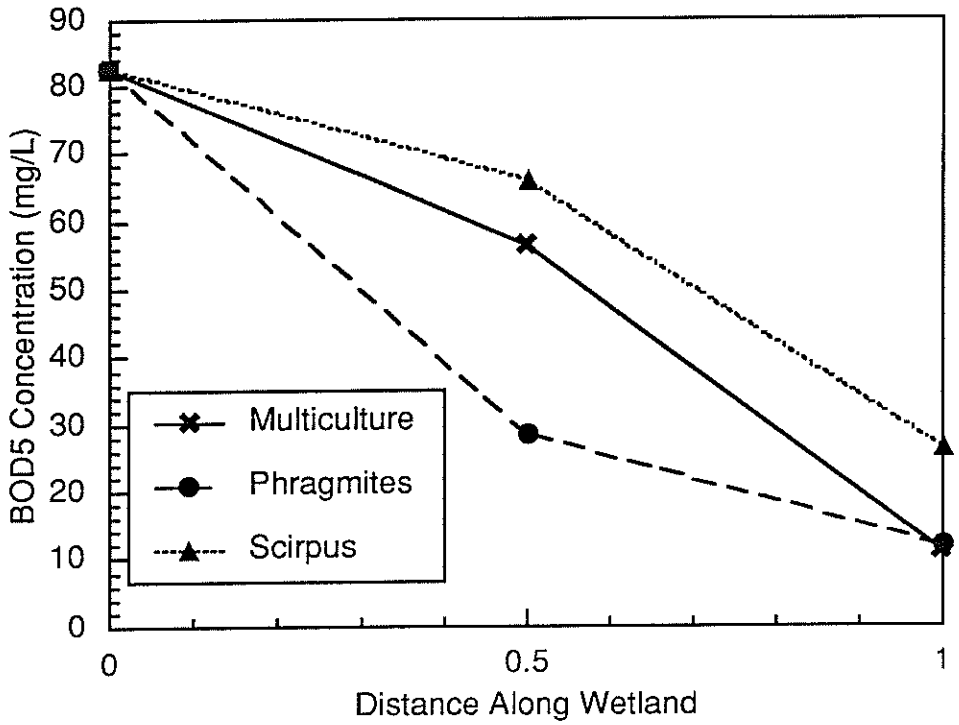

Figure 8. Average BOD_5 concentrations as a function of the distance along the three wetland cells.

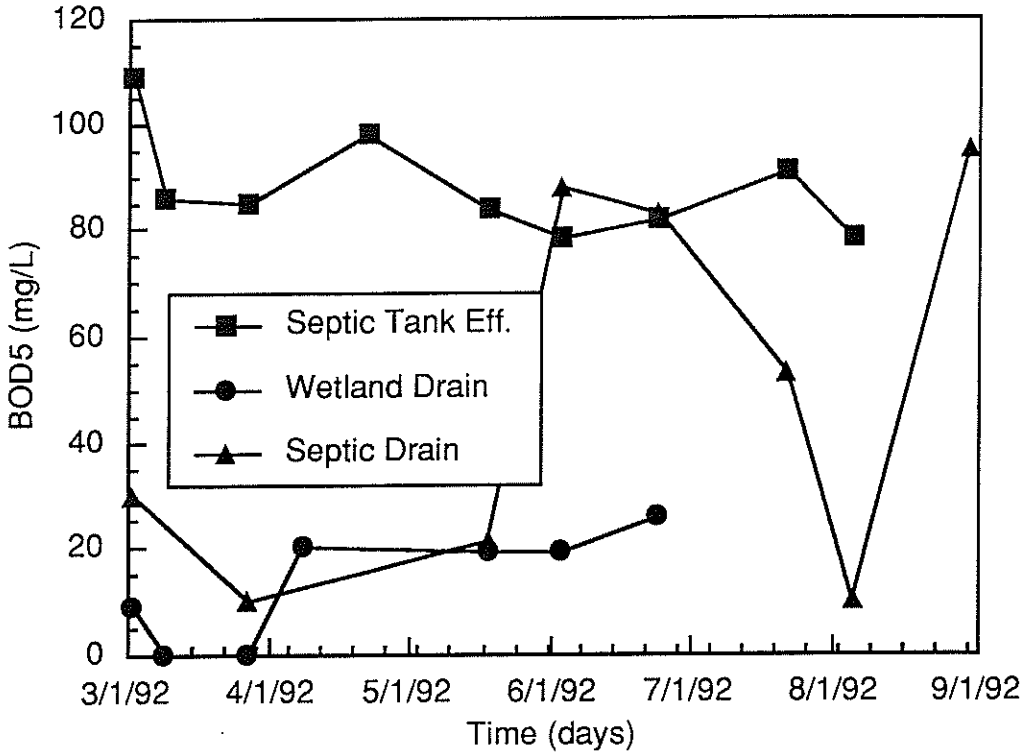

Figure 9. Comparison of septic tank effluent, septic drain, and wetland drain water quality for BOD_5.

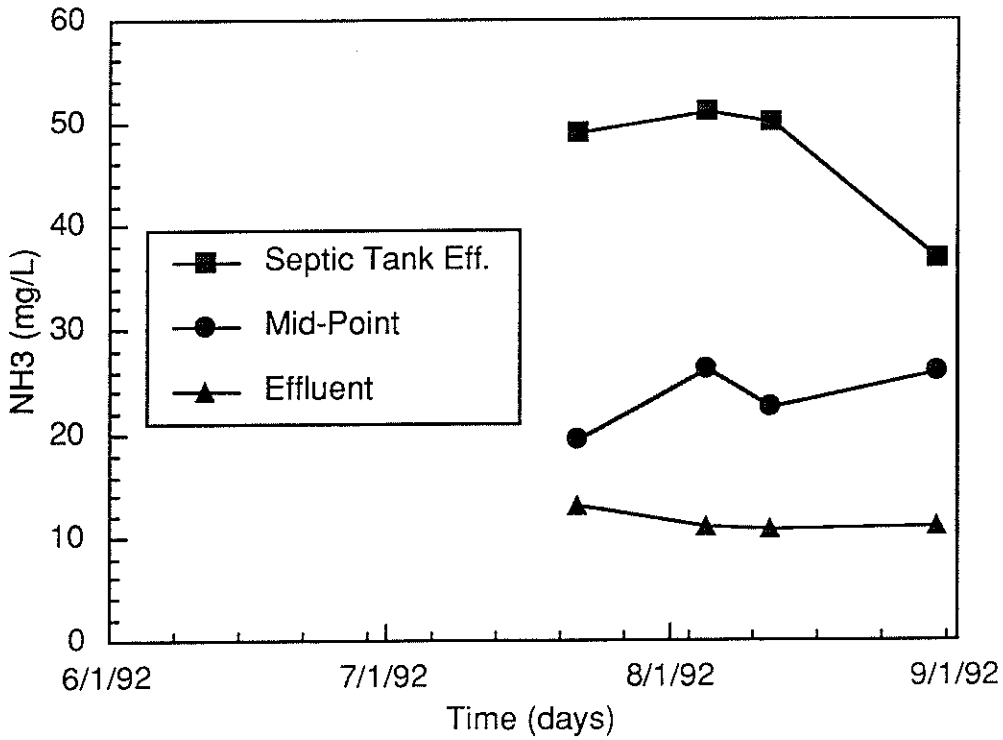

Figure 10. Ammonia data for the Multiculture cell.

