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Design Manual

Constructed Wetlands and Aquatic Plant Systems for Municipal Wastewater Treatment

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Notice

Contents

Chapter **Page**

Contents (continued)

Figures

Number **Page**

Contents (continued)

Tables

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CHAPTER 1

Aquatic Treatment System

1 .1 Introduction

The trend over the past 70 years in the construction of water pollution control facilities for metropolitan areas has been toward “concrete and steel” alternatives. With the advent of higher energy prices and higher labor costs, these systems have become significant cost items for the communities that operate them. For small communities in particular, this cost represents a higher percentage of the budget than historically allocated to water pollution control. Processes that use relatively more land and are lower in energy use and labor costs are therefore becoming attractive alternatives for these communities.

The high cost of some conventional treatment processes has produced economic pressures and has caused engineers to search for creative, cost-effective and environmentally sound ways to control water pollution.

One technical approach is to construct artificial ecosystems as a functional part of wastewater treatment. Wastewater has been treated and reused successfully as a water and nutrient resource in agriculture, silviculture, aquaculture, golf course and green belt irrigation. The conceptual change that has allowed these innovative processes is to approach wastewater treatment as “water pollution control” with the production of useful resources (water and plant nutrients) rather than as a liability.

The interest in aquatic wastewater treatment systems can be attributed to three basic factors:

1. Recognition of the natural treatment functions of aquatic plant systems and wetlands, particularly as nutrient sinks and buffering zones.

2. In the case of wetlands, emerging or renewed application of aesthetic, wildlife, and other incidental environmental benefits associated with the preservation and enhancement of wetlands.

3. Rapidly escalating costs of construction and operation associated with conventional treatment facilities.

7.7.7 Scope

Application of wastewater to wetlands and aquatic pond systems must be free of unreasonable risks to public health. Pathogenic organisms may be present in both wastewaters and sludges and their control is one of the fundamental reasons for waste management. Public health considerations of aquatic plant systems and constructed wetlands are discussed in Chapter 2.

The portion of this manual concerning constructed wetlands (Chapter 3) focuses on studies of pilot- and full-scale systems that have published results. The general case in favor of constructed wetland systems is tied to the fact that they can operate in cold as well as warm climates.

The discussion of aquatic plant systems (Chapter 4) concentrates on the results with water hyacinth systems operated in the warm southern regions of the United States. A few duckweed systems have been tried either alone or in conjunction with hyacinths. The projects discussed in this manual reflect this geographical distribution of project sites and of the plant species that have been studied extensively.

A list of existing constructed wetlands and aquatic plant systems is presented in Appendix A.

7.7.2 Potential Uses of Natural Systems

Where natural wetlands are located conveniently to municipalities, the major cost of implementing a discharge system is for pumping treatment plant effluent to the site. Once there, further wastewater treatment occurs by the application of natural processes. In some cases, the wetland alternative can be the least cost advanced wastewater treatment and disposal alternative. In locations where poorly drained land that is unsuitable for land application is available, wetlands can often be constructed inexpensively with minimal diking.

In considering the application of wastewaters to wetlands, the relationship between hydrology and ecosystem characteristics needs to be recognized. Factors such as source of water, velocity, flow rate, renewal rate, and frequency of inundation have a major bearing on the chemical and physical properties of the wetland substrate. These properties in turn influence the character and health of the ecosystem, as reflected by species composition and richness, primary productivity, organic deposition and flux, and nutrient cycling (1). In general, water movement through wetlands tends to have a positive impact on the ecosystem (2). Rather than wasting water, upland swamps appear to save water and thus promote increased regional production indirectly (3).

1.2 Classification

In aquatic systems, wastewater is treated principally by means of bacterial metabolism and physical sedimentation, as is the case in conventional activated sludge and trickling filter systems. The aquatic plants themselves bring about little actual treatment of the wastewater (4). Their function is generally to support components of the aquatic environment that improve the wastewater treatment capability and/or reliability of that environment (5). Some specific functions of aquatic plants in aquatic treatment systems are summarized in Table 1-1 The morphology of some typical aquatic plants is shown schematically in Figure 1-1.

Table 1-1. Functions of Aquatic Plants In Aquatic Treatment Systems (8)

Plant Parts	Function
Roots and/or stems in the water column	1. Surfaces on which bacteria grow 2. Media for filtration and adsorption of solids
Stems and/or leaves at or above the water surface	1. Attenuate sunlight and thus can prevent the growth of algae 2. Reduce the effects of wind on the water, i.e., the transfer of gases between the atmosphere and water 3. Important in the transfer of gases to and from the submerged parts of plant.

Wetlands are those areas that are inundated or saturated by surface or ground water at a frequency and duration sufficient to maintain saturated conditions. These can be either preexisting natural wetlands (e.g. marshes, swamps, bogs, cypress domes and strands, etc.) or constructed wetland systems. Constructed systems can range from creation of a marsh in a natural setting where one did not permanently exist before to intensive construction involving earth moving, grading, impermeable barriers or erection of containers such as tanks or trenches. The vegetation that is introduced or emerges from these constructed systems will generally be similar to that found in the natural wetlands (6).

There are three basic functions of wetlands that make them potentially attractive for wastewater treatment (7):

1. Physical entrapment of pollutants through sorption in the surface soils and organic litter.

2. Utilization and transformation of elements by microorganisms.

3. Low energy and low maintenance requirements to attain consistent treatment levels.

Wetlands are comparatively shallow (typically less than 0.6 m (2 ft)) bodies of slow-moving water in which dense stands of water tolerant plants such as cattails, bulrushes, or reeds are grown. In man-made systems, these bodies are artificially created and are typically long, narrow trenches or channels (8).

Three major systems involving wastewater and wetlands can be observed in the United States (9).

1. Disposal of treated effluent into natural wetlands

2. Use of effluents or partially treated wastewater for enhancement, restoration, or creation of wetlands

3. Use of constructed wetlands for wastewater treatment

These three categories provide some degree of wastewater treatment, either directly or indirectly. In the United States, however, there are some constraints on the use of natural wetlands as functional components of wastewater treatment systems.

Almost all natural wetlands are waters of the United States and, as such, a permit is required for any discharge. The water quality requirements for this discharge are specified by the applicable federal, state, and/or local agencies and typically are at least equal to secondary effluent standards. 1O)

On the other hand, constructed wetlands designed and built for the express purpose of treating municipal wastewater are not waters of the United States.

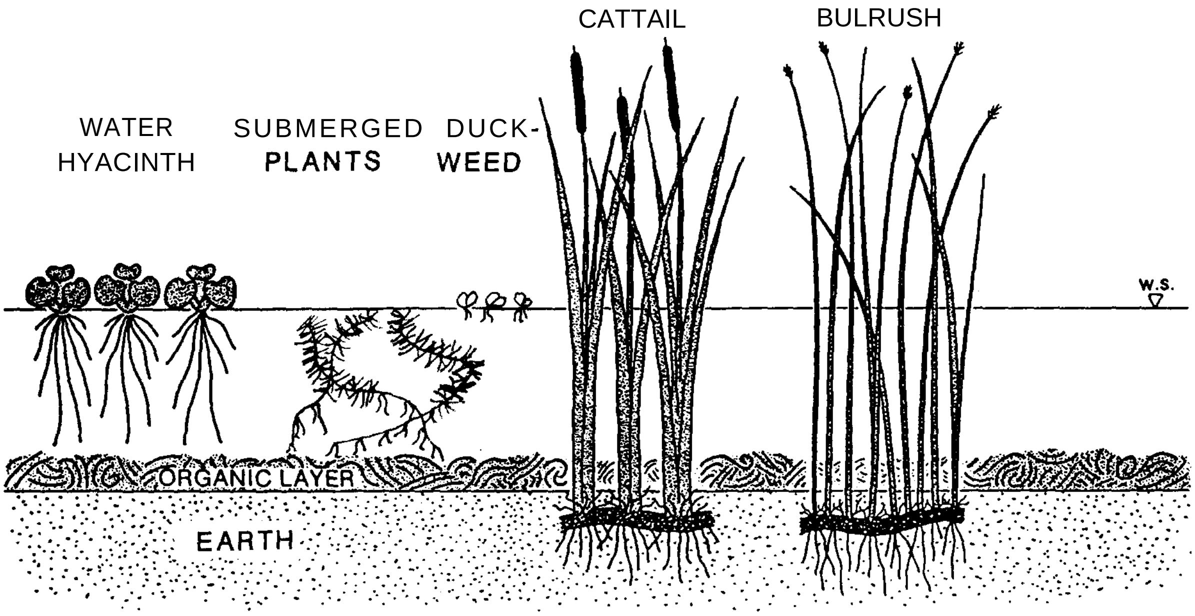
There are three categories of aquatic treatment systems considered in this manual:

1. Natural Wetlands
2. Constructed Wetlands
3. Aquatic Plant Systems

7.2.1 Natural Wetlands

While the interest in wetlands for wastewater treatment is fairly recent, the term wetlands is also a relatively new expression, encompassing what for years have simply been referred to as marshes, swamps, or bogs. The difference in these wetlands is related to a large extent to the vegetation which dominates the area. Grasses or forbs are generally

Figure I-I. Common aquatic plants.



dominant in marshes, trees and shrubs characterize swamps, and sedge/peat vegetation occurs in various bogs.

Natural wetlands are effective as wastewater treatment processes for a number of reasons. Natural wetlands support a large and diverse population of bacteria which grow on the submerged roots and stems of aquatic plants and are of particular importance in the removal of BOD_5 from wastewater. In addition, the quiescent water conditions of a wetland are conducive to the sedimentation of wastewater solids. Other aspects of wetlands that facilitate wastewater treatment are the adsorption/filtration potential of the aquatic plants' roots and stems, the ion exchange/adsorption capacity of wetlands' natural sediments, and the mitigating effect that the plants themselves have on climatic forces such as wind, sunlight and temperature (9).

Natural wetland systems are typically characterized by emergent aquatic vegetation such as cattails *(Typha),* rushes (Scirpus), and reeds *(Phragmites).* They can also contain some of the floating and submerged plant species discussed in Chapter 4 as well as phreatophytes (plants whose roots extend to the ground-water table or the saturated soil area immediately above it) (10). Most states (except Florida, and a few others considering special wetland standards) make no distinction between the wetland and the adjacent surface waters and apply the same requirements to both. Under these conditions, economics will not favor the utilization of natural wetlands as a major component in a wastewater treatment process as the basic treatment must be provided prior to discharge to the wetland.

Special situations may arise in which natural wetlands may provide further effluent polishing or, if the wetland is isolated from other surface waters, more basic treatment. The use of treated effluent for enhancement, restoration, or creation of wetlands can be a very desirable and environmentally compatible activity (10).

7.2.2 Constructed Wetlands

Studies in the United States have focused on peatlands, bogs, cypress domes and strands, as well as cattails, reeds, rushes, and related plants in wetland settings (6). Constructed wetlands are either free water surface systems (FWS) with shallow water depths or subsurface flow systems (SFS) with water flowing laterally through the sand or gravel. A constructed wetland involving bulrushes in gravel filled trenches was developed at the Max Planck Institute in West Germany. This patented process has seen limited application to date in the United States.

The constructed wetlands at Santee, California, was operated in a similar fashion.

1.2.3 Aquatic Plant Systems

Aquatic plant systems are shallow ponds with floating or submerged aquatic plants. The most thoroughly studied systems are those which use water hyacinth or duckweed. These systems include two types based on the dominant plant types. The first type uses floating plants and is distinguished by the ability of these plants to derive their carbon-dioxide and oxygen needs from the atmosphere directly. The plants receive their mineral nutrients from the water. The second type of system consists of submerged plants and is distinguished by the ability of these plants to absorb oxygen, carbon-dioxide, and minerals from the water column. Submerged plants are relatively easily inhibited by high turbidity in the water because their photosynthetic parts are below the water.

1.3 Natural Wetlands

Examples of pollutant removal in natural wetlands receiving treated wastewater are presented in Table 1-2. The values for percent removal show quite a range for treatment. This summary table is included to indicate the general finding for natural wetlands systems, i.e., that levels of removal for BOD_5 and SS can be high but are not consistently high. Nutrient removals from several specific natural wetlands projects are presented in Table 1-3 (11).

Table 1-2. Percent **Removal for Several Pollutants from Secondary Effluent in Natural Wetlands (6)**

Pollutant	Removal, percent
BOD_5	70-96
Suspended Solids	60-90
Nitrogen	40-90
Phosphorus	Seasonal

Current experience with wetland systems is generally limited to the further treatment of secondary effluents (6). Factors to be considered are potential disruption of the existing wildlife habitat and ecosystems in a natural wetland, loss of water via evapotranspiration for all wetlands in arid climates, the potential for increased breeding of mosquitos or flies, and the development of odor. The major benefits that can be realized from use of wetlands include preservation of open space, wildlife habitat enhancement, increased recreation potential, streamflow stabilization and augmentation in addition to wastewater treatment (6).

1.4 Constructed Wetlands

Constructed wetlands have the positive characteristics of a natural wetland and can also be controlled to eliminate the negative aspects of natural wetlands. The removal efficiency of typical pollutants are reported in Table 1-4.

Bacteria attached to plant stems and the humic deposits are the major factor for BOD_5 removal. With respect to phosphorus removal, the contact opportunities with the soil are limited in most natural wetland systems (an exception might be peat bogs) and release of phosphorus has been observed during the winter in some cases. The surface area for constructed marshes ranges from 24.6 to 39.6 m^2/m^3 of applied wastewater per day (23-37 ac/mgd) (6).

The major costs and energy requirements for constructed wetlands are associated with pre-application treatment, pumping and transmission to the site, distribution at the site, minor earthwork, and land costs. In addition, a constructed system may require the installation of a barrier layer to limit percolation to groundwater and additional containment structures in case of flooding (6).

Possible constraints to the use of constructed wetlands for wastewater treatment include the following:

1. Geographical limitations of plant species, as well as the potential that a newly introduced plant species will become a nuisance or an agricultural competitor.
2. Constructed wetlands that discharge to surface water require 4 to 10 times more land area than a conventional wastewater treatment facility. Zero-discharge constructed wetlands require 10 to 100 times the area of conventional wastewater treatment plants. An example of a zero-discharge system is the Incline Village Wetlands Enhancement Facility near Carson City, Nevada.
3. Plant biomass harvesting is constrained by high plant moisture content and wetland configuration.
4. Some types of constructed wetlands may provide breeding grounds for disease producing organisms and insects and may generate odors if not properly managed.

Constructed wetlands, however, offer the engineer greater hydraulic control for general use and are not restricted by many of the environmental concerns and user conflicts associated with natural wetlands. Unlike natural wetlands, which are confined by availability and proximity to the wastewater source, constructed wetlands can be built anywhere, including lands with limited alternative uses. They also offer greater flexibility scope for design and management options and thus may provide superior performance and reliability (1).

1.4.1 Free Water Surface Systems (FWS)

These systems typically consist of basins or channels, with some sort of subsurface barrier to

Table 1-3. **Summary of Nutrient Removal from Natural Wetlands**

Project	Flow, m^3/d	Wetland Type	Percent Reduction TDP[a]	NH_3-N	NO_3-N	TN[b]
Brillion Marsh, WI	757	Marsh	13		51	
Houghton Lake, MI	379	Peatland	95	71	99[c]	-
Wildwood, FL	946	Swamp/Marsh	98			90
Concord, MA	2,309	Marsh	47	58	20	
Bellaire, MI	1,136[d]	Peatland	88			64
Coots Paradise, Town of Dundas, Ontario, Canada	-	Marsh	80			60-70
Whitney Mobile Park, Home Park, FL	-227	Cypress Dome	91			89

[a] Total dissolved phosphorus.
[b] Total nitrogen.
[c] Nitrate and nitrite.
[d] May-November only.

Table 1-4. **Summary of Nutrient Removal from Constructed Wetlands**

Project	Flow, m^3/d	Wetland Type	BOD_5, mg/L Influent	BOD_5, mg/L Effluent	SS, mg/L Influent	SS, mg/L Effluent	Percent Reduction BOD_5	Percent Reduction SS	Hydraulic Surface Loading Rate, m^3 ha-d
Listowel, Ontario (12)	17	FWS[a]	56	10	111	a	82	93	
Santee, CA (10)		SFS[b]	118	30	57	5.5	75	90	
Sidney, Australia (13)	240	SFS	33	4.6	57	4.5	86	92	
Arcata, CA	11,350	FWS	36	13	43	31	64	28	907
Emmitsburg, MD	132	SFS	62	18	30	8.3	71	73	1,543
Gustine, CA	3,785	FWS	150	24	140	19	64	86	412

[a] Free Water Surface System.
[b] Subsurface Flow System.

prevent seepage, soil or another suitable medium to support the emergent vegetation, and water at a relatively shallow depth flowing through the unit. The shallow water depth, low flow velocity, and presence of the plant stalks and litter regulate water flow and, especially in long, narrow channels minimize short circuiting.

Results from Listowel, Ontario are related in Chapter 3 to theoretical results using mathematical modeling for BOD_5 removal. The general result, shown in Chapter 3, is that Equation 3-5 gives correct order-of-magnitude predictions of the system response. For greater accuracy in predicting effluent BOD_5 levels for a FWS, system the coefficient of specific surface for microbial growth must be estimated. This coefficient is related to the surface area of the vegetation stems and leaves in the water column. Predicted results are not extremely sensitive to this coefficient, as shown in Chapter 3. Water temperature has a large influence on microbial activity and must be known rather accurately to predict the extent of BOD_5 degradation in the constructed wetland.

1.4.2 Subsurface Flow Systems (SFS)

These systems are essentially horizontal trickling filters when they use rock media. They have the added component of emergent plants with extensive root systems within the media. Systems using sand or soil media are also used. Soil media systems designated as the Root-Zone-Method (RZM) were developed in West Germany.

A theoretical basis for design of a SFS is shown in Chapter 3 (Equation 3-7). Unlike the FWS system equation, in which the specific surface area is important but not critical, the media porosity is critical to predicting the required area for a given level of treatment. Media porosity has a direct mathematical relationship with the microbial degradation rate constant.

The general ability of the equations shown in Chapter 3 to predict the extent of BOD_5 removal should be used in conjunction with pilot studies. The mathematical and theoretical basis is not refined enough to allow engineering design of a treatment system from the equations alone.

1.5 Aquatic Plant Systems

1.51 Floating Plant Systems

The water hyacinth ***Eichhornia crassipes*** has been studied extensively for use in improving the wastewater effluent from oxidation ponds and as the major component in an integrated, advanced wastewater treatment system. The major characteristics of water hyacinths that make them an attractive biological support media for bacteria are their extensive root system and rapid growth rate. The major characteristic that limits their widespread use is their temperature sensitivity (i.e., they are rapidly killed by winter frost conditions.) Duckweed systems have been studied alone and as components of water hyacinths in polyculture systems.

The major advantage of duckweeds is their lower sensitivity to cold climates, while their major disadvantages have been their shallow root systems and sensitivity to wind. Several projects which have provided valuable performance data for water hyacinth and duckweed systems are summarized in Table 1-5. The Orlando and San Diego projects will be discussed in more detail in the case studies of Chapter 4.

1.5.2 Submerged Plant Systems

Submerged plants are either suspended in the water column or rooted in the bottom sediments. Typically, their photosynthetic parts are in the water column. The potential for use of submerged plants for polishing of effluent seems at least theoretically an attractive option. The tendency of these plants to be shaded out by algal growths and to be killed or severely harmed by anaerobic conditions limits their practical usefulness.

Table **1-5. Summary of Wastewater Treatment Performance of Aquatic Plant Systems**

			BOD_5, mg/L		SS, mg/L		Percent Reduction		Hydraulic Surface Loading Rate,
Project	Flow, m^3/d	Plant Type	Influent	Effluent	Influent	Effluent	BOD_5	SS	m^3/ha-d
Orlando, FL	30,280	Water Hyacinth	4.9	3.1	3.8	3	37	21	2,525
San Diego, CA	378	Water Hyacinth	160	15	120	20	91	83	590
NSTL, MS	8	Duckweed and Penny-wart	35	5.3	47.7	11.5	85	76	504
Austin, TX	1,700	Water Hyacinth	42	12	40	9	73	78	140
N. Biloxi, MS (Cedar Lake)	49	Duckweed	30	15	155	12	50	92	700
Disney World, FL	30	Water Hyacinth	200	26	50	14	87	72	300

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CHAPTER 2

Environmental and Public Health Considerations

2.1 Introduction

Protection of public health is the fundamental purpose of waste treatment. Environmental protection is the second major purpose. It is the responsibility of the engineers, scientists and public officials involved to ensure that waste treatment systems achieve this goal (1).

Two converging trends encourage engineers to consider natural processes such as constructed wetland systems and aquatic plant systems. The first trend is the ever increasing demand for water at a time when the least cost water sources have already been used. The second trend is the increasing volume of biological and chemical wastes that potentially enter the surface water system of the United States from wastewater treatment plants. The Clean Water Grant Program did much to upgrade water pollution control facilities so that the United States population could expect even higher standards of water quality.

The cost to construct and operate wastewater treatment facilities that accomplish advanced treatment in terms of further BOD_5 or nitrogen removal is high compared to the cost of primary and secondary treatment. The search for a different approach for polishing effluent and for nutrient removal has caused renewed interest in land application and wetlands application of effluent from conventional wastewater treatment facilities. Systems that are more “natural” in the sense that they are influenced more by natural environmental conditions of temperature, rainfall, sunlight, and wind action are useful alternatives to conventional systems. Compared to conventional systems, natural systems use less electrical energy and require less labor for operation.

From a public health and environmental health viewpoint, natural systems have potentially more points of contact with the environment and with the public, because of the larger land area involved in the system. Effluent monitoring is complicated because indicator organisms (total coliform bacteria counts) do not clearly indicate the extent of wastewater treatment (i.e., removal of pathogenic organisms). Any future application of treated wastewater to constructed wetland and aquatic plant systems must be free of unreasonable risks to public health. Public access to these systems can be controlled with fencing so that public health issues center on the characteristics of the effluent and health issues, if any, for the plant operators.

The principal contaminants of concern in wastewater fall into the following categories: nitrogen, phosphorus, pathogenic organisms, heavy metals, and trace organics. The pathogens include bacteria, viruses, protozoa and helminths. The heavy metals include cadmium, copper, chromium, lead, mercury, selenium, and zinc. Trace organics include highly stable synthetic compounds (especially chlorinated hydrocarbons).

The major health concern is possible pollution by nitrogen, metals, pathogens or organics. These pollutants and their potential pathways of greatest concern are summarized in Table 2-1.

Table 2-1. Pollutants and Pathways of Concern

Pollutant	Pathway
Nitrogen	
Health	Infant water supply
Environmental	Eutrophication
Phosphorus	
Health	No direct Impact
Environmental	Eutrophication
Pathogens	
Health	Water supplies, crops, aerosols
Environmental	Soil accumulation, Infect wildlife
Metals	
Health	Water supplies, crops, or animals in human food chain
Environmental	Long-term soil damage, toxic to plants or wildlife
Trace organics	
Health	Waler supplies, food chain, crops or animals
Environmental	Soil accumulation

2.2 Nitrogen

Nitrogen is limited in drinking water to protect the health of infants and may be limited in surface waters to prevent eutrophication. Nitrogen can be removed in pond systems by plant or algal uptake, nitrification and denitrification and loss of ammonia gas to the atmosphere (evaporative stripping = volatilization). Nitrogen removal in aquatic plant systems is 26-96 percent, primarily due to nitrification/denitrification (2,3). In constructed wetlands, nitrogen removal ranges from 25-85 percent by the same mechanism (4).

2.3 Phosphorus

Phosphorus removal in wetlands and aquatic plant systems is not very effective because of the limited contact opportunities between the wastewater and the soil. A 28-57 percent phosphorus removal in the National Space Technology Lab studies with water hyacinths has been reported (5). The principal mechanisms for phosphorus removal are plant uptake or retention in the soil.

2.4 Pathogens

The pathogens of concern in aquatic treatment systems are parasites, bacteria, and viruses. The pathways of concern are to the surface waters receiving discharge from a constructed wetland or aquatic plant system. Pathways which are generally not a concern are groundwater contamination and offsite transmission via aerosols. Groundwater will not be contaminated in systems that are sealed by an impervious clay or synthetic material barrier.

Public health effects of wastewater treatment facilities include the influence on plant workers of aerosols from pond aerators. Based on several comprehensive investigations reported, it can be said that people who have been exposed to aerosolized microorganisms from wastewater treatment processes generally do not become infected or ill (6).

2.4.1 Parasites

Research has been conducted on transmission of parasitic diseases to animals and man by means of land application of municipal wastewater and sludge (6). A significant study completed at the San Angelo, Texas, wastewater irrigation site (7) indicated that parasites do not increase in cattle grazed or wastewater irrigated pastures during the period of the study. These results are similar to those reported earlier in Poland (8,9) and Australia (10). These studies, although not on wetlands systems, indicate that the potential for serious problems does not seem to be present.

2.4.2 Bacteria

Wildlife may be affected by wetlands systems because anaerobic muds may contain the causative organism of avian botulism *(Clostridium botulinum).* Control of this wildlife pathogen can be accomplished largely by multiple dispersion points for FWS wetlands. This pathogen is not a problem for wild fowl in SFS wetlands or aquatic plant systems.

The major paths for the transmission of human disease from wastewater are: direct contact with applied wastewater, aerosol transport, food chain, and improperly treated drinking water.

At Santee, California, subsurface flow systems (SFS) were studied with respect to the contribution of vegetation to removal of coliform bacteria in constructed wetlands. Each wetland bed consisted of a plastic lined (Hypalon, 0.76 mm) excavation, 18.5 m long x 3.5 m wide x 0.76 m deep (60.7 ft x 11.5 ft x 2.5 ft), containing emergent vegetation growing in gravel. Influent flow was from primary municipal wastewater. The hydraulic application rate was 5 cm (0.2 in)/d and the mean influent total coliform level of 6.75 x 107 MPN/100 mL was reduced to 5.77 x 106 MPN/100 mL (99 percent removal) in the vegetated bed (7). Hydraulic residence time was 5.5 days. The population decline of coliforms is due to sedimentation, filtration, and absorption. Sunlight has been shown to have a lethal effect on coliforms (11).

In a study of free water surface (FWS) wetlands in Listowel Ontario, Canada, fecal coliform removal efficiency was approximately 90 percent when operated at a 6-7 day residence time (12). Gearheart et al. found a total coliform removal efficiency of 93-99 percent during winter and 66-98 percent during summer at 7.5 days retention time in free water surface wetlands in Arcata, California (13).

Pathogenic bacteria and viruses are removed in aquatic plant systems by the same mechanisms as in pond systems. These include predation, sedimentation, absorption, and die-off from unfavorable environmental conditions, including UV in sunlight and temperatures unfavorable for cell reproduction. In order to quantify the magnitude of the contribution from the above mechanisms, Gersberg et al. (14) measured the rate of inactivation of coliform bacteria in sealed bags with in situ incubation below the gravel surface of a SFS wetland. The result when compared to the decay rate through the wetland system was twice that for the *in* situ decay rate (i.e., without contact with the wetland vegetation). The difference indicates that half the degradation is due to vegetation effects including bacterial absorption to root surfaces and substrate biofilm.

One strong advantage of constructed wetlands over natural wetlands is that the final effluent can be chlorinated. Chlorine disinfection of constructed wetland effluent and aquatic plant systems can produce waters suitable for unrestricted reuse applications, since total coliform levels can be reduced to <2 MPN/100 mL (7). There is a growing tendency to use chlorine as a disinfectant less often in cases where the production of trihalomethane

(THM) compounds is likely. Disinfection of wetland effluent with ultraviolet (UV) or ozone are alternatives that do not produce THMs.

2.4.3 Viruses

Viruses in most treatment systems are more resistant to inactivation than are bacteria. The removal efficiency of a SFS system was tested at Santee, California. An indicator of viral pollution (MS-2 bacteriophages) was reported to be 98.3 percent removed for a demonstration-scale (800 m^2 [8,600 sq ft]) bulrush bed at Santee at a detention time of 5.5 days (7). This involved spiking the influent wastewater with MS-2 virus and studying subsequent removal efficiency. MS-2 virus was chosen because it is an RNA bacteriophage nearly the same size as enteroviruses and is more resistant to UV light (15) heat (16) and disinfection (17) than most enteric viruses.

2.5 Metals

Heavy metals are common environmental pollutants that are produced as the result of industrial, commercial and domestic activities. New pretreatment standards require some industrial discharges, such as electroplating and metal finishing operations, to limit heavy metal levels to very low residual concentrations (18). Studies in New York City show that heavy metals can be found in municipal wastewater even when major industrial sources are not part of the system (19).

Conventional primary and secondary unit processes at municipal wastewater treatment plants are inadequate for efficient removal of heavy metals. Advanced processes including chemical precipitation, electrolysis, reverse osmosis, and ion exchange are used for pretreatment of known sources of heavy metals in industrial wastewater. Use of these processes to remove low concentrations of heavy metals in municipal wastewater has the disadvantage of high capital cost and high operation and maintenance costs. Additional disadvantages can be relatively high electrical power costs for electrolysis and reverse osmosis processes and production of large amounts of bulky sludges with long settling times in the chemical precipitation processes.