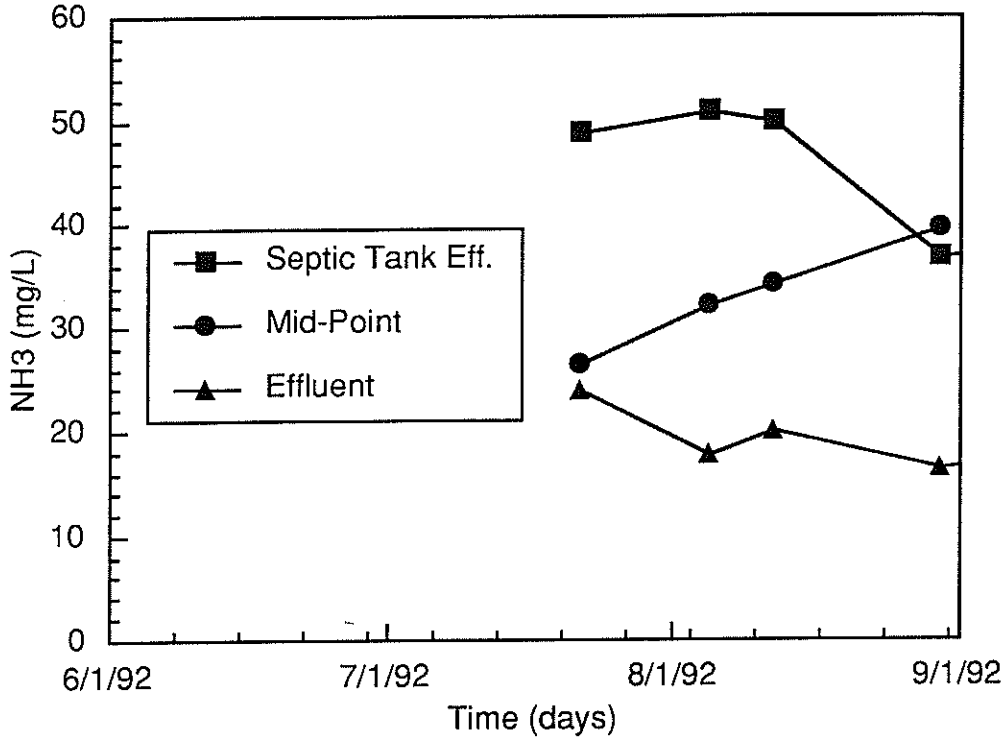

Figure 11. Ammonia data for the Phragmites cell.

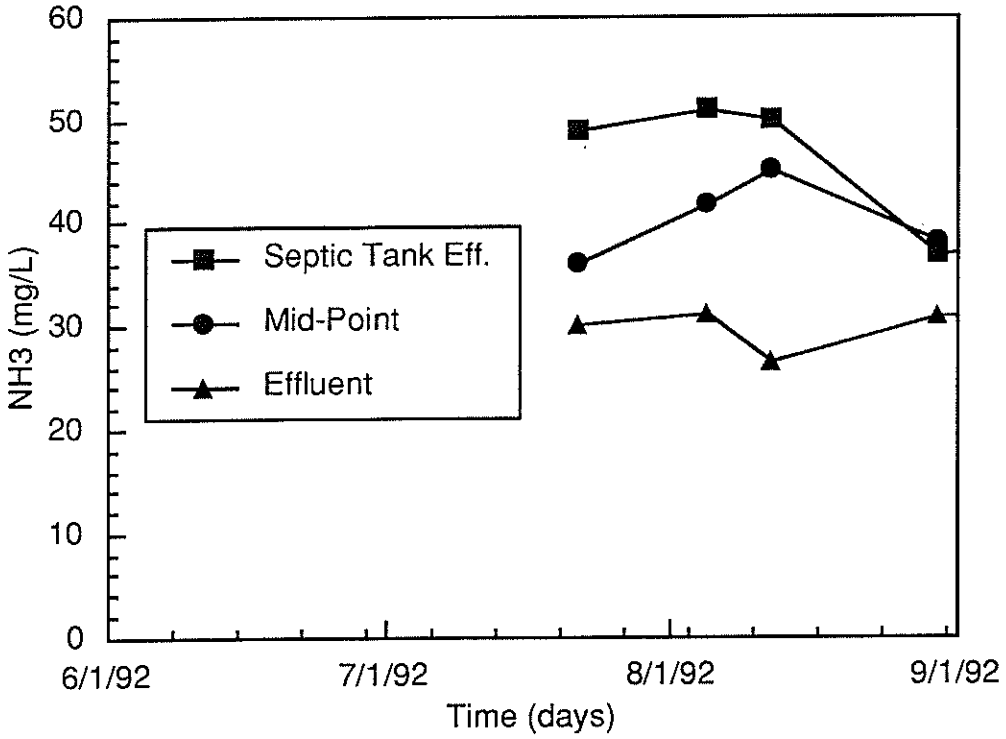

Figure 12. Ammonia data for the Scirpus cell.

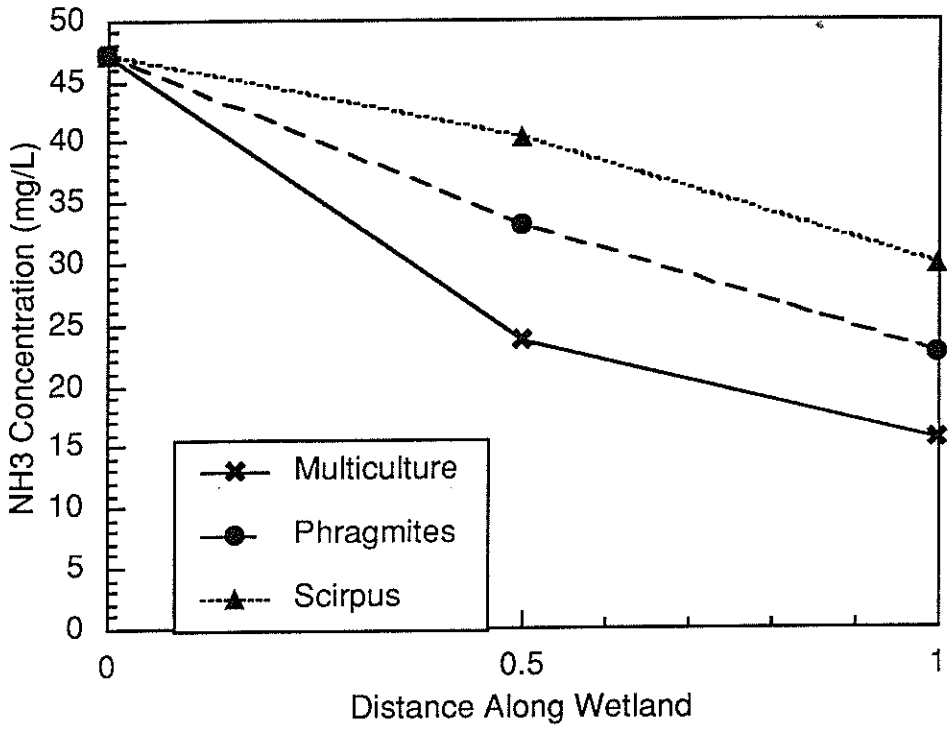

Figure 13. Average ammonia concentration as a function of the distance along the three wetland cells.

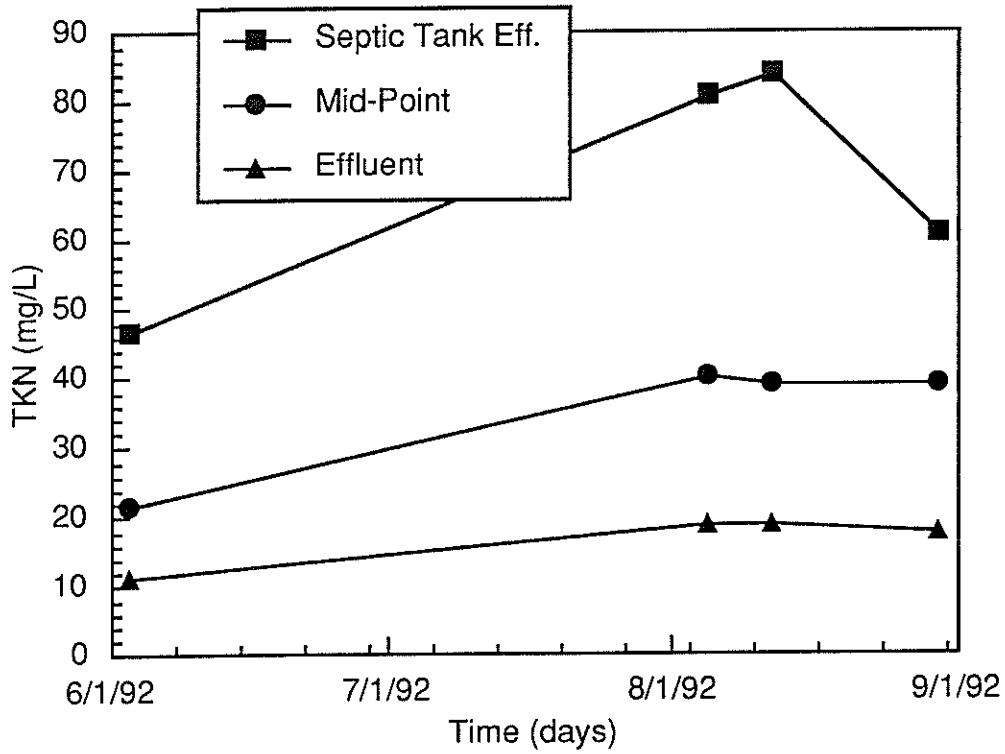

Figure 14. Total Kjeldahl Nitogen (TKN) data for the Multiculture cell.