Since the metal-laden sludges are often disposed of in land fills, a treatment process that precipitates and holds heavy metals in the confined area of a constructed wetland accomplishes the same level of removal at lower labor and energy costs (i.e., the heavy metals are returned to the confined environment of the landfill or the constructed wetland). The goal of treatment for heavy metals is to remove the metals from the larger environment and from the food chain, especially the food chain in river and ocean waters, The heavy metals are deposited in landfills or wetlands depending on how they are removed.

Constructed wetlands (SFS) at Santee, California received municipal wastewater that was spiked with the heavy metals copper, zinc and cadmium. At hydraulic retention times of 5.5 days, removal efficiencies were 99, 97, and 99 percent respectively (20). The removal in the constructed wetlands was attributed to precipitation-adsorption phenomena. Chemical precipitation is enhanced by wetland metabolism, especially of algal cells which deplete dissolved CO_2 levels and raise the pH. Metals removal in MIS wetlands should not be expected to be significant. In one case, metals removal in a water hyacinth system was 85 percent for cadmium, 92 percent for mercury, and 60 percent for selenium (6).

2.6 Trace Organics

Municipal and industrial wastewaters contain variable concentrations of synthetic organic compounds. During 1960-1970, environmental researchers became aware of the tendency of some organic contaminants to resist removal in conventional wastewater treatment and to persist in the environment for very long periods. A more disturbing observation was that persistent, toxic compounds were found to accumulate in food chains because of the tendency of the compounds to be fat soluble. A compound can disappear from solution in an aqueous system by a number of mechanisms. Among the mechanisms are: biological, chemical, photochemical alternatives, and physicochemical processes such as absorption, sedimentation, and evaporative stripping. Biological degradation of easily degraded organic compounds is considered the most important of these (21).

Evaporative stripping is a major mechanism for land treatment systems that employ spray irrigation (6); however, it is not a major mechanism for organic compound removal from wetlands or aquatic plant systems. Absorption of trace organics by the organic matter and clay particles present in the treatment system is thought to be the primary physicochemical mechanism for removal of refractory compounds in wetlands and aquatic plant systems (6). The extent to which trace organics are removed by a water hyacinth system is shown in Table 2-2.

Table 2-2. Trace Organic Removal in Pilot-Scale Hyacinth Basins* (6)

Parameter	Conventration, pg/L Untreated Wastewater	Hyacinth Effluent
Benzene	2.0	Not Detexcted
Toulene	6.3	Not Detexcted
Ethylbenzene	3.3	Not Detexcted
Chlorobenzene	1.1	Not Detexcted
Chloroform	4.7	0.3
Chlorodibromomethane	5.7	Not Detexcted
1,1,1-Trichloroethane	4.4	Not Detexcted
Tetrachloroethylene	4.7	0.4
Phenol	6.2	1.2
Butylbenzyl phthalate	2.1	0.4
Diethyl phthalate	0.8	0.2
lsophorone	0.3	0.1
Naphthalane	0.7	0.1
1,4-Dichlorobenzene	1.1	Not Detexcted

*4.5 day detention time, 76 m^3/d flow, 3 sets of 2 basins each in parallel, plant density 10-25 k/m^2 (net weight).

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CHAPTER 3

Design of Constructed Wetlands

The use of constructed wetlands can be a cost-effective treatment alternative. Constructing a wetland where one did not exist before avoids the regulatory entanglements associated with natural wetlands and allows design of the wetland for optimum wastewater treatment. Typically, a constructed wetland should perform better than a natural wetland of equal area because the bottom is usually graded and the hydraulic regime in the system is controlled (1).

In addition to treating municipal wastewaters, constructed wetlands have been used for a variety of industrial applications. The fdree water surface (FWS) wetland is widely used as an inexpensive method of treating acid mine drainage (1). A FWS wetlands treatment facility for the Fabius Coal Preparation Plant, operated by the TVA, is described in the Case Studies section of this Chapter.

3.1 Types of Constructed Wetlands

Constructed wetlands include FWS, as well as the more recently developed subsurface flow systems (SFS). The latter systems involve subsurface flow through a permeable medium. The “root-zone method” and “rock-reed-filter” are other names for these systems that have been used in the literature. Because emergent aquatic vegetation is used in these systems they depend on the same basic microbiological reactions for treatment. The media type (soil or rock) affects the hydraulics of the system.

3.1.1 Free **Water** *Surface Systems with Emergent Plants*

A FWS system typically consists of basins or channels, with a natural or constructed subsurface barrier of clay or impervious geotechnical material to prevent seepage, soil or another suitable medium to support the emergent vegetation, and water at a relatively shallow depth flowing over the soil surface. The shallow water depth, low flow velocity, and presence of the plant stalks and litter regulate water flow and, especially in long, narrow channels, ensure plug-flow conditions **(1).**

3.1.2 Subsurface Flow Systems with Emergent Plants

A SFS wetland is a constructed wetland consisting of a trench or bed underlain with an impermeable layer of clay or synthetic liner. The bed contains media which will support the growth of emergent vegetation. The system is built with a slight inclination (1-3 percent) between inlet and outlet. As shown in Figure 3-1, primary or pond effluent is introduced into the end of the system where it flows into a transverse channel filled with broken stones.

Alternatively, the inlet channel can be perforated or gated pipe. From there the wastewater flows horizontally through the rhizosphere of the wetland plants. During the passage of the wastewater through the rhizosphere, the wastewater is treated by filtration, sorption and precipitation processes in the soil and by microbiological degradation. The resulting physical-chemical and biochemical processes correspond to the mechanical and biological processes in conventional mechanical treatment systems including denitrification. The effluent is collected at the outlet channel which is often filled with coarse gravel and may be discharged directly into the receiving water.

Within the class of constructed wetland systems, the SFS systems studied most completely in the United States are those with sand or rock media, (e.g., Santee, California; Emmitsburg, Maryland).

3.2 Site Selection

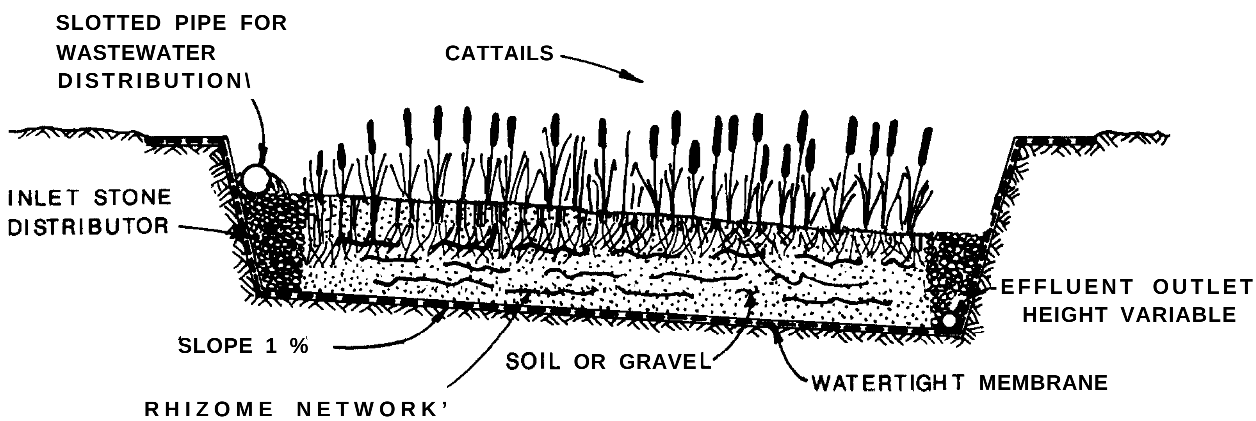
3.2.1 Topography

A constructed wetland can be constructed almost anywhere. The emergent plant species used can tolerate winter freezing much better than aquatic plant systems. In Ontario, experimental systems have been built in heavy clay soils (Listowel) and in an abandoned mine-tailing basin (Cobalt). Because grading and excavating represent a major cost factor, topography is an important consideration in the selection of an appropriate site.

3.2.2 Soil Permeability for Free **Water** *Surface Systems*

In selecting a site for a free water surface wetland the underlying soil permeability must be considered. The most desirable soil permeability is 10^{-6} to 10^{-7} m/s (0.14-0.014 in/hr) (2). Sandy clays and silty clay loams can be suitable when compacted. Sandy soils

Figure 3-1. Typical cross section - SFS system.



are too permeable to support wetland vegetation unless there is a restrictive layer in the soil profile that would result in a perched high ground water table. Highly permeable soils can be used for small wastewater flows by forming narrow trenches and lining the trench walls and bottom with clay or an artificial liner. In heavy clay soils, additions of peat moss or top soil will improve soil permeability and accelerate initial plant growth (3).

3.2.3 Hydrological Factors

The performance of any constructed wetland system is dependent upon the system hydrology as well as other factors. Precipitation, infiltration, evapotranspiration (ET), hydraulic loading rate, and water depth can all affect the removal of organics, nutrients, and trace elements not only by altering the detention time, but also by either concentrating or diluting the wastewater. A hydrologic budget should be prepared to properly design a constructed wetland treatment system. Changes in the detention time or water volume can significantly affect the treatment performance (4).

For a constructed wetland, the water balance can be expressed as follows:

$$Q_i - Q_o + P - ET = [dV/dt] \qquad (3\text{-}1)$$

where,

Q_i = influent wastewater flow, volume/time,
Q_o = effluent wastewater flow, volume/time,
P = precipitation, volume/time
ET = evapotranspiration, volume/time
V = volume of water, and
t = time.

Ground-water inflow and infiltration are excluded from Equation 3-1 because of the imperrneable barrier.

Historical climatic records can be used to estimate precipitation and evapotranspiration. Empirical methods such as the Thornthwaite equation can be used to estimate evapotranspiration. Pan evaporation measurements may be useful if the wetlands will contain a significant percentage of open water areas. If required, estimates of water losses due to infiltration can be obtained by conducting infiltration tests such as outlined in the *Design Manual for Land Treatment Systems* (5). Then, if the system operates at a relatively constant water depth (dV/dt = 0), the effluent flow rate can be estimated using Equation (3-1) (4).

3.2.4 Water Rights Considerations

In the western states, both riparian and appropriative water rights may be affected by adopting a constructed wetlands system. The effects can include site drainage (quality and quantity), change of location for surface water discharge, and reduction of the quantity of a surface water discharge. If an existing surface discharge is to be affected, replacement of downstream water rights may be necessary.

3.3 Performance Expectations

Wetland systems can significantly reduce biological oxygen demand (BOD_5), suspended solids (SS), and nitrogen, as well as metals, trace organics, and pathogens. The basic treatment mechanisms are listed in Table 3-1 and include sedimentation, chemical precipitation and adsorption, and microbial interactions with BOD_5, SS, and nitrogen, as well as some uptake by the vegetation. The performance of several pilot-scale wetland systems is summarized in Table 3-2.

Removal rates for a large-scale pilot study of a SFS system near Sidney, Australia, have been reported (6). Trenches were 100 m long x 4 m wide x 0.5 m

Table 3-1. Removal Mechanisms in Wetlands for the Contaminants in Wastewater (from 8)

Mechanism	Contaminant Effected[a]: Settleable Solids	Colloidal Solids	BOD	N	P	Heavy Metals	Refractory Organics	Bacteria and Virus	Description
Physical									
Sedimentation	P	S	I	I	I	I	I	I	Gravitational settling of solids (and constituent contaminants) in pond/marsh settings.
Filtration	S	S							Particulates filtered mechanically as water passes through substrate, root masses, or fish.
Adsorption		S							Interparticle attractive forces (van der Waals force).
Chemical									
Precipitation				P	P				Formation of or co-precipitation with insoluble compounds.
Adsorption				P	P	S			Adsorption on substrate and plant surfaces.
Decomposition						P		P	Decomposition or alteration of less stable compounds by phenomena such as UV Irradiation, oxidation, and reduction.
Biological									
Bacterial Metabolism[b]		P	P	P			P		Removal of colloidal solids and soluble organics by suspended, benthic, and plant-supported bacteria. Bacterial nitnfication/ denitrification.
Plant Metabolism[b]							S	S	Uptake and metabolism of organics by plants. Root excretions may be toxic to organisms of enteric origin.
Plant Adsorption				s	s	S	S		Under proper conditions, significant quantities of these contaminants will be taken up by plants.
Natural Die-Off								P	Natural decay of organisms in an unfavorable environment.

[a] P = primary effect; S = secondary effect; I = incremental effect (effect occurring incidental lo removal of another contaminant).
[b] The term metabolism includes both biosynthesls and catabolic reactions.

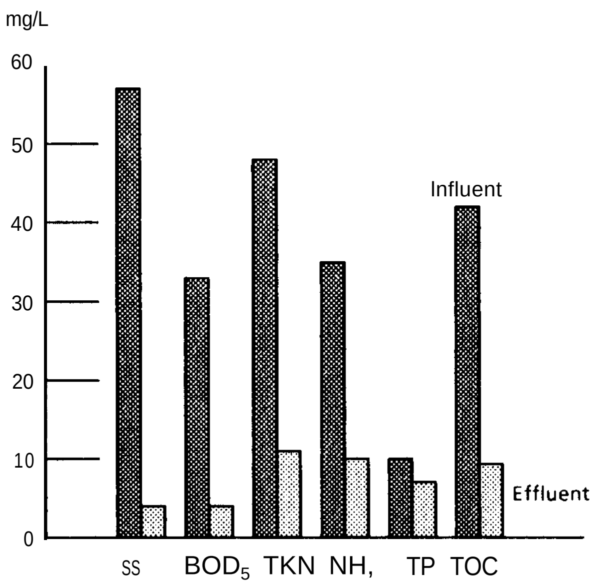
Table 3-2. Performance of Pilot-Scale Constructed Wetland Systems (1)

Location	Wetland Type	Effluent Concentration, mg/L: BOD_5	SS	NH_4	NO_3	TN	TP
Listowel, Ontario	Open water, channel	10	8	6	0.2	8.9	0.6
Arcata, CA	Open water, channel	<20	<8	<10	0.7	11.6	6.1
Santee, CA	Gravel-filled channels	<30	<8	<5	<0.2	-	
Vermontville, MI	Seepage basin wetland			2	1.2	6.2	2.1

* Alum treatment provided prior to the wetland component.

deep (328 ft x 13 ft x 1.6 ft) with gravel. Plant species studied were *Myriophyllum aquaticum* (parrot feather); *Schoenoplectus validus* (bulrush); and *Typha orientails* (cumbungi). Secondary effluent was the system influent flow. Hydraulic loading rate was 264 m^3/ha-d (28,225 gpd/ac), and detention time was 9 days. Typical influent and effluent concentrations are plotted in Figure 3-2. Examination of the plot reveals that the gravel planted emergent plant systems were able to remove significant levels of SS, BOD_5, and nitrogen. Phosphorus removal was slight, which is consistent with the experience of other researchers with rock and sand based systems.