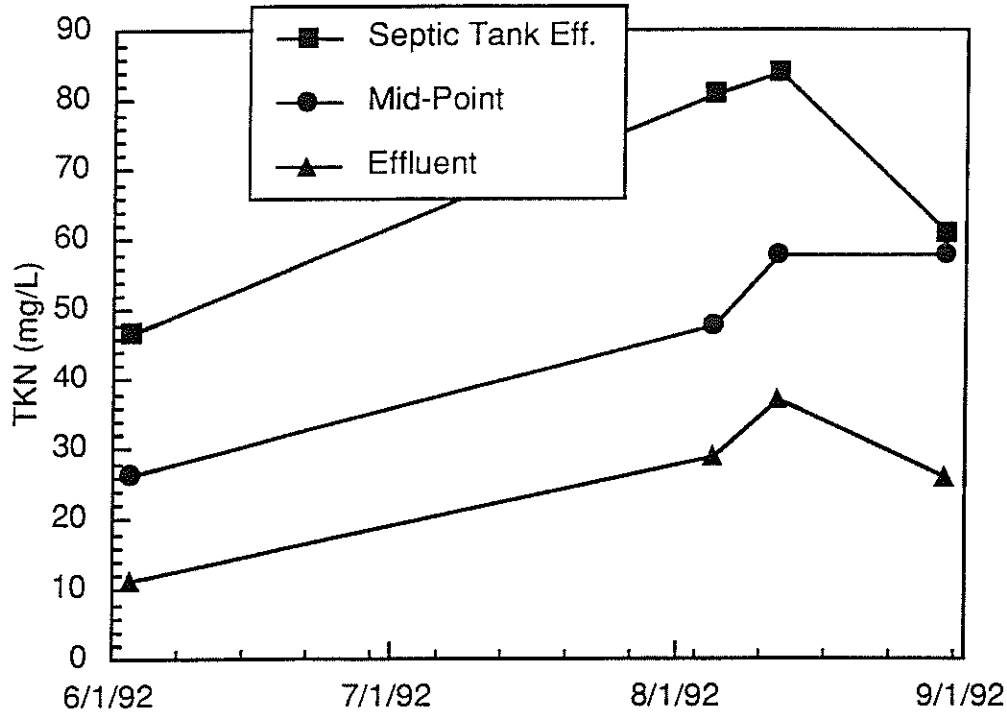

Figure 15. Total Kjeldahl Nitrogen (TKN) data for the Phragmites cell.

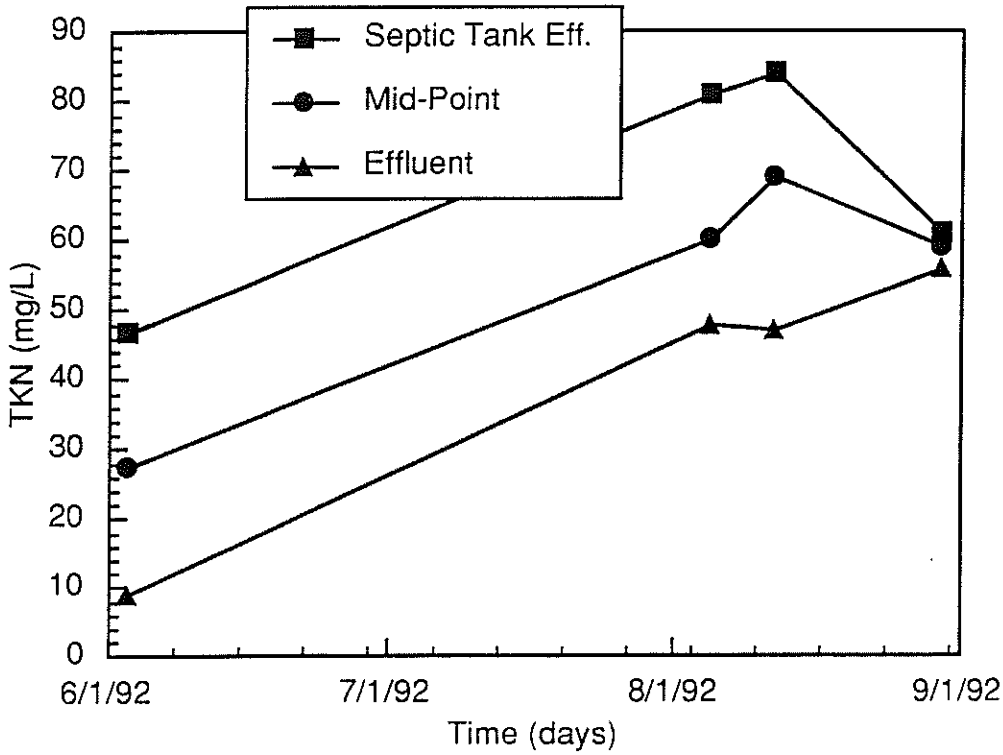

Figure 16. Total Kjeldahl Nitrogen (TKN) data for the Scirpus cell.

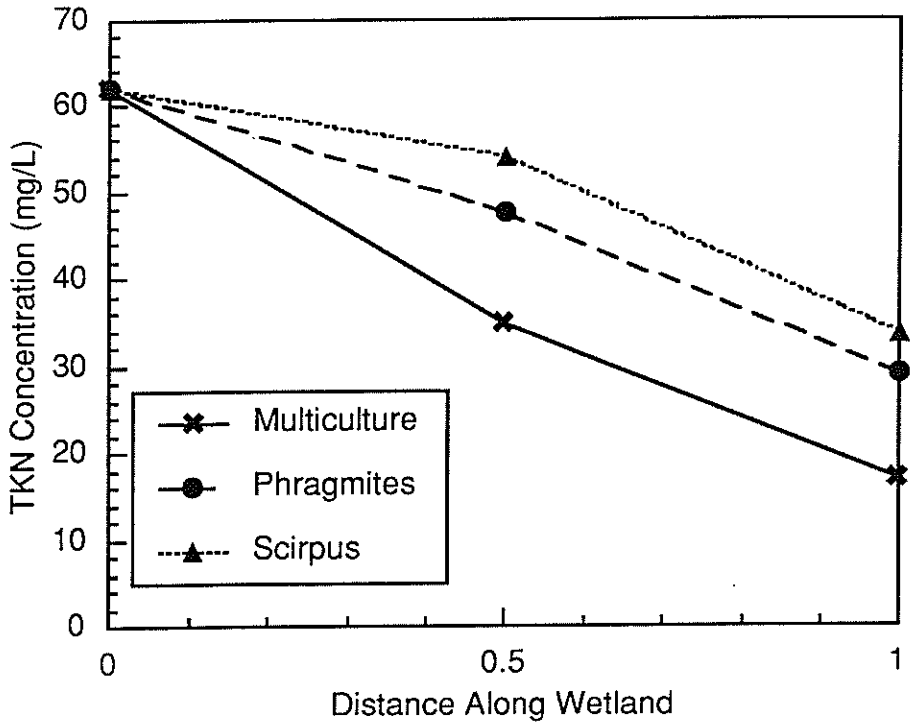

Figure 17. Average Total Kjeldahl Nitrogen (TKN) concentration as a function of the distance along the three wetland cells.

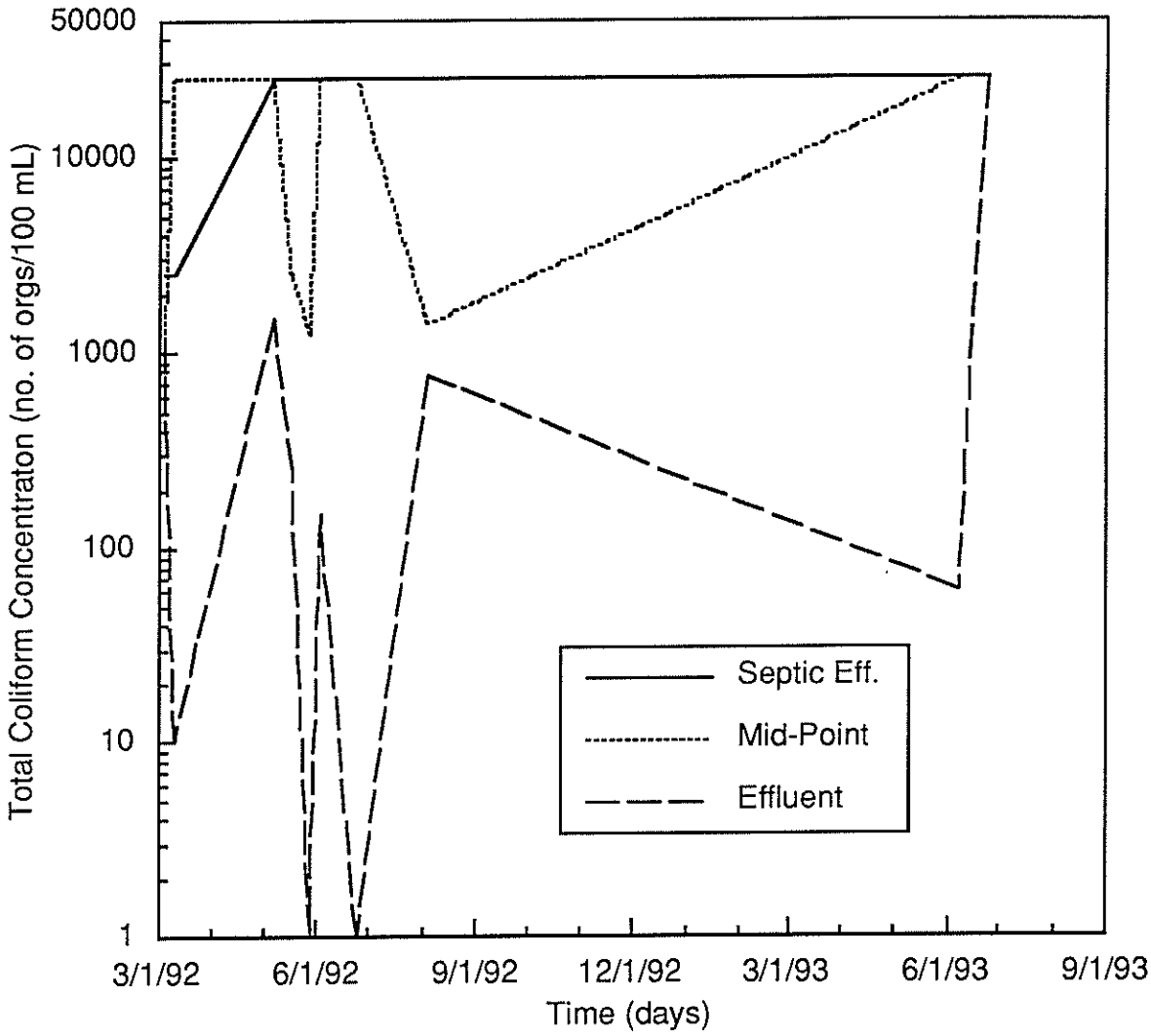

Figure 18. Total Coliform data for the Multiculture cell. (Note that a count of 0 organisms/100 mL is reported as 1 organism/100 mL.)

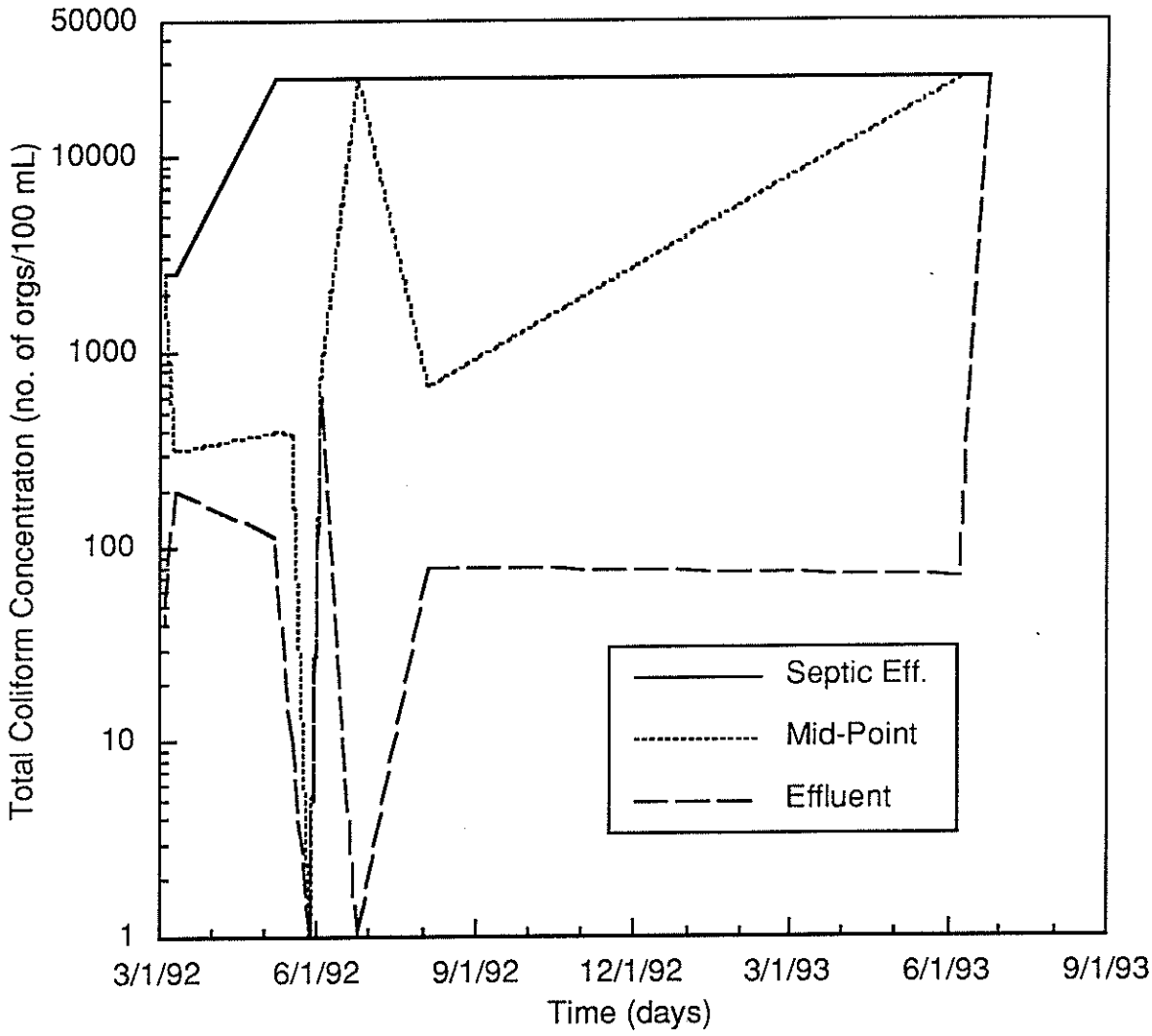

Figure 19. Total Coliform data for the Phragmites cell. (Note that a count of 0 organisms/100 mL is reported as 1 organism/100 mL)