Figure 3-2. Pilot-scale constructed wetland gravel planted trench with bulrush (6).



Gearheart and Finney (7) concluded from pilot studies on FSW wetlands in Arcata, CA, that wetlands have the ability to dampen spikes in effluent characteristics from an oxidation pond so that the wetland effluent is more stable and consistent. Constructed wetlands also reduce SS and fecal coliform levels and bring pH values to nearly neutral values. The ability of constructed wetlands to produce a consistent effluent from a low capital investment with low labor and energy requirements is a key benefit that is noteworthy.

The treatment processes that occur in an artificial wetland are similar to those that occur in other forms of land treatment. Removal of settleable organics occurs primarily as a result of sedimentation. Removal of colloidal and soluble organics occurs primarily by aerobic microbial oxidation.

3.3.1 BOD_5 Removal in FWS Wetlands

In FWS wetlands, removal of the soluble BOD_5 is due to microbial growth attached to plant roots, stems, and leaf litter that has fallen into the water. Because algae are typically not present if plant coverage is complete, the major sources of oxygen for these reactions are reaeration at the water surface and plant translocation of oxygen from the leaves to the rhizosphere (1).

Specific criteria presented below are suitable for low to moderate organic loadings. The organic loading should be distributed over a significant portion of the area and not applied at a single point. The design water depth should be 600 mm (24 in) (1) or less to ensure adequate oxygen distribution, and partial effluent recirculation might be considered in the summer months to overcome ET losses and maintain design flow rates and oxygen levels.

BOD_5 removal in a wetland has been described by a first-order model as follows (1):

$$[C_e/C_o = \exp(-K_T t) \qquad (3\text{-}2)$$

where,

C_e = effluent BOD_5, mg/L
C_o = influent BOD_5, mg/L
K_T = temperature-dependent first-order reaction rateconstant, d^{-1}
t = hydraulic residence time, d

Hydraulic residence time can be represented as:

$$t = LWd \div Q \qquad (3\text{-}3)$$

where,

L = length
W = width
d = depth
Q = average flow rate = ($flow_{in}$ + $flow_{out}$) ÷ 2

This equation represents hydraulic residence time for an unrestricted flow system.

In a FWS wetland, a portion of the available volume will be occupied by the vegetation, so the actual detention time will be a function of the porosity (n), which can be defined as the remaining cross-sectional area available for flow.

$$n = V_v \div V \qquad (3\text{-}4)$$

Where V_V and V are volume of voids and total volume, respectively.

The product (nod) is, in effect, the “equivalent depth” of flow in the system. The ratio of residence time from dye studies to theoretical residence time calculated from the physical dimensions of the system, should equal the ratio of n•d:d.

Combining the relationships in Equations 3-3 and 3-4 with the general model (Equation 3-2) results in Equation 3-5 (1):

$$C_e/C_o = A \exp[(-0.7\ K_T (A_v)^{1.75}\ L\ W\ d\ n) \div Q] \quad (3\text{-}5)$$

where,

- A = fraction of BOD_5 not removed as settleable solids near headworks of the system (as decimal fraction)
- A_v = specific surface area for microbial activity, m^2/m^3
- L = length of system (parallel to flow path), m
- W = width of system, m
- d = design depth of system, m
- n = porosity of system (as a decimal fraction)
- Q = average hydraulic loading on the system, m^3/d

The temperature-dependent rate constant is calculated from the rate constant for 20°C and the correction factor of 1.1 (9). The rate constant K_T (in d^{-1}) at water temperature T (°C) can therefore be defined by Equation 3-6.

$$K_T = K_{20}\ (1.1)^{(T-20)} \quad (3\text{-}6)$$

where K_{20} is the rate constant at 20°C.

Other coefficients in Equation 3-5 have been estimated (1).

- A = 0.52
- K_{20} = 0.0057 d^{-1}
- A_v = 15.7 m^2/m^3
- n = 0.75

Typical values used to test the equation against actual values at Listowel, Ontario, are listed in Table 3-3.

Table 3-3. Predicted vs. Actual C_e/C_o Values for Constructed Wetlands [Actual Values from Listowel, Ontario (1)]

Distance Along Channel, m	Summer		Winter	
	Predicted	Actual	Predicted	Actual
0	0.52	0.52	0.52	0.52
67	0.38	0.36	0.40	0.40
134	0.27	0.41	0.31	0.20
200	0.20	0.30	0.24	0.19
267	0.14	0.27	0.18	0.17
334 (final effluent)	0.10	0.17	0.14	0.17

For Listowel, Ontario:

- T = 17.8°C (summer), 3.0°C (winter)
- Q = 35 m^3/d (summer), 18.0 m^3/d (winter)
- W = 4 m
- d = 0.14 m (summer), 0.24 m (winter)

A sample calculation for the above coefficients using Equation 3-5 yields the following results:

- A = 0.52
- K_{20} = 0.0057 d^{-1}
- A_v = 15.7 m^2/m^3
- n = 0.75
- Y = 17.8°C (summer)
- Q = 34.6 m^3/d (summer)
- W = 4 m
- d = 0.14 m (summer), 0.24 m (winter)

Predicted C_e/C_o = 0.312 for L = 134 m
Predicted C_e/C_o = 0.187 for L = 267 m

Equation 3-5 is presented here as an example of the mathematical expression needed for design purposes. The coefficients have been estimated from the actual data at Listowel, Ontario. The sensitivity of the equation to the specific surface area (A_v), and the water temperature (T), were examined.

Figure 3-3 shows the sensitivity of the C_e/C_o ratio to A_v; it indicates that, for values of 12-16 m^2/m^3 (3.7-4.9 sq ft/cu ft), corresponding to an average reed stalk diameter of 12-16 mm (0.49-0.66 in), the C_e/C_o ratio can range from 0.18 to 0.098 at the end of a 335-m (1,100-ft) wetland channel. For a stalk diameter of 12 mm (0.5 in) and a vegetation volume of 5 percent, it was estimated that the specific surface area is 15.7 m^2/m^3 (4.8 sq ft/cu ft) (1). This is a parameter that cannot be measured directly in an actual wetland environment. It represents the surface area from all plant litter in the water column including the reed stems, leaves, and roots. The sensitivity of the equation to the specific area coefficient is not high. This means that specific area can be estimated and predicted results are likely to match actual results. If the equation proved to be sensitive to the estimate of specific area, then it would mean that this coefficient would have to be known accurately, which is not possible, and the equation would have been of limited value.

The sensitivity of Equation 3-5 to temperature was calculated by varying it in the range 5-25°C (41-77°F) for the predicted C_e/C_o ratio at Listowel. As shown in Figure 3-4, the degree of treatment at 5°C (41°F) is significantly reduced compared to that at 25°C (77°F). This indicates that the equation is sensitive to temperature and therefore temperature must be accurately predicted for use in the equation. As a practical matter, in winter the depth of the wetland must generally be increased to allow for ice depth. The increase in detention time in winter from greater depth has a compensating effect on the C_e/C_o ratio.

3.3.2 BOD^5 Removal in SFS Wetlands

The major oxygen source for the subsurface components (soil, gravel, rock, and other media, in

Figure 3-3. Sensitivity of C_e/C_o ratio to A_v.

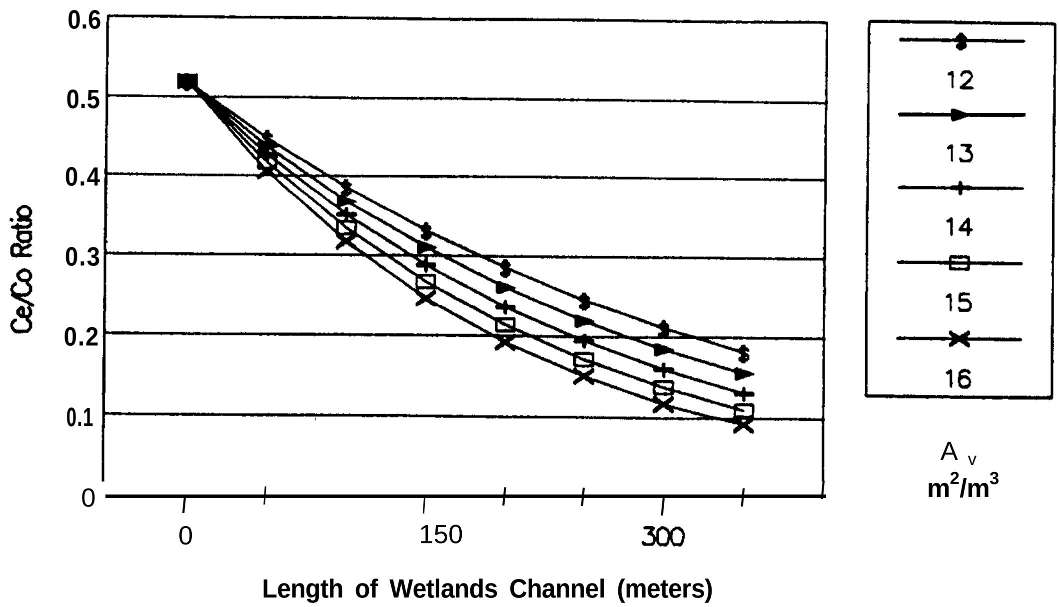
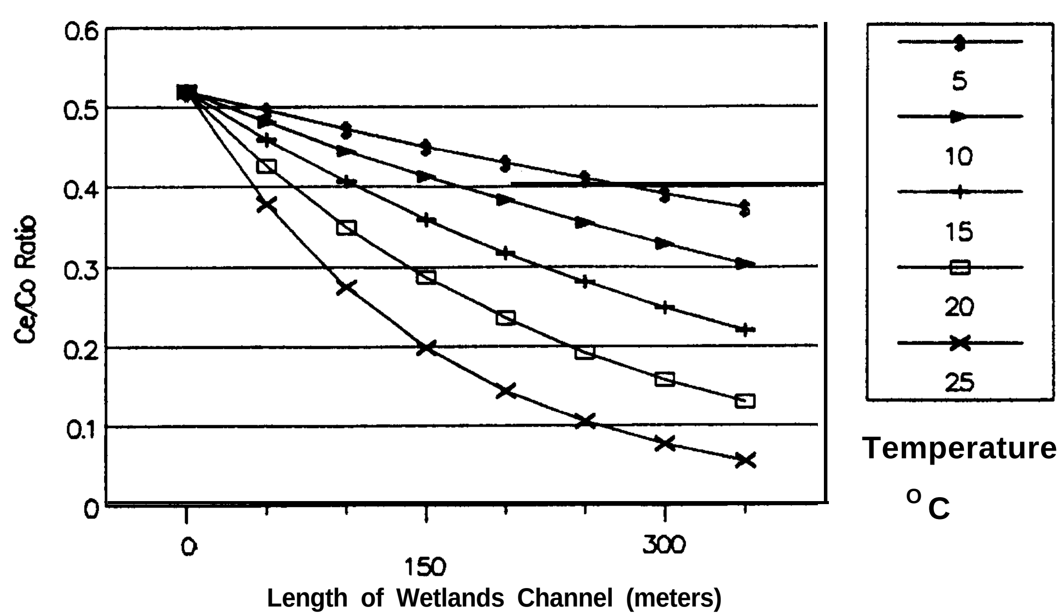


Figure 3-4. Sensitivity of C_e/C_o ratio to temperature.



trenches or beds) is the oxygen transmitted by the vegetation to the root zone. In most cases the subsurface flow system is designed to maintain flow below the surface of the bed, so there can be very little direct atmospheric reaeration (1). The selection of plant species is therefore an important factor.

Work at the pilot wetlands in Santee, California (10), indicated that most of the horizontally growing root mass of cattails was confined to the top 300 mm (12 in) of the profile. The root zone of reeds extended to more than 600 mm (24 in) and bulrushes to 760 mm (30 in.). In the cooler climate of western Europe the effective root zone depth for reeds is also considered to be 600 mm (24 in) (1). The gravel bed at the Santee system was 760 mm (30 in) deep, and the water level was maintained just below the surface (10). The BOD_5 removals observed in the three parallel bulrush, reed, and cattail units at Santee reflect the expanded aerobic zone made possible by the root penetration of the various plants.

Removal of BOD_5 in subsurface flow systems can be described with first-order plug-flow kinetics, as described in Equation 3-2 for free water surface systems. Equation 3-2 can be rearranged and used to estimate the required surface area for a subsurface flow system. Both forms of the equation are shown below for convenience.

$$[C_e/C_o] = \exp(-K_T t) \qquad (3\text{-}2)$$

$$A_s = [Q (\ln C_o - \ln C_e)] \div (K_T\ d\ n) \qquad (3\text{-}7)$$

where,

- C_e = effluent BOD_5, mg/L
- C_o = influent BOD_5, mg/L
- K_T = temperature-dependent first-order reaction rate constant, d^{-1}
- t = hydraulic residence time, d
- Q = average flow rate through the system, m^3/d
- d = depth of submergence, m
- = porosity of the bed, as a fraction
- A_s = surface area of the system, m^2

The cross sectional area for flow through a subsurface flow system is calculated according to the following equation:

$$A_c = Q \div k_s S \qquad (3\text{-}8)$$

where,

- A_C = d•W, cross-sectional area of wetland bed, perpendicular to the direction of flow, m^2
- d = bed depth, m
- R = bed width, m
- k_s =hydraulic conductivity of the medium, m^3/m^2-d
- S = slope of the bed, or hydraulic gradient (as a fraction or decimal)

The bed width is calculated by the following equation.

$$W = A_c \div d \qquad (3\text{-}9)$$

Cross sectional area and bed width are established by Darcy's law:

$$Q = k_s A_s S \qquad (3\text{-}10)$$

Bed cross sectional area and bed width are independent of temperature (climate) and organic loading since they are controlled by the hydraulic characteristics of the media.

The value of K_T can be calculated using Equation 3-6 and a known K_{20} for subsurface flow wetlands system. Typical media types including medium to coarse sands have K_{20} values of approximately 1.28 d^{-1}. Based on European data and data from Santee, California, the K_{20} values presented in Table 3-3B have been tested for media up to gravelly sand size at warm temperatures (T>20°C) (1). The combined effect of large media size (with a resulting small porosity value) and low temperatures represent a system that has not been studied and the above equations may not accurately predict the results. Expected porosities (n) hydraulic conductivity and K_{20} are listed in Table 3-4.