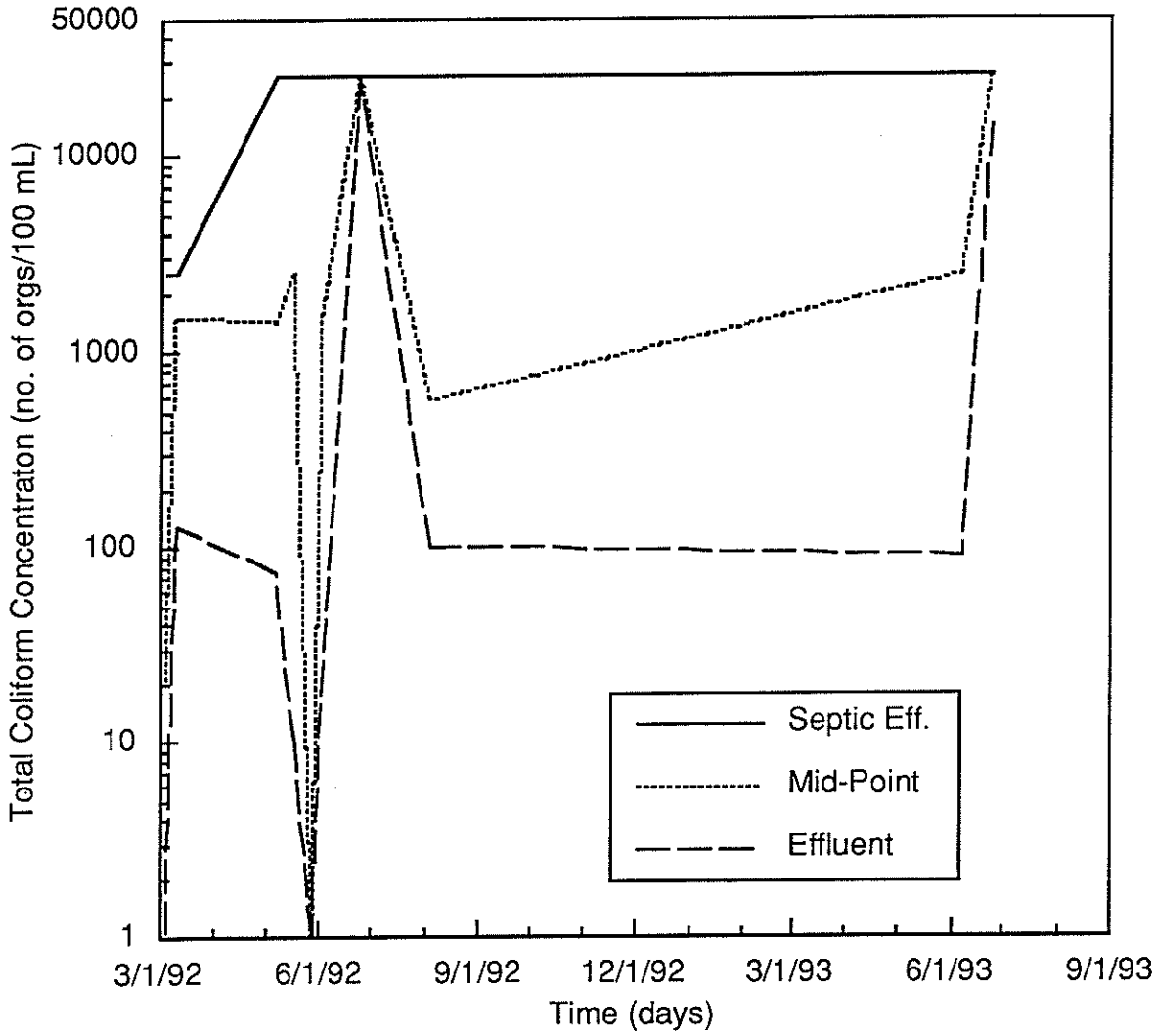

Figure 20. Total Coliform data for the Scirpus cell. (Note that a count of 0 organisms/100 mL is reported as 1 organism/100 mL.)

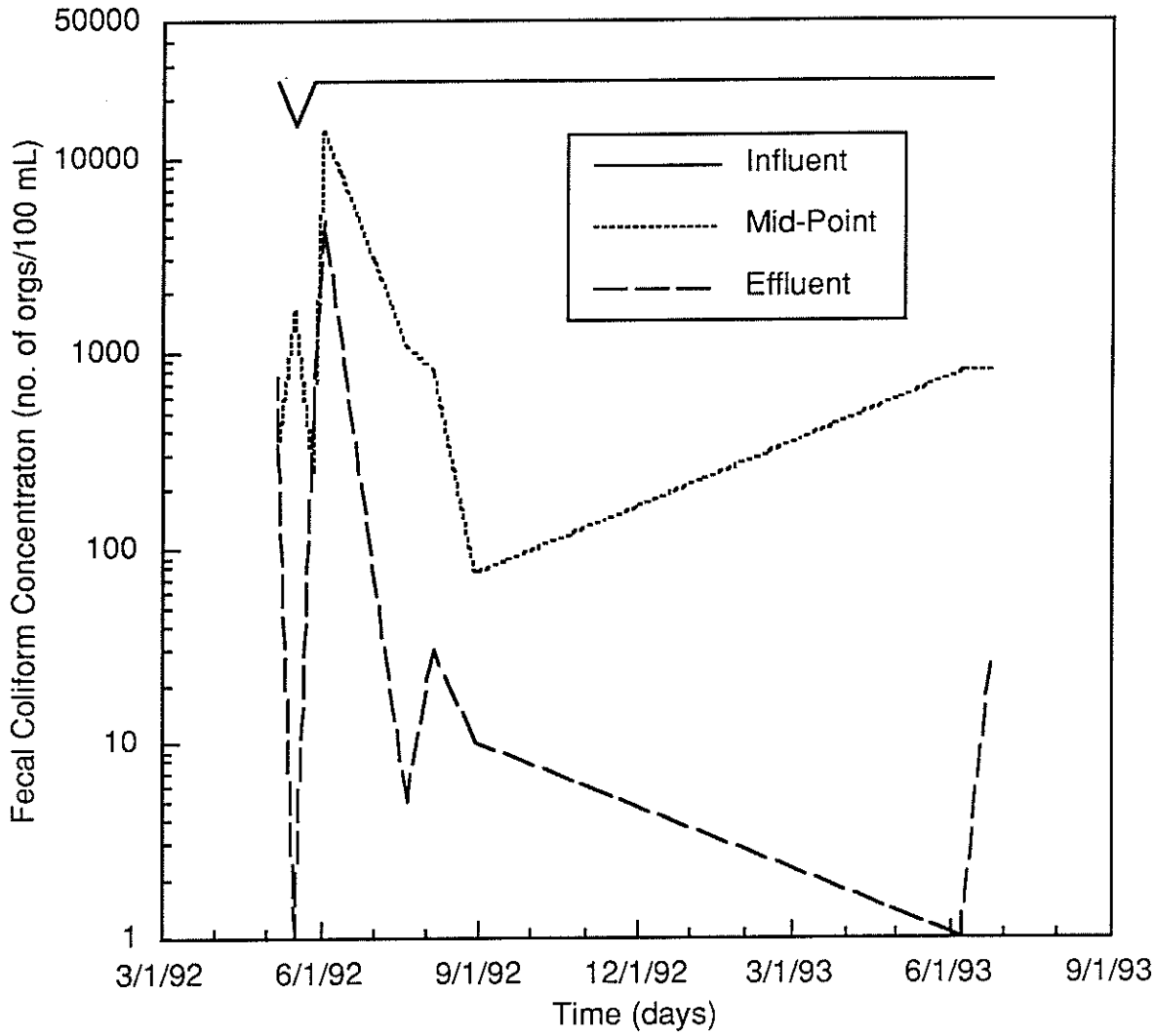

Figure 21. Fecal Coliform data for the Multiculture cell. (Note that a count of 0 organisms/100 mL is reported as 1 organism/100 mL.)

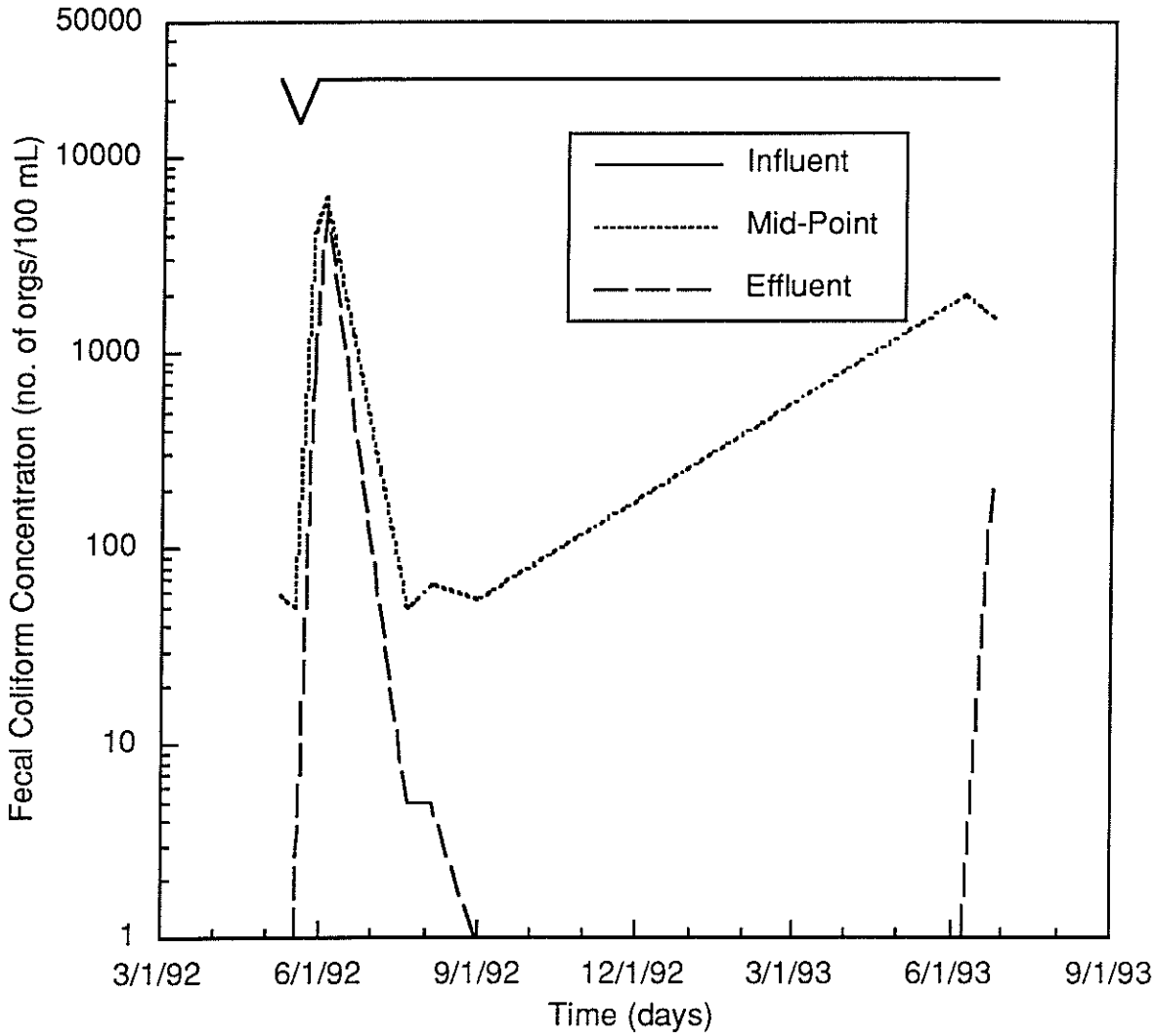

Figure 22. Fecal Coliform data for the Phragmites cell. (Note that a count of 0 organisms/100 mL is reported as 1 organism/100 mL.)

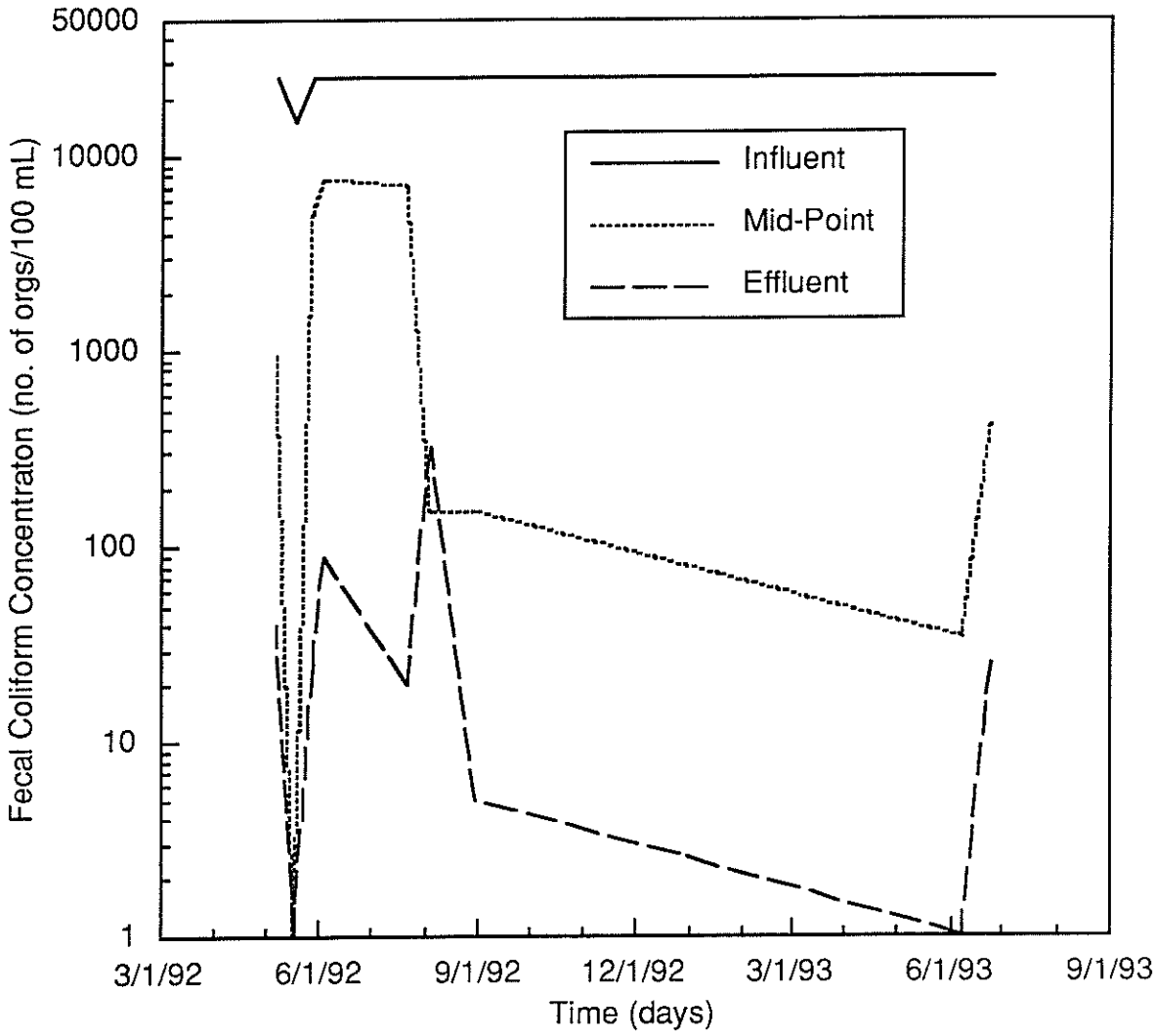

Figure 23. Fecal Coliform data for the Scirpus cell. (Note that a count of 0 organisms/100 mL is reported as 1 organism/100 mL).

DISCUSSION AND CONCLUSIONS

Evaluation of the System's Performance

The performance of each wetland cell for the five tests performed is ranked in Table 5. The multiculture cell performed best, and the Phragmites cell, second best. The Scirpus cell performed least well. It is thought that one of the reasons the multiculture performed best was that the plants' growth cycle is not synchronized. In other words, in the multiculture channel some of the plants are more tolerant of cold weather; others can tolerate hot weather; some bloom early, others later. Species grow at different times of the year, and store nutrients in their roots and tubers at different times of the year. Some are more tolerant of high organic or pollutant loadings than others (e.g., NH_3). This diversity is appropriate particularly in a system that is expected to operate year round under variable climatic and loading conditions. Additionally with increased plant diversity there is an increased microbial community (Hatano et al. 1993). A multiculture wetland traps and processes more nutrients more efficiently than a monoculture wetland like a highly diverse mid-successional forest uses and reuses the energy from light more efficiently compared with a monotypic climax forest. This analogy extends to the diversity of microorganisms found in the multiculture versus the monoculture wetlands which resembles the diversity of the microbes, animals, and birds in a mid-successional forest compared with low diversity in a climax forest.