Table 3-4. Media Characteristics for Subsurface Flow **Systems**

Media Type	Max. 10% Grain Size, mm	Porosity (n)	Hydraulic Conductivity (k_s), m^3/m^2-d	K_{20}
Medium Sand	1	0.42	420	**1.84**
Coarse Sand	2	0.39	480	1.35
Gravelly Sand	8	0.35	500	0.86

Sample Design Problem - Subsurface Flow System
Calculate the required area and bed depth for a SFS system where influent wastewater is from a facultative lagoon. Assume influent BOD_5 to the wetlands will be 130 mg/L. The desired effluent BOD_5 is 20 mg/L. The predominant wetland plant type in surrounding marshes is cattail. Water temperatures are 6°C (43°F) in winter and 15°C (59°F) in summer. Wastewater flow is 950 m^3/d (0.25 mgd)

Solution:

1. Choose cattail for this SFS since it is successfully growing in local wetlands. From the discussion above, it is known from studies at Santee, California, that cattail rhizomes penetrate approximately 0.3 m (1 ft) into the medium. The bed media depth (d) should therefore be 0.3 m (1 fit).

2. The bed slope is based on the site topography. Most systems have been designed with slope of 1 percent or slightly higher. For this design choose a slope of 1 percent for ease of construction (s = 0.01).

3. Reed et al. (1) have indicated the need to check the value $k_sS < 8.60$. Choose a media of coarse sand and from Table 3-4, n = 0.39, k_s =480 and K_{20} = 1.35.

$$k_sS = (480)\ (0.01) = 4.8 < 8.60$$

4. Solve for the first-order temperature-dependent rate constant (K_T) using Equation 3-6.

$$K_T = K_{20}\ (1.1)^{T-20}$$

Winter:

$$K_T = 1.35\ (1.1)^{6-20} = 0.36$$

Summer:

$$K_T = 1.35\ (1.1)^{15-20} = 0.84$$

5. Determine the cross section area (A_c) of the bed with Equation 3-8.

$$A_C = Q \div k_sS \qquad (3\text{-}8)$$

$$A_C = 950 \div (480)(0.01) = 198\ m^2$$

6. Determine the bed width using Equation (3-9).

$$W = A_c \div d \qquad (3\text{-}9)$$

$$w = 198 \div 0.3 = 660\ m$$

7. Determine the surface area required with Equation 3-7.

$$As = [Q\ (\ln C_o - \ln C_e)] \div (K_T\ d\ n) \qquad (3\text{-}7)$$

Winter:

$$As = [(950)(4.87-3.00)] \div [(0.36)(0.3)(0.39)]$$
$$= 42{,}177\ m^2 = 4.22\ ha\ (10.4\ ac)$$

Summer:

$$A_s = 18{,}076\ m^2 = 1.81\ ha\ (4.5\ ac)$$

Winter conditions control, so the total bed area must be 4.22 ha (10.4 ac).

8. Determine the bed length (L) and the detention time (t) in the system.

$$L = A_s \div W \qquad (3\text{-}11)$$

$$L = 42{,}177 \div 660 = 63.9\ m\ (210\ ft)$$

$$t = V_v \div Q = LWdn \div Q \qquad (3\text{-}12)$$

$$t = (63.9)(660)(0.3)(0.39) \div 950$$
$$= 5.2\ days$$

9. Divide the required width into individual cells 60 m wide for better hydraulic control at the inlet zone. Construct 11 cells, each 60 m x 64 m (197 ft x 210 ft).

All 11 cells are required in winter. In summer several cells could be dried out for regrading or controlled burning (spring or fall). All cells should remain in service during winter and summer except for brief draining for maintenance. The recovery rate for a cell that has been allowed to go dormant and dries out fully is slow.

3.3.3 *Suspended Solids Removal*

Suspended solids removal is very effective in both types of constructed wetlands, as shown by the data in Table 3-2 and Figure 3-2. Most of the removal occurs within the first few meters beyond the inlet, owing to the quiescent conditions and the shallow depth of liquid in the system. Controlled dispersion of the influent flow with proper diffuser pipe design can help to insure low velocities for solids removal **and** even loading of the wetland so that anoxic conditions are prevented at the upstream end of the channels.

If the water in the wetlands is not shielded from sunlight by the vegetation, algae could become a problem. Algae contribute to effluent SS and cause large diurnal swings in oxygen levels in the water column.

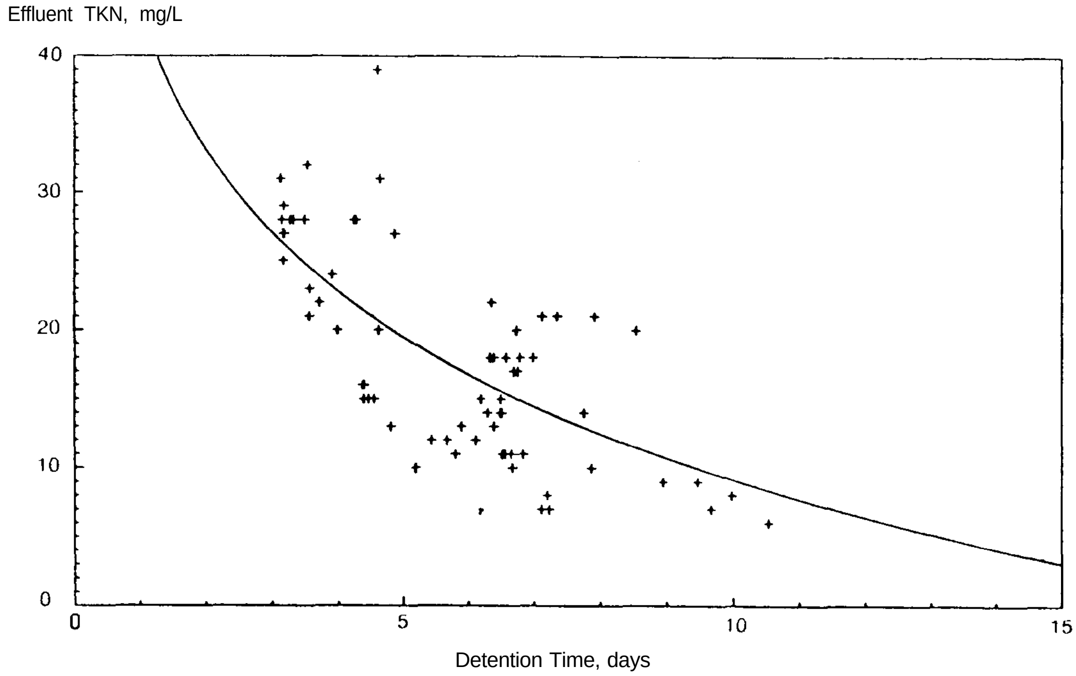
3.3.4 ***Nitrogen Removal***

Nitrification/denitrification is the major path of nitrogen removal (1). Removals of 60-86 percent were reported at Santee (11). It has been shown that artificial wetlands may be managed so as to fuel the process of denitrification by using carbon sources derived from biomass produced within the wetlands itself (11). Nitrogen (TKN) removals have been reported that indicate detention times of 5-7 days will generally produce an effluent with TKN <10 mg/L. Typical pilot-scale results are shown in Figure 3-5 along with a regression curve superimposed on the scatter of data (6).

3.3.5 Phosphorus Removal

Phosphorus removal in many wetland systems is not very effective because of the limited contact opportunities between the wastewater and the soil. The exceptions are the submerged bed designs when proper soils are selected as the medium for the system. A significant clay content and the presence

Figure 3-5. **Regression curve of TKN vs. retention time in the effluent of an alternating Typha/open-water/gravel system. The curve is a logarithmic fit and has a correlation coefficient of 0.70 (6).**



of iron and aluminum will enhance the potential for phosphorus removal (1). Use of such soils will, however, reduce the hydraulic capacity and require a much greater area for treatment.

3.3.6 **Metals Removal**

There are limited data available on the metal removal capability of FWS wetlands; because the removal mechanisms are similar to those described above for phosphorus, the response is not very effective.

There is greater opportunity for contact and sorption in SFS systems and metals removal can be very effective (1). The predominant removal mechanisms in the artificial wetlands were attributed to precipitation-absorption phenomena. Precipitation was enhanced by wetland metabolism which increased the pH of inflowing acidic waters to near neutrality. Removal of Cu, Zn, and Cd at the rates of 99, 97, and 99 percent respectively, for a residence time of 5.5 days in the Santee, California, wetlands were reported (12). Phosphorus removal and metals removal will likely be finite due to exhaustion of exchange sites.

3.4 Process Variables

Constructed wetland systems can be considered attached growth biological reactors, and their performance can be described with first-order plug-flow kinetics. Design guides for BOD_5 loading are presented in this section for both the FWS and SFS types. These guidelines were derived from a relatively limited data base, so caution should be used in their application. A pilot test is strongly recommended for large-scale projects.

***3.4.1 Design* Objectives**

There are limits to the technology of using constructed wetlands for high BOD_5 wastewater treatment. Although limited data are available on the use of wetlands for treating primary effluent, constructed wetlands have been used in a number of locations for polishing secondary effluent (4). The uses for constructed wetlands also include: a) acid mine drainage treatment, b) stormwater treatment, and c) enhancement of existing wetlands.

Secondary effluent polishing has been accomplished in pilot- and full-scale systems at Incline Village's Carson River wetlands system, and at Arcata, California (see Section 3.8.1) where polishing secondary effluent for release into Humboldt Bay was a lower cost alternative that participation in a regional deep-ocean outfall pipeline.

The FWS wetland is widely used as an inexpensive method of treating acid mine drainage. More than 20 such systems were constructed in 1984-1985 in Pennsylvania, West Virginia, Ohio, and Maryland (1). Oxygen for oxidation of mine wastes is supplied from the root zone of the emergent vegetation and from floating algae. Floating algae remove carbon dioxide from the water column and thereby raise the pH. The net effect of the pH rise and interaction of metals from mine waste is physical-chemical precipitation of metals in the soil and mud of the wetland. The iron concentration can be reduced from 25-100 mg/L to less than 2 mg/L in these systems (1).

Enhancement of existing wetlands is a significant result of constructed wetlands systems. The Incline Village General Improvement District wetland system near Minden, Nevada, includes a wetland constructed adjacent to an existing natural warm springs wetland. The addition of a more predictable water supply to the wetland system allowed a larger more stable population of wetland fowl and desert wildlife to be established in the vicinity of the wetland.

In the Arcata, California constructed wetland system, the goal of meeting the NPDES discharge requirements as well as enhancing the waters of Humboldt Bay have been generally met. "The wastewater project will meet a state reclamation policy in that it reuses wastewater for the creation of the marsh and the invertebrates of the oxidation ponds could be used for fish food in the salmon aquaculture project. The recreation lake water will continue to provide nutrients for enrichment of the mudflats of Humboldt Bay and food for juvenile salmonids planted in the lake as part of the ocean ranching project" (7).

3.4.2 BOD_5 Loading Rates

There are two goals for organic load control in a constructed wetland system. The first is provision of a carbon source for denitrifying bacteria. The second is control of organic loading to prevent overloading of the oxygen transfer ability of the emergent plants in the wetland system. If the carbon source is not available for denitrification, then lower overall nitrogen removal will result. However, heavy organic loading, especially if not evenly distributed, will cause plant die off and odors.

Organic loading in a FWS wetland can be controlled by step-feed distribution as well as recycle of wetland discharges. A mass loading rate of about 112 kg BOD_5/ha-d (100 Ib/ac-d) is a typical upper loading rate.

The mathematical justification for this typical loading capacity of a WS constructed wetland is established by estimating the oxygen transfer capacity of the wetland vegetation. Estimation of loading by this method is a two step process: 1) first, calculate the required oxygen; then 2) calculate the available oxygen for the assumed surface area. The following two equations are used (1):

$$\text{Required Oxygen} = 1.5\ BOD_5 \qquad (3\text{-}13)$$

$$\text{Available Oxygen} = (Tr\ O_2)\ (A_s) \div 1{,}000 \qquad (3\text{-}14)$$

where,

O_2 = oxygen required
BOD_5 = organic loading, kg/d
$Tr\ O_2$ = oxygen transfer rate for the vegetation, 20 g/m^{2}-d
A_s = surface area, m^2

As a safety factor, available oxygen should exceed required oxygen by a factor of 2 (1). Commonly used emergent plants can transmit 5-45 g O_2/d per m^2 of wetland surface (45-400 Ib/ac-d). At a typical oxygen transfer rate of 20 g/m2-d (180 Ib/ac-d), the organic loading rate for a wetland should be 133 kg BOD_5/ha-d (118 Ib/ac-d) (1).

3.4.3 Hydraulic Loading Rates

Hydraulic loading rate for FWS systems is closely tied to the hydrological factors for each wetland and these factors are specific to the site. Organic loading rate is also closely tied to the hydraulic loading rate. Hydraulic loading rates of 150-500 m^3/ha-d (16,000-54,000 gpd/ac), have been reported (13), and, in general, the site-specific conditions of weather, soil conditions (permeability especially), and vegetation type must be considered in establishing the hydraulic loading rate. From the results obtained at Listowel, Ontario, it appears that hydraulic loading rates of 200 m^3/ha-d (21,000 gpd/ac) will provide maximum treatment efficiencies.

The water losses due to evapotranspiration can affect the feasibility of the various wetland designs in arid climates and their performance during the warm summer months in all locations. In the western states, where appropriate laws govern the use of water, it may be necessary to replace the volume of water lost to protect the rights of downstream water users. Evaporative water losses in the summer months decrease the water volume in the system, and therefore the concentration of remaining pollutants tends to increase even though treatment is very effective on a mass removal basis (1).

In the special case of a wetland that is constructed to have zero discharge, the hydraulic loading can become a major concern and the dominant design consideration. In a zero-discharge wetland, water is disposed of through the mechanisms of evaporation, transpiration, and ground-water recharge.

3.4.4 Water *Depth in FWS Systems*

The water level in the system and the duration of flooding can be important factors for the selection and maintenance of wetland vegetation (1). Cattails grow well in submerged soils and may dominate where standing water depth is over 150 mm (6 in). Reeds occur along the shorelines of water bodies where the water table is below the surface but will also grow in water deeper than 1.5 m (5 ft). Growth is best in standing water but the depth seems to have no direct effect. The common reed is a poor competitor and may give way to other species in nutrient-rich shallow waters. Bulrushes can tolerate long periods of soil submergence and occur at water depths of 7.5-250 mm (0.3-10 in) in California (14). In deeper water, bulrushes may give way to cattails. Sedges generally occur along the shore or in shallower water than bulrushes (1).

3.4.5 Detention Time

Treatment performance in constructed wetlands is a function of detention time, among other factors. Ground slope, water depth, vegetation, areal extent, and geometric shape control the flow velocity and, thus, the detention time through a wetlands treatment system (7).

A detention time of 6-7 days has been reported to be optimal for the treatment of primary and secondary wastewater (15). Shorter detention times do not provide adequate time for pollutant degradation to occur; longer detention times can lead to stagnant, anaerobic conditions.

Two climatic factors can significantly affect the detention time at a constant hydraulic loading rate. In the summertime, evapotranspiration can significantly increase the detention time, while ice formation in wintertime can significantly decrease the detention time. The recommended water depth at Listowel, for summertime is approximately 100 mm (4 in) and should be increased to approximately 300 mm (12 in) in winter if ice formation is expected, to minimize the effect of climate on the detention time.

Estimating the detention time in wetland systems can be difficult for several reasons. First, large dead spaces may exist in the wetlands due to differences in topography, plant growth, solids sedimentation, and the degree of flow channelization (i.e. short-circuiting). Only a fraction of the surface area, in wetlands, may be available for wastewater flow.

3.5 Pre-Application Treatment

To reduce capital and operating costs, minimal pretreatment of wastewater prior to discharge to a wetland is desirable. However, the level of pretreatment will also influence the quality of the final marsh effluent, and therefore effluent quality objectives must be considered (15).

Preceding wetland treatment with a conventional primary treatment plant is capital intensive and impractical unless such a facility is already in existence. Pretreatment with a conventional lagoon is land consumptive and may generate hydrogen sulfide in winter and algal problems in warmer weather. Based on studies at Listowel, some reduction of SS and BOD_5 is desirable to reduce oxygen demand and prevent sludge accumulations in the upper reaches of the marsh. Phosphorus reduction by chemical addition is recommended in the pretreatment step when phosphorus is required.

3.6 Vegetation

The major benefit of plants is the transferring of oxygen to the root zone. Their physical presence in the system (the stalks, roots, and rhizomes) penetrate the soil or support medium, and transport oxygen deeper than it would naturally travel by diffusion alone (1).

Perhaps most important in the FWS wetlands are the submerged portions of the leaves, stalks, and litter, which serve as the substrate for attached microbial growth. It is the responses of this attached biota that is believed responsible for much of the treatment that occurs (1).

The emergent plants most frequently found in wastewater wetlands include cattails, reeds, rushes, bulrushes and sedges. Information on their distribution in the United States and some of the major environmental requirements of each are provided in Table 3-5 (1).

3.6.1 Cattails

Cattails ***(Typha*** spp.) are ubiquitous in distribution, hardy, capable of thriving under diverse environmental conditions, and easy to propagate and thus represent an ideal plant species for constructed wetlands. They are also capable of producing a large annual biomass and provide a small potential for N and P removal, when harvesting is practiced. Cattail rhizomes planted at approximately 1-m (3.3-ft) intervals can produce a dense stand within three months (3).

3.6.2 Bulrushes

Rushes are members of the genus *Juncus* and are perennial, grasslike herbs that grow in clumps (5). Bulrushes *(Scirpus* spp.) are ubiquitous plants that grow in a diverse range of inland and coastal waters, brackish and salt marshes and wetlands. Bulrushes are capable of growing well in water that is 5 cm (2 in) to 3 m (10 ft) deep. Desirable temperatures are 16-27°C (61-81°F) (1). Bulrushes are found growing in a pH of 4-9 (16).

3.6.3 Reeds

Reeds (Phagmites communis) are tall annual grasses with an extensive perennial rhizome. Reeds have been used in Europe in the root-zone method and are the most widespread emergent aquatic plant. Systems utilizing reeds may be more effective in the transfer of oxygen because the rhizomes penetrate vertically, and more deeply than cattails (1).

Table 3-5. Emergent Aquatic Plants for Wastewater Treatment

Common Name	Scientific Name	Distribution	Temperature, °C Desirable	Temperature, °C Seed Germination	Max. Salinity Tolerance, ppt*	Effective pH Range
Cattail	*Typha* spp.	Throughout the world	10-30	12-24	30	4-10
Common reed	*Phragmites communis*	Throughout the world	12-23	10-30	45	2-8
Rush	*Juncus* spp.	Throughout the world	16-26		20	5-7.5
Bulrush	*Scirpus* spp.	Throughout the world	18-27		20	4-9
Sedge	*Carex* spp.	Throughout the world	14-32			5-7.5

*ppt = parts per thousand.

3.7 Physical Design Factors

3.7.1 System Configurations

Studies at Listowel have demonstrated the importance of a long length-to-width ratio to insure plug flow hydraulics (3). In the model (Equation 3-5) plug-flow hydraulics is assumed as the major form of transport. Internal flow distribution must therefore be achieved by using high length-to-width ratios or by internal berming or barriers (3).

3.7.2 Distribution System

The distribution system for a series of channels each with high length-to-width ratios can be constructed simply using a manifold pipe and gate valves at the head of each channel. For each system the influent flow must have controls to allow distribution to the preferred channels and wetland segments as well as an overflow outlet for dispersion of excess flows and emergency diversions. Distribution of inflow at multiple points in the wetland is a key requirement for controlled and efficient operation of the wetland. For systems with recycle, a pump station with return pipeline to the distribution system must be constructed. Alternatively, the plug-flow channels can be folded back to the inlet to minimize recycle costs. Flow monitoring is an important component of the influent distribution system.

3.7.3 Outlet Structures

The configuration of the outlet structure for a constructed wetland depends on the character of the receiving water and the number of subunits in the constructed wetland. The outlet structure for the surface flow type of wetland is shown in Figure 3-1, and includes a trench and outlet pipe with adjustable level for water level control in the wetland. Outlet structure controls must be able to control depth of water in the wetlands especially for winter ice conditions where deeper wetland conditions are required to maintain treatment levels. Outlet structures must be constructed to prevent ice damage and closed control points during freezing weather.

3.7.4 Vector Control in Free Water Surface *Wetlands*

FWS wetlands provide an ideal breeding environment for many insect pest species, particularly mosquitoes. In Listowel, population densities of Culex pipiens were directly related to the presence of high organic loadings and inversely related to surface water coverage by dense duckweed (Lemna spp.) growths. Mosquitoes are not a problem for subsurface flow wetlands (this is one of the major reasons for using the subsurface type design).

3.7.5 Harvesting of Vegetation

Generally, harvesting of wetland vegetation is not necessary especially for subsurface flow systems (2). For free water surface systems, dry grasses are sometimes burned off annually to help maintain the hydraulic profile of the wetland, and avoid build-up of grassy hillocks, which encourage channelization. Harvesting of plant biomass is normally not regarded as a practical method for nutrient removal. For example, in Listowel, a single, late-season harvest removed 200 g of plant material (dry weight)/m^3 (1.7 lb/l,000 gal) but only 8 percent and 10 percent of the annual N and P loading to the marsh, respectively (3).

An earlier harvest, prior to translocation of nutrients by the cattails, or several harvests per season would be more effective for nutrient removal purposes. Harvesting may be desirable to reduce the excessive accumulation of litter that could shorten the life span of a FWS wetland (3).

3.8 Case Studies

This section provides case study summaries of four systems (three FWS and one SFS) which are representative of current knowledge and practice. The four systems are in Arcata, California; Emmitsburg, Maryland; Gustine, California; and Jackson County, Alabama. The Arcata system was chosen because of the pilot work performed and because one of the main goals of the project was to enhance the beneficial uses of the area surface waters. The Emmitsburg system was chosen because it is a submerged bed system operating in a relatively cold winter climate. The Gustine system was used because of the pilot scale study information and because it attempts to control the influent quality to the wetlands system. The Jackson County system was chosen because it is used in the treatment of wastewaters associated with mining operations.

3.8.1 Arcata, California

The Arcata System is a FWS system that discharges municipal oxidation pond effluent into a marsh.

3.8.1.1 History

The City of Arcata wastewater treatment plant was constructed in the 1940s when the first sewers were installed. At that time, the wastewater received primary treatment before discharge to Humboldt Bay. Oxidation ponds were added in 1958 followed by the addition of chlorination facilities in 1968 and dechlorination facilities in 1975.

In April 1975, the Comprehensive Basin Plan for the North Coast Region was adopted by the California State Water Resources Control Board and was incorporated into the Bays and Estuaries Policy (16). The stated policy concerning discharges to Humboldt Bay was that all wastewater discharges to enclosed bays and estuaries be "phased out at the earliest practicable date." The Regional Water Quality Control Board was empowered to grant exemptions if the discharger could demonstrate "that the wastewater in question would consistently be treated and discharged in such a manner that it would enhance the quality of receiving waters above that which would occur in the absence of the discharge."

In 1977, the City of Arcata proposed to the Regional Water Quality Control Board the use of a wastewater treatment process consisting of existing primary sedimentation facilities and 22.3-ha (55-ac) oxidation pond facilities, and three new constructed marshes (12.6 ha [31 ac]). The effluent from the marsh system would flow through a 6.9-ha (17-ac) recreation lake before being discharged to Humboldt Bay. The City claimed that the system would protect all of the existing beneficial uses of Humboldt Bay and would result in the fuller realization of existing beneficial uses or in the creation of new beneficial uses.

The State Water Resources Control Board funded a three-year pilot study which began in September of 1979. The results of the pilot work were promising and, in 1983, the Board agreed that the marsh system would enhance the beneficial uses of Humboldt Bay for scenic enjoyment and educational study, and that a full-scale marsh system would meet the requirements of the Basin Plan. In 1986, the marsh treatment system was completed and placed in operation.

3.8.1.2 Design Objectives

Design objectives for the marsh system at Arcata were that the marsh effluent meet the NPDES discharge requirements listed in Table 3-6 as well as enhance Humboldt Bay waters. To provide for enhancement of Humboldt Bay waters the marsh system should also be designed and operated as a wildlife habitat.

Table 3-6. **City of Arcata, CA Wastewater Discharge Requirements**

Constituents*	30-Day Average	7-Day Average	Daily Maximum
BOD_5 (20^oC), mg/L	30	45	60
Suspended Solids, mg/L	30	45	60
Settleable Solids, mL/L	0.1	-	0.2
Total Coliforms, MPN/100 mL	23	-	230
Cl_2 Residual, mg/L			0.1
Grease and Oil, mg/L	15		20
Toxicity Conc., tu	1.5	2.0	2.5

*6.5 $\geq$ pH $\leq$ 8.5 at all times.

3.8.1.3 Pilot Plant Results

a. Pilot Facilities Description

The pilot facilities consisted of 12 experimental cells, 6.1 m wide (20 ft), 61 m long (200 ft), and approximately 1.2 m deep (4 ft) (17). The 12 cells consisted of three groups of four cells each (See Figure 3-6). The depth of water in the cells was set approximately at either 0.3 or 0.6 m (1 or 2 ft) using 60^o V-notch weirs. Seepage from the cells was prevented by the use of clay in cell bottoms and berms. Although the cells were initially seeded with alkali bulrush and hardstem bulrush, the marsh cells went through a succession of aquatic plants with the major species at the end of the three-year study being hardstem bulrush, cattails, water cress, marsh pennywort, and duckweed.

b. Experimental Design

The first year of the three-year study was devoted to construction of the experimental facilities and the establishment of the marsh system. The remaining two years of the study were spent documenting the performance of the 12 cells under steady state operation. The experimental design consisted of combinations of three hydraulic loading rates (2,400, 1,200, and 600 m^3/ha-d) (260,000, 130,000, 65,000 gpd/ac) and two water depths (0.3 and 0.6 m [1 and 2 ft]). This design provided a replicate for each of the combinations. However, variations in actual weir heights and measured flow rates from the design values resulted in variation in the hydraulic loading rates and the hydraulic detention time between replicate cells (see Table 3-7). In the second year of operation the hydraulic loading rate in the first four cells was reduced from 2,400 to 300 m^3/ha-d (260,000 to 32,500 gpd/ac).

The influent to the marsh system was effluent from the City's 22.3 ha (55 ac) oxidation pond. The twelve cells were routinely monitored for influent and effluent BOD_5, SS, total and fecal coliform, organic nitrogen, ammonia, nitrate, phosphates, metals, pH, DO, turbidity and toxicity by bioassay. In addition, several

Figun 3-6. Arcata, CA pilot marsh system.

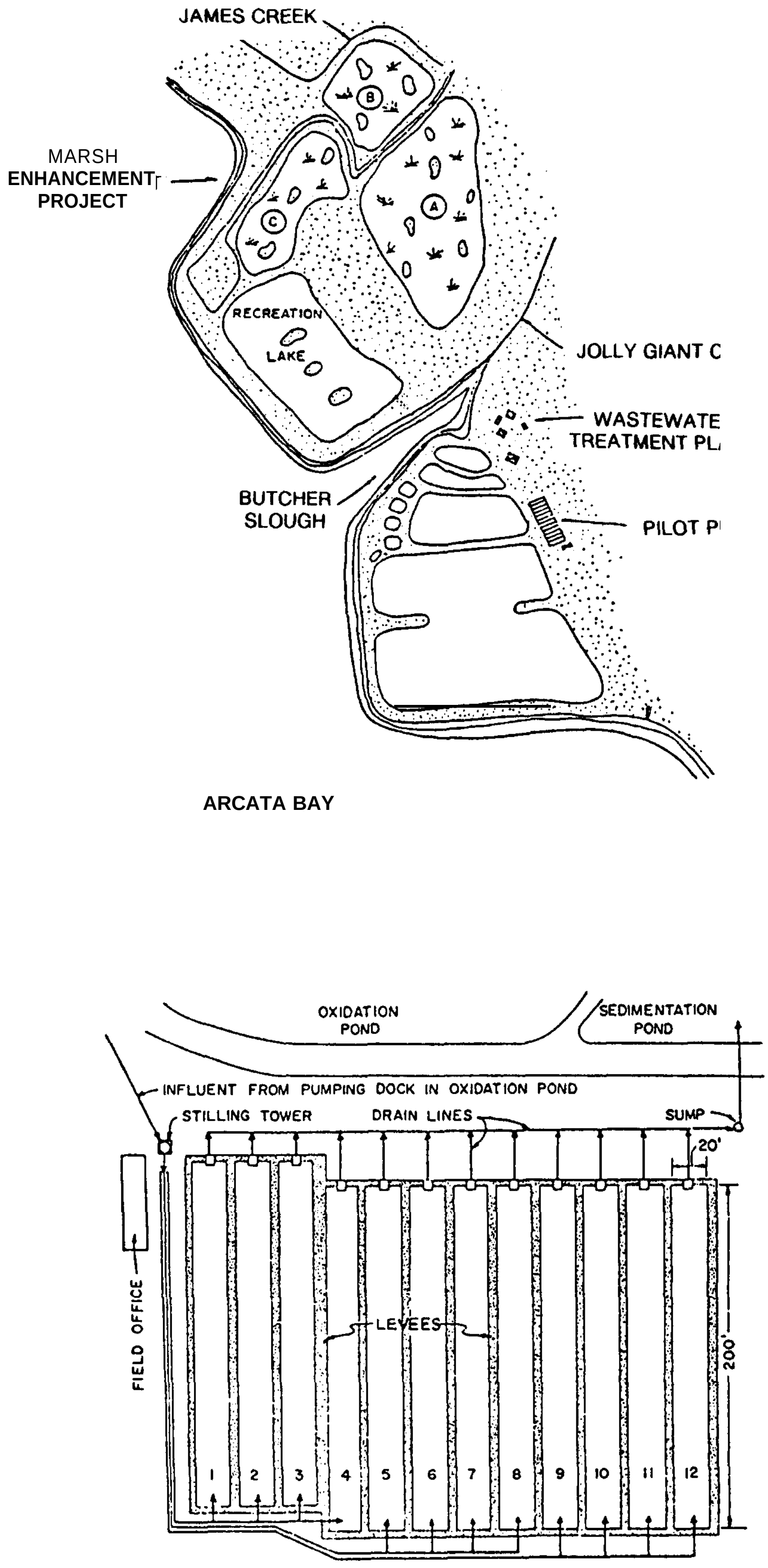


Table 3-7. Arcata, CA Pilot Marsh System Hydraulic Loading Rates and Detention Times (18)