Table 5. Ranking of the three wetland cells for each of the five tests performed at the Sevilleta constructed wetland

WETLAND CELL	TYPE OF TEST					
	BOD_5	Fecal Coliform	Total Coliform	TKN	NH_3	Total
Multiculture	1	1	1	1	1	5
Phragmites	1	1	1	2	2	7
Scirpus	3	2	2	3	3	13

This system was planted in September 1991 before the field station was completed in October. Therefore the plants in the wetland overwintered with little nutrient input from the field station until the early spring 1992. The data presented here, therefore, should be considered informational about the system's performance at its inception, rather than a measure of its average performance after establishment. The station's use was intermittent during the first year of operation. One to four people were at the station before the beginning of May, which coincides with cooler temperatures in New Mexico. Influent BOD_5 was low. The station population increased to 25 people over one weekend in the middle of May. Subsequently, for a short period of time, all cells showed high BOD_5 when the use of the station increased, until the plants and their microbial associates adjusted to this increase, through growth and increase in population.

Biochemical Oxygen Demand

During the first year, the average percent BOD_5 removal was within the range of other systems of the same size in experiments performed by the Tennessee Valley Authority (Choate et al. 1993).

Although the data are too variable and limited for statistical comparison, the three cells appeared to differ in the following way. In the multiculture, the mid-cell samples peaked and then alternated

between high and low readings. The end-cell samples peaked and then declined throughout the season and returned to zero by the first part of August.

The mid-cell Phragmites sample also peaked in mid-May but then declined steadily throughout the rest of the sampling period, finishing lower than the multiculture mid-cell sample and about the same as the Scirpus mid-cell sample. The end-cell sample did not peak and maintained the lowest consistent reading throughout the heavy-use period, and finally went to zero at the beginning of August.

The mid-cell Scirpus sample peaked but then stayed almost as high as the septic tank BOD_5 until the station population declined at the end of August. The end-cell samples peaked, but did not go as high as the multiculture end-cell samples, fluctuated throughout June, July and August, and finally declined to zero at the end of August when the station population declined. This was the last of the three cells to decline to zero. It did so approximately a month later than the other two cells.

Nitrogen

The multiculture achieved the best nitrogen removal of the three cells. Two causes for a better performance are suggested by the literature (Gunnison and Barko 1989). The first is that the rooting depths amongst plant species created a greater area used by the plant root zone than in either monoculture. This means a greater volume of wetland was available for removal of nutrients than in the monocultures. The second is that emergent plant/microbial associations are complex and may vary from plant species to species. Additionally, not all microorganisms process the same substances over a the same amount of time. Different plant species have varying proportions of microorganism types which means that some associations will be better sequestering certain nutrients than others.

Total and Fecal Coliform Bacteria

There was so much variability in the results of the total coliform analyses (Figures 18-20) that it is not possible to detect statistical differences in performance between the wetland cells. Furthermore, the fact that the influent total coliform concentration exceeded the highest measurable

concentration makes it impossible to calculate the actual coliform removal. The last samples, collected on June 24, 1993, may have been improperly analyzed as all but one of them were found to have greater than the maximum detectable coliform concentration. If this sample is ignored, it is clear that each of the wetland channels is capable of providing, in excess of three orders of magnitude, destruction of total coliform organisms. It also is apparent that during low-flow conditions (i.e., prior to arrival of summer research staff), the wetlands are capable of providing nearly complete destruction of coliform organisms.

There is much less scatter in the fecal coliform results (Figures 21-23), possibly reflecting lack of organism regrowth in the wetland environment. Nevertheless, there is still too much variability to detect statistical differences in performance of the individual cells. One conclusion that can be drawn from these data is that the effluent fecal coliform concentrations are at least one order of magnitude lower than the total coliform concentrations.

Results confirm the ability of the constructed wetlands to provide a high degree of removal of total and fecal coliform organisms. However, the resulting water quality does not reliably meet New Mexico Drinking Water Act criteria for absence of these organisms. These results contained too much variability to detect any statistical difference in performance among the three wetland channels.

Future Research Needs

The most important research need is to measure the long term performance of each cell.

1. The long-term performance of each wetland cell should be investigated over a period of at least three years. Important parameters include removal of traditional wastewater constituents (i.e., BOD_5, nitrogen species, and coliform bacteria), plant diversity and growth including seasonal biomass production rates as a function of hydraulic and nutrient loading, and the hydraulic characteristics of each wetland cell, particularly with respect to plugging.

2. In the arid southwest water resources are especially precious. Accordingly a future study should include a complete water balance (inflow, outflow, groundwater infiltration, and evapotranspiration) as part of the study.
3. Wetland cells' response to transient hydraulic, pollutant, and nutrient loading resulting from little use of the research station during the academic year, followed by heavy use during the summer research season, must be examined.
4. Different operational strategies of wetland performance should be investigated. These include raising or lowering water levels in the SFS wetlands to improve performance during seasonal transients and/or harvesting wetland plants to determine which nutrients, their amount and percentage of total nutrients are removed by harvesting.
5. Planned perturbations and the responses of the multiculture and monocultures should be examined.
6. A closer examination of the plant/microorganism associations in each channel is needed:
    a. determining of what kinds of microbial associates and the proportions of different microorganisms, and
    b. altering associations between plants and microorganisms to determine if system efficiency of processing can be changed.
7. Examine ways to maximize wastewater improvement so that water from the SFS wetland can be used for irrigation or to create wildlife habitat.
8. Study the means of improving nitrification by:
    a. supplemental aeration,
    b. alternative fill and drawdown,
    c. recirculation with air entrainment,
    d. the effects of changing plant associations on oxygen transfer.

9. Study the means of improving denitrification:
    a. bed depths,
    b. root zone depths, and
    c. additional of carbon supply via a direct line from the primary treatment source to the rear end of the cell.

BIBLIOGRAPHY

Andrews, T.L. 1990. Constructed wetlands for treating 450, 1,000 and 10,000 gpd of septic effluent. In Proceedings of the Municipal Marshlands Conference. Show Low, Arizona, September 1990.

Armstrong, W. 1964. Oxygen diffusion from the roots of some British bog plants. Nature. 204:801.

Armstrong, W. 1978. Root aeration in the wetland Condition.In Plant Life in Anaerobic Environments. Edited by D. Hook and R.M. Crawford. Ann Arbor Science Publications, Ann Arbor, Michigan. 269.

Bastian, R. 1990. Needs and problems in sewage treatment and effluent disposal facing small communities; the role of wetland treatment alternative. In Proceedings of the Municipal Marshlands Conference. Show Low, Arizona, September 1990.

Brewer, S. 1991. Manmade wetlands filter water naturally. The Albuquerque Journal. 6 January 1991: pages B1 and B3.

Brix, H. 1987. Treatment of wastewater in the rhizosphere of wetland plants—the root-zone method. Water Science Technology. 19:107.

Brix, H. 1993a. Wastewater treatment in constructed wetland: System design, removal processes, and treatment performance. In Constructed Wetlands for Water Quality Improvement. Edited by Gerald A. Moshiri, 9-22, Ann Arbor, Lewis Publishers, CRC Press, Inc.

Brix, H. 1993b. Macrophyte-mediated oxygen transfer in wetlands: Transport mechanisms and rates. In Constructed Wetlands for Water Quality Improvement. Edited by Gerald A. Moshiri, 391-398. Ann Arbor, Lewis Publishers, CRC Press, Inc.

Chapelle, F.H. 1993. Ground-water Microbiology and Geochemistry. New York, John Wiley and Sons, Inc.

CH2M-Hill. 1990. Ground-water Report for the Ground-Water Protection Policy and Action Plan, City of Albuquerque, Country of Bernalillo, New Mexico. Albuquerque, New Mexico.

Choate, K.D., J.T. Watson, and G.R. Steiner. 1993. TVA's constructed wetlands demonstration. In Constructed Wetlands for Water Quality Improvement. Edited by Gerald A. Moshiri, 509-516. Ann Arbor, Lewis Publishers, CRC Press, Inc.

Coleman, R. 1994. A constructed wetland at high elevation in north central New Mexico: Inorganic nitrogen removal and resistance to freezing in New Mexico. Proceedings of the Alternative On-Site Liquid Waste Disposal Technologies Conference. Bernalillo County Environmental Health Department.

Conley, L. M., R.I. Dick, and L.W. Lion. 1991. An assessment of the root zone method of wastewater treatment, Research Journal of the Water Pollution Control Federation. 63:239-247.

Cooper, P.F. 1993. The use of reed bed systems to treat domestic sewage: The european design and operations guidelines for reed bed treatment systems. In Constructed Wetlands for Water Quality Improvement. Edited by Gerald A. Moshiri, 203-217. Ann Arbor, Lewis Publishers, CRC Press, Inc.