	Marsh Cell Number											
	1	2	3	4	5	6	7	8	9	10	11	12
Flow, m^3/d												
9/1I/80-12/31/81	17.2	17.1	15.2	15.8	9.0	8.2	8.4	8.4	5.4	5.4	4.4	4.3
1/1/82-1-/31/82	3.5	1.5	1.4	1.5	9.0	8.2	8.4	8.4	5.4	5.4	4.4	4.3
Hydraulic Loading, m^3/m2-d												
9/1/80-12/31/81	0.24	0.24	0.19	0.22	0.12	0.11	0.11	0.11	0.07	0.07	0.06	0.06
I/1/82-1-/31/82	0.05	0.02	0.02	0.02	0.12	0.11	0.11	0.11	0.07	0.07	0.06	0.06
Depth, m												
9/1/80-10/31/82	0.55	0.40	0.61	0.36	0.49	0.30	0.55	0.33	0.55	0.33	0.50	0.35
Detention Time, hr												
9/1/80-12/31/81	52	38	65	37	88	59	106	58	180	90	183	132
1/1/82-1-/31/82	257	411	697	369	88	59	106	58	160	90	183	132

tracer studies and a disinfection efficiency study were performed.

Following the first pilot study an additional study was sponsored by the State Water Resources Control Board (18). The focus of this study was to determine the effect of harvesting on performance, wildlife, and mosquito production and to investigate indicator organism speciation and removal. Ten of the original 12 cells were restructured and rehabilitated for the study by harvesting the plants from portions of some cells and installing baffles in others (see Table 3-8). The hydraulic loading rate in all cells was maintained at 700 m^3/ha-d (74,000 gpd/ac) and water level was set at 0.6 m (2 ft), providing a theoretical hydraulic detention time of 7.5 days. Harvesting was accomplished by hand, using a weed eater, machetes and rakes.

Table 3-8. Experimental Vegetation and Compartments for Marsh Cells - Arcata, CA (32)

Cell 1	Effluent 50 percent of cell harvested[a]
Cell 2	100 percent of cell harvested
Cell 3	Cell left intact from previous season (Hardstem bulrush)
Cell 4	Alternating 6-m (20-ft) strips harvested starting with effluent 6m (20 ft)[b]
Cell 5	Cell left intact from previous season (Cattail)
Cell 6	Marsh cell divided into four 30 m x 6 m (100 ft x 20 ft) compartments
Cell 7	Marsh cell divided into four 15 m x 6 m (50 ft x 20 ft) compartments
Cell 8	Marsh cell divided into four 7.5 m x 6 m (25 ft x 20 ft) compartments
Cell 9	Alternating 15-m (50-H) strips harvested with the last 15 m (50 ft) interval vegetated
Cell 10	lnfluent 50 percent of cell was harvested

[a] Cells were harvested In November 1984.
[b] Cellular compartments were constructed with baffles which allow flow to transfer to next compartment by use of three V-notch weirs.

As in the first pilot study, oxidation pond effluent was the influent to the marsh cells and the marsh cells were monitored routinely for influent and effluent BOD_5, SS, ammonia, nitrate, phosphates, pH, DO, turbidity, total and fecal coliforms. Special studies of indicator organism speciation and mosquito populations were also performed.

c. Experimental Results

lnfluent BOD_5 during the first pilot study averaged 24.5 mg/L with a standard deviation of 12.3 mg/L. The average removal percentage for all cells was 46 percent. As expected the lower hydraulic loading rates produced better effluent quality. The respective percentage removals for 2,400, 1,200, 600, and 300 m^3/ha-d (260,000, 130,000, 65,000, and 32,500 gpd/ac) were 35, 45, 55, and 75 percent (see Table 3-9). Although there were seasonal increases in the influent BOD_5 concentration associated with algal blooms, variation in BOD_5 removal in the marsh system appeared to be due to factors which are difficult to quantify, such as the succession of plant species rather than seasonal factors such as temperature and sunlight. In general, the marsh system proved to be effective at all the loading rates investigated in producing an effluent which would meet the discharge requirements with the exception of the first spring and summer of operation.

In interpreting the results with respect to BOD_5 removal, the investigators used a mathematical model developed by Atkinson, in which it is assumed that soluble substrate is removed by a thin film of attached microorganisms (17):

$$-\ln [S_e/S_i] = (f\ h\ k_o)\ w\ Z \div Q \qquad (3\text{-}15)$$

S_e = effluent concentration, mg/L
S_i = influent concentration, mg/L
f = proportionalityy factor
h = thickness of slime, m
k_o = maximum reactor rate, d^{-1}
w = width of section (width of cell), m
Z = filter depth (length of cell), m
Q = volumetric flow rate, m^3/d

Table 3-9. Average Annual BOD_5 Concentration (mg/L) - Arcata, CA (17)

	1981		1982		1981-1982	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
Influent	27.3	13.4	21.9	9.5	25.2	12.3
1*	18.7	8.7	2.8	3.8		
2	18.2	9.3	7.8	6.2		
3	18.1	7.3	5.7	4.4		
4	17.7	6.8	5.3	5.1		
5	16.1	9.1	10.7	5.4	13.9	8.2
6	13.8	8.0	6.4	3.8	10.7	7.6
7	18.0	7.7	7.9	4.7	14.0	8.3
8	23.9	31.3	6.2	4.0	16.8	25.8
9	16.7	10.5	7.1	4.5	12.8	9.8
10	17.8	11.2	7.7	5.4	13.7	10.5
11	14.3	9.6	4.4	2.8	10.4	9.1
12	13.6	8.8	4.7	3.2	10.1	8.2

* Effluent from Cell 1.

The Arcata investigators determined (f h k_o) to be 4.95 m/d. They also compared effluent BOD_5 to the BOD_6 mass loading and proposed a linear relationship for determining the areal requirements for a marsh system treating oxidation pond effluent.

Influent SS averaged 34.9 mg/L with a standard deviation of 18.9 mg/L. Although there was a larger average value and range for the influent SS concentrations as compared to BOD_5, the effluent values were very stable during the study and did not vary significantly with loading rate. The SS removal averaged 85 percent for all loading rates with the highest and lowest average removal rates being 87 percent and 83 percent.

During the first two-year study, no violations of Arcata's NPDES toxicity standard in either the marsh influent or effluent from any of the experimental cells were observed. Total nitrogen removal was measured during a six-month period and averaged 30 percent for all cells. Average ammonia removal over the two-year period varied from 0 to 33 percent for the various cells. Average phosphorus removal was quite low, with the highest average removal percentage being 10 percent.

A disinfection study was conducted in the summer of 1982 to demonstrate that lower SS and pH in the marsh effluent would result in a lower chlorine demand. However, it was discovered that the marsh effluent contained both volatile and non-volatile compounds which resulted in a higher chlorine demand compared to the oxidation pond effluent. It was shown that the volatile compounds, such as hydrogen sulfide, could be removed by air stripping, thereby reducing the chlorine demand. It was further concluded that SS are not a major factor in chlorine demand in the Arcata system.

The second pilot study was primarily concerned with the effects of harvesting and baffles on the performance of marsh systems. In summary, it was concluded that harvesting resulted in statistically significant degradation of effluent quality for BOD_5 and statistically non-significant degradation for SS. Baffles did not significantly increase or decrease effluent BOD_5 and SS compared to the control cells which were neither baffled nor harvested. The results of the study with respect to the impacts of harvesting and baffles on the removal of other pollutants were inconclusive.

No conclusions were drawn concerning the effects of harvesting and use of baffles on mosquito populations. The results of the 1985 sampling were compared with earlier years and it was concluded that the mosquito population had decreased and in general, the pilot marsh cells produced approximately the same densities of mosquitoes as the adjacent natural marsh system.

Approximately 90 percent of the total coliforms and more than 95 percent of the fecal coliforms were removed in the pilot marsh cells. Based on the results of sampling for 35 species of bacteria, significant differences in the species composition of the influent and effluent were not observed.

3.8.1.4 Design Factors

Design of the final treatment system at Arcata was largely influenced by the existing facilities and by the results of the first pilot study. It was decided to use the previously constructed Arcata Marsh and Wildlife Sanctuary as a final polishing marsh system and to convert a portion of the existing aerated ponds into an intermediate marsh system. A flow diagram for the overall wastewater treatment system is provided in Figure 3-7.

The primary purpose of the intermediate marsh system is to remove SS prior to chlorination and dechlorination. The surface area of the intermediate marsh system was determined based on a short-term study, designed to determine the maximum hydraulic loading rate that met effluent SS standards. Although a maximum rate was not identified, the maximum rate used in the study, 12,000 m^3/ha-d (1.28 mgd/ac), provided acceptable effluent SS levels. The full-scale intermediate marsh system is 16.2 ha (4 ac), which results in design average and maximum month hydraulic loading rates of 5,400 and 14,000 m^3/ha-d (0.58 and 1.5 mgd/ac).

The intermediate marsh system was designed with several 15-m (50-ft) stretches of open space which span the full width of the marsh cell (see Figure 3-8). The purpose of the open space is to provide a

Figure 3-7. Arcata, CA wastewater treatment facilities flow diagram.

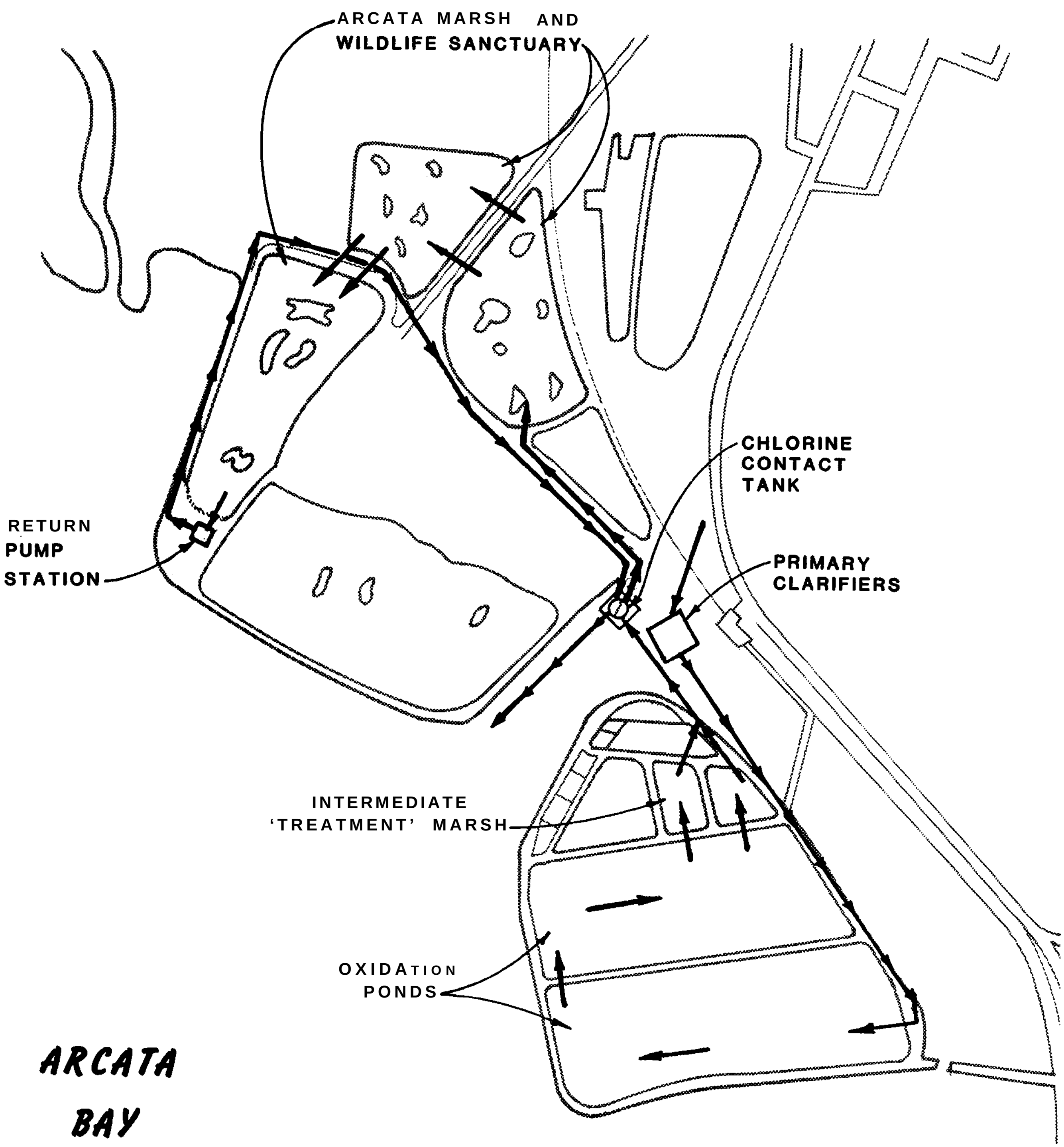
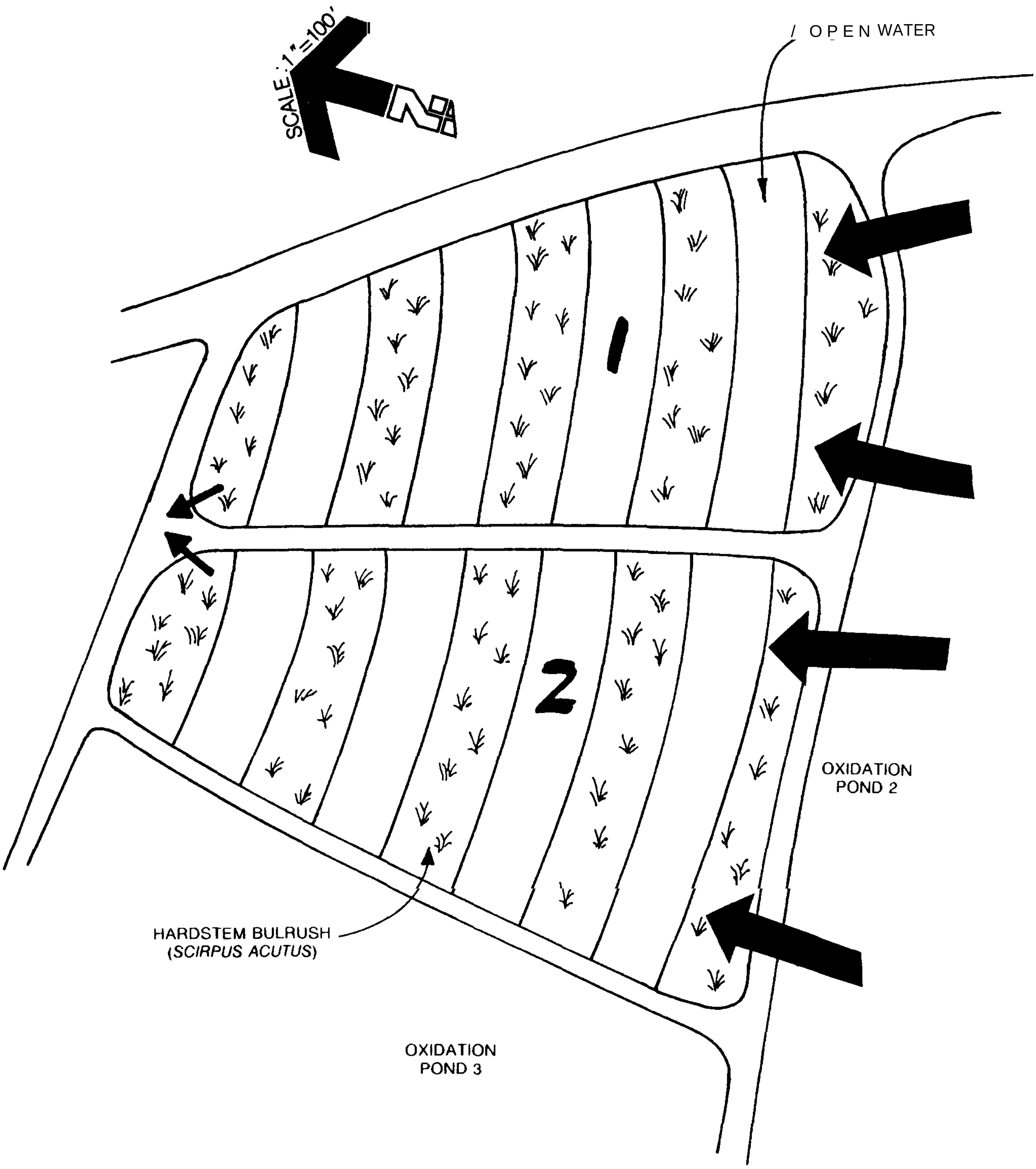


Figure 3-8. Arcata, CA intermediate FWS system.



habitat for fish which will control the mosquito population and for wildlife. Another mosquito control measure was the decision to plant the marsh system with hardstem bulrush because it allows fish better access to the planted areas. Routine solids removal from the intermediate marsh system is planned.

It is anticipated the effluent quality from the intermediate marsh will meet the discharge requirements the majority of the year. However, to enhance the Humboldt Bay waters through the creation of a wildlife habitat, the City of Arcata is required to pass a minimum of 8,700 m^3 (2.3 Mgal) of effluent through the Arcata Marsh and Wildlife Sanctuary daily. The resulting hydraulic loading rate is 700 m^3/ha-d (74,000 gpd/ac).

3.8.1.5 Operating Characteristics
One-half of the intermediate marsh system was planted in March 1986 and the other half during the summer months of 1987. Currently the water level in the two intermediate marsh cells is set at 1.1 m (3.5 ft) and the total influent flow is passed evenly through the cells. Once both cells are fully established the water level will be reduced to 0.6 m (2 ft). After chlorination and dechlorination, approximately 11,350 m^3/d (3 mgd) of effluent is diverted to the polishing marsh system at the Arcata Marsh and Wildlife Sanctuary. Effluent from the polishing marsh is chlorinated, dechlorinated and discharged to Arcata Bay. Effluent flows in excess of 1,350 m^3/d (3 mgd) from the oxidation pond are chlorinated, dechlorinated and discharged directly to Humboldt Bay.

The intermediate marsh system is in the process of plant establishment and startup. As expected, the wastewater treatment performance of the one cell planted in March 1986 was not very good in the first season, but the operators are confident the intermediate marsh system will perform as designed as it matures biologically and when the second cell is planted and brought into service.

The polishing marsh system has been receiving effluent from the intermediate marsh system since June 1986. Influent and effluent BOD_5 and SS values for the first seven months of operation are summarized in Table 3-10. The polishing marsh has performed as expected in terms of BOD_5 removal but not as well as hoped in terms of SS removal. The primary cause for the high effluent SS has been algae. It is expected that the planting of vegetation near the effluent collection point will lower the SS concentrations.

Mosquitoes have not been a problem in either of the marsh systems. Chlorine usage following the intermediate marsh system has remained the same as before the intermediate marsh was constructed. There was a problem with stickleback fish being carried over with the polishing marsh effluent into the chlorine contact tank. This problem was solved by installing a smaller mesh screen in front of the effluent pipes and by establishing thick vegetation in the effluent area.

Table 3-10. Arcata, CA Marsh and Wildlife Sanctuary Wastewater Treatment Plant Performance

	Influent, mg/L		Effluent, mg/L	
	BOD_5	SS	BOD_5	SS
Aug 1986	34	49	8	17
Sept	32	52	6	13
Oct	41	46	7	15
Nov	46	39	21	42
Dec	48	55	20	39
Jan 1987	32	32	15	35
Feb	20	27	19	58
Average	36.1	42.9	13.7	31.3

3.8.1.6 Costs
The construction of both the intermediate and final wetlands systems at Arcata was totally financed by the City of Arcata. The total cost of the Arcata Marsh and Wildlife Sanctuary project (final wetland system) was $514,600 including planning and environmental studies and land acquisition. A cost breakdown summary is provided in Table 3-11.

Table 3-11. Arcata, CA Marsh and Wildlife Sanctuary Project Expenditures

Item	cost, $
Plan of Study	14,000
EIR, Management Plan, and Permits	20,500
Land Acquistion	76,100
Construction	235,000
Accessways (trails, etc.)	19,000
Expenditures from Treatment Plant Modifications to Transport and Return Wastewater	150,000
Total	514,600

3.8.1.7 Monitoring
In addition to the monitoring required in the discharge permit, influent and effluent water quality for both of the marsh systems is monitored weekly for BOD_5 and SS. Monitoring for mosquitoes and vegetation coverage is on a regular basis.

3.8.2 Emmitsburg, Maryland

3.8.2.1 History
In 1984 the town of Emmitsburg, Maryland was facing a sewer connection moratorium from the state water quality regulatory agency because of wastewater discharge violations. Planning was underway to construct new treatment facilities but in the interim

the town needed to upgrade its existing facilities to avoid the moratorium. The town decided to use a SFS constructed wetland system to treat a portion of its effluent flow. The design and construction was cooperatively undertaken by the town and the SaLUT Corporation.

The system was started up in the summer of 1984 and continued in operation until March 1986, at which time the system did not receive any wastewater for several days. The resulting stress on the system eventually caused the death of all the cattails. The system was reseeded in October 1986.

3.8.2.2 Project Description

The Emmitsburg system is a single basin, 76.3 m (250 ft) long, 9.2 m (30 ft) wide, and 0.9 m (3 ft) deep, filled with 0.6 m (2 ft) of crushed rock. Clay was used in the bottom of the basin to prevent ground-water contamination. Perforated pipes placed near the bottom of the basin are used for influent distribution and effluent collection. The water level during normal operation is approximately 5 cm (2 in) below the surface of the gravel. The system was seeded with 200 broadleaf cattail plants in August 1984 and another 200 plants in July 1985. By March 1986 approximately 35 percent of the basin surface area was covered by cattails. The planting density used in this project should have been at least an order of magnitude higher. Until the plants cover the entire basin, performance will not be representative of a SFS system as defined in this manual.

The influent to the Emmitsburg system is trickling filter effluent. Influent flows have varied between 95 and 132 m^3/d (25,000-35,000 gpd), which corresponds to a surface hydraulic loading rate of 1,420-1,870 m^3/ha-d (152,000-200,000 gpd/ac). Effluent samples are collected and analyzed weekly for BOD_5, SS, total dissolved solids, DO, and pH.

3.8.2.3 Operating Characteristics

The influent BOD_5 concentrations to the wetlands system range between 10 and 180 mg/L while SS concentrations normally range between 10 and 60 mg/L. Results from two years of operation are presented in Table 3-12 and Figures 3-9 and 10. As can been seen in Figures 3-9 and 10, the performance of the wetlands system has been very good even with the limited plant coverage. Odors in the effluent have been an occasional problem but the frequency of noticeable odors is decreasing as cattail coverage increases.

3.8.2.4 Costs

The Emmitsburg system was designed by SaLUT, Inc. and constructed primarily as an in-house project by the township's Public Works Department. Engineering and construction costs of the Emmitsburg system were less than $35,000.

3.8.3 Gustine, California

3.8.3.1 History

The City of Gustine, California is a small agricultural town on the west side of the San Joaquin Valley. The city treats approximately 4,500 m^3/d (1.2 mgd) of wastewater of which about one-third originates from domestic and commercial sources and the remainder from three dairy products industries. The wastewater is of high strength, averaging over 1,200 mg/L BOD_5, which reflects the industrial component of the waste.

Until recently, the city's wastewater treatment plant consisted of 14 oxidation ponds operated in series. The ponds covered approximately 21.8 ha (54 ac) and provided about 70 days detention time. Treated effluent was discharged without disinfection to a small stream leading to the San Joaquin River.

As with many oxidation pond systems in the United States, mandatory secondary treatment levels were not achieved with any consistency. The discharge regularly exceeded 30 mg/L SS and periodically exceeded 30 mg/L BOD_5.

The city applied for and received federal funding to analyze alternatives and develop a facilities plan. Alternatives included the following:

- Oxidation pond treatment followed by land application (irrigation).
- Oxidation pond treatment followed by reuse in the form of seasonal flooding of local duck clubs to attract migrating water fowl.
- Oxidation pond treatment followed by effluent polishing to meet secondary treatment standards for river disposal using sand filters, microscreens, or submerged rock filters.
- Conventional activated sludge treatment to meet secondary treatment standards for river disposal.
- Oxidation pond pretreatment followed by effluent polishing in a constructed marsh (using emergent aquatic vegetation) to meet secondary treatment standards for river disposal.

From an analysis of the alternatives it was found that the oxidation pond/constructed marsh was the most cost-effective solution. The advantages of this alternative were that suitable land was available, the treatment method was compatible with the surrounding area (a lowland area with naturally occurring aquatic vegetation and virtually no development) and the consumption of very little energy.

3.8.3.2 Design Objectives

The primary objective of the Gustine project is to upgrade the treatment plant effluent quality to meet 30 mg/L BOD_5 and SS (30-day average). Mosquito

Table 3-12. Performance of the Emmitsburg, MD SFS (19)

Season	Average Flow, m^3/d	BOD_5, mg/L		SS, mg/L				
		Influent	Effluent	Influent	Effluent	Effluent DO, mg/L	Odor of Effluent	Area Covered With Cattails, %
Fall 1984	117	29	12	25	7	1.0	strong	< 5
Winter 1985	111	68	29	37	9	0.3	noticeable	< I 0
Spring 1985	130	117	38	37	13	0.0	occasional	<20
Summer 1985	100	87	11	28	10	1.3	none	<25
Fall 1985	97	28	7	29	7	2.1	occasional	<30
Winter 1988	106	40	11	25	4			<35

Figure 3-9. BOD performance data for Emmitsburg, MD SFS (19).

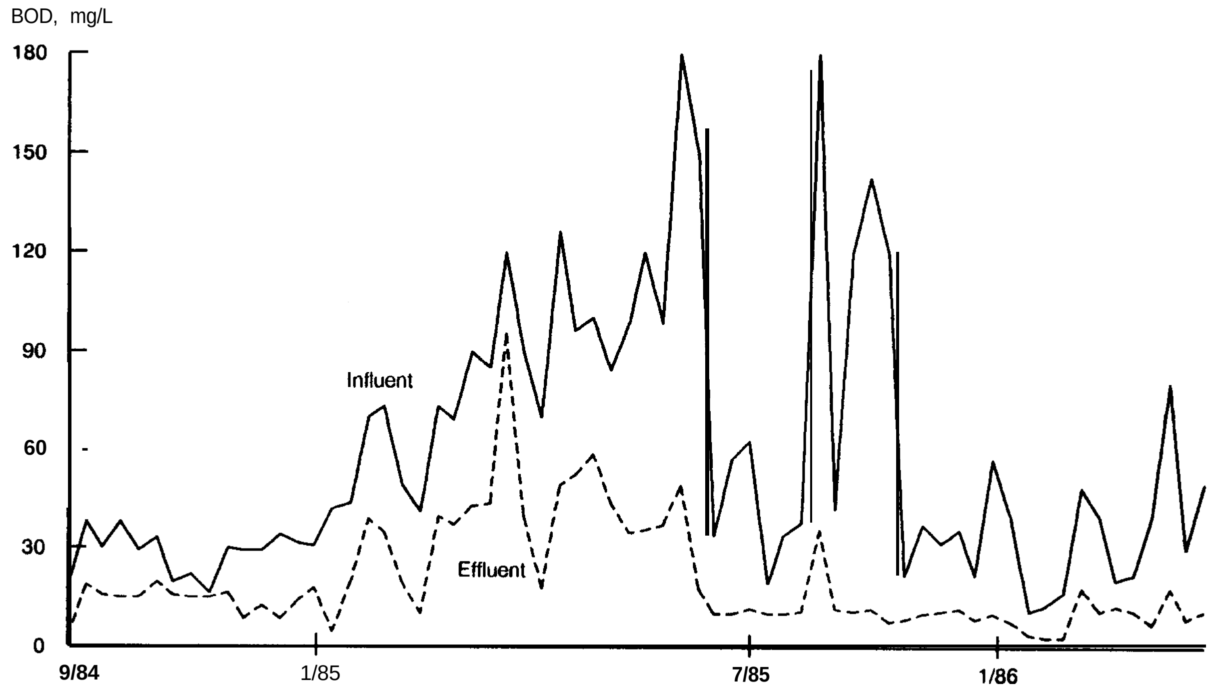