Dahm, C.N., E.H. Trotter, and J.R. Sedell 1987. Role of anaerobic zones and processes in steam ecosystem productivity. 157-178. In Chemical Quality of Water and the Hydrologic Cycle. R.C. Averett and D.M. McKnight (eds). Chelsea, Michigan, Lewis Publishers, Inc.

Dornbush, J.N. 1993. Constructed wastewater wetlands: The answer in South Dakota's challenging environment. In Constructed Wetlands for Water Quality Improvement. Edited by Gerald A. Moshiri, 569-576. Ann Arbor, Lewis Publishers, CRC Press, Inc.

Gallaher, J.H. and D.M. McQuillan. 1987. Groundwater Quality and Public Health. Albuquerque South Valley. New Mexico Environmental Improvement Division.

Gaume, Norm. 6 March 1994. Personal Communication.

Gersberg, R.M. 1986. Role of aquatic plants in waste water treatment by artificial wetlands. Water Research 20:363-367.

Green, M.B. and J. Upton. 1993. Reed bed treatment for small communities: U.K. experience. In Constructed Wetlands for Water Quality Improvement. Edited by Gerald A. Moshiri, 517-524. Ann Arbor, Lewis Publishers, CRC Press, Inc.

Grisham, A. D., A. Richards and other New Mexico Environmental Department and State Engineer Office staff. 1991. The Rural Homeowner's Water Guide. New Mexico State Engineer Office, New Mexico Environment Department.

Gunnison, D. and J.W. Barko. 1989. The rhizosphere ecology of submerged macrophytes. Water Resources Bulletin. 25:193.

Hammer, D.A., (ed). 1989. Constructed Wetlands for Wastewater Treatment: Municipal, Industrial, and Agricultural. Chelsea, Michigan, Lewis Publishers.

Hatano, K., C.C. Trettin, C.H. House, and A. G. Wollum, II. 1993. Microbial populations and decomposition activity in three subsurface flow constructed wetlands. In Constructed Wetlands for Water Quality Improvement. Edited by Gerald A. Moshiri, 541-547. Ann Arbor, Lewis Publishers, CRC Press, Inc.

Heggen, R.J., B.M. Thomson, J.R. Mathews, and A. Tefera. 1979. Groundwater Quality Study for the City of Albuquerque, North Valley: Bureau of Engineering Research Report No. CE-49. Albuquerque. City of Albuquerque.

Lekven, C.C., R.W. Crites, and R.A. Beggs. 1993. Subsurface flow wetlands at Mesquite, Nevada. In Constructed Wetlands for Water Quality Improvement. Edited by Gerald A. Moshiri, 261-267. Ann Arbor, Lewis Publishers, CRC Press, Inc.

Martin, H. Personal Communication. April 6,1994. New Mexico Water Utilities and Technical Assistance Program, Santa Fe, New Mexico.

Martin, W.C. and C.R. Hutchens. 1980. A Flora of New Mexico. 1980. Vaduz, Germany. J. Cramer.

McKee, K.L., I.A. Mendelssohn, and D. M. Burdick. 1989. Effects of long-term flooding on root metabolic response in five freshwater marsh plant species, Canadian Journal of Botany. 67:346.

Metcalf and Eddy, Inc. 1991. Wastewater Engineering, 3rd Edition. New York, New York, McGraw-Hill, Inc.

Moshiri, Gerald A. (ed). 1993. Constructed Wetland for Water Quality Improvement. Ann Arbor, Lewis Publishers, CRC Press, Inc.

Ogden, M.N. 1990. The treatment of septage using natural systems. In Proceedings of the Municipal Marshlands Conference. Show Low, Arizona, September 1990.

Reed, S.C., Chairman, Task Force on Natural Systems. 1988. Natural Systems for Waste Management and Treatment. Manual of Practice FD-16. New York, McGraw Hill Book Company.

Reed, S.C. 1990. An Inventory of Constructed Wetlands Used foWastewater Treatment in the United States. Prepared for USEPA RREL, Cincinnati, Ohio.

Reed, S.C. and R.W. Crites. 1984. Handbook of Land Treatment Systems for Industrial and Municipal Wastes. Noyes Publication, Park Ridge, New Jersey.

Reddy, K.R. and W. F. DeBusk 1987. Nutrient storage capabilities of aquatic plants. In Aquatic Plants for Water Treatment and Resource Recovery. K.R. Reddy and W.H. Smith, (eds.). 337-357. Magnolia Publishing Inc., Florida.

Shutes, R.B., J.B. Ellis, D.M. Revitt, and T.T. Zhang. 1993. The use of Typha latifolia for wetlands for heavy metal pollution control in urban wetlands. In Constructed Wetlands for Water Quality Improvement. Edited by Gerald A. Moshiri. 407-414. Ann Arbor, Lewis Publishers, CRC Press, Inc.

Smith, Craig S., M.S. Adams, and T.D. Gustafson. 1988. The importance of below ground mineral element stores in Cattails (*Typha latifolia* L.). Aquatic Botany. 30:343-352.

Standard Methods for the Examination of Water and Wastewater, 18th edition, 1993. L.S. Clesceri, A. Greenberg, and R. Tussell (eds). Washington D.C., American Public Health Association.

Steiner, G.R., J.T. Watson, D.A. Hammer, and D.F. Harker. 1987. Municipal wastewater treatment with artificial wetlands—a TVA/Kentucky demonstration. In Aquatic Plants for Water Treatment and Resource Recovery. Edited by K.R. Reddy and W.H Smith, 923. Magnolia Publishers, Magnolia, Florida.

Steiner, G.R., J.T. Watson, and K.D. Choate. 1993. General design, construction and operation guidelines for small constructed wetlands wastewater treatment systems. In Constructed Wetlands for Water Quality Improvement. Edited by Gerald A. Moshiri, 499-508. Ann Arbor, Lewis Publishers, CRC Press, Inc.

Steiner, G.R. and D.W. Combs. 1993. Small constructed wetlands systems for domestic wastewater treatment and their performance. In Constructed Wetlands for Water Quality Improvement. Edited by Gerald A. Moshiri, 491-498. Ann Arbor, Lewis Publishers, CRC Press, Inc.

Stengel, E. 1993. Species-specific aeration of water by different vegetation types in constructed wetland. In Constructed Wetlands for Water Quality Improvement. Edited by Gerald A. Moshiri, 427-434. Ann Arbor, Lewis Publishers, CRC Press, Inc.

Thomson, B.M. and D.M. McQuillan 1984. Nitrate contamination in groundwater in Albuquerque, 204-216. In Selected Papers on Water Quality and Pollution in New Mexico. Proceedings of a symposium on Water Quality and Pollution in New Mexico. Compiled by W. J. Stone. Hydrologic Report #7. Socorro, New Mexico. New Mexico Bureau of Mines and Minerals. A Division of New Mexico Institute of Mining and Technology.

Trotter, E.H., D. Tafoya and L. Sandoval. 1990. Plant distribution and competition in floodplains may be influenced by the ability to use different forms of nitrogen. Poster. Ecological Society Meeting. Snowbird, Utah.

U.S. Environmental Protection Agency 1988. Office of Research and Development, Center for Environmental Research Information. Design Manual. Constructed Wetlands and Aquatic Plant Systems for Municipal Wastewater Treatment. EPA/625/1-88/02.

U.S. Environmental Protection Aagency—Region 6. 1993. Water Management Division Municipal Facilities Branch Technical Section. Guidance for Design and Construction of a Subsurface Flow Constructed Wetland.

Wetzel, R.G. 1993. Constructed wetlands: Scientific foundations are critical. In Constructed Wetlands for Water Quality Improvement. Edited by Gerald A. Moshiri, 3-7. Ann Arbor, Lewis Publishers, CRC Press, Inc.

Wilhelm, M., S.R. Lawry, and D.D. Hardy. 1990. Creation and management of wetlands using municipal wastewater in northern Arizona: A status report. In Proceedings of the Municipal Marshlands Conference. Show Low, Arizona.

Wolverton, B.C. and R.C. McDonald. 1979. Upgrading facultative wastewater lagoons with vascular aquatic plants. Journal of the Water Pollution Control Federation. 51:305-313.

Wolverton, B.C. 1987. Artificial marshes for wastewater treatment and resource recovery. In Aquatic Plants for Water Treatment and Resource Recovery. Magnolia Publishing Inc., Magnolia, Florida.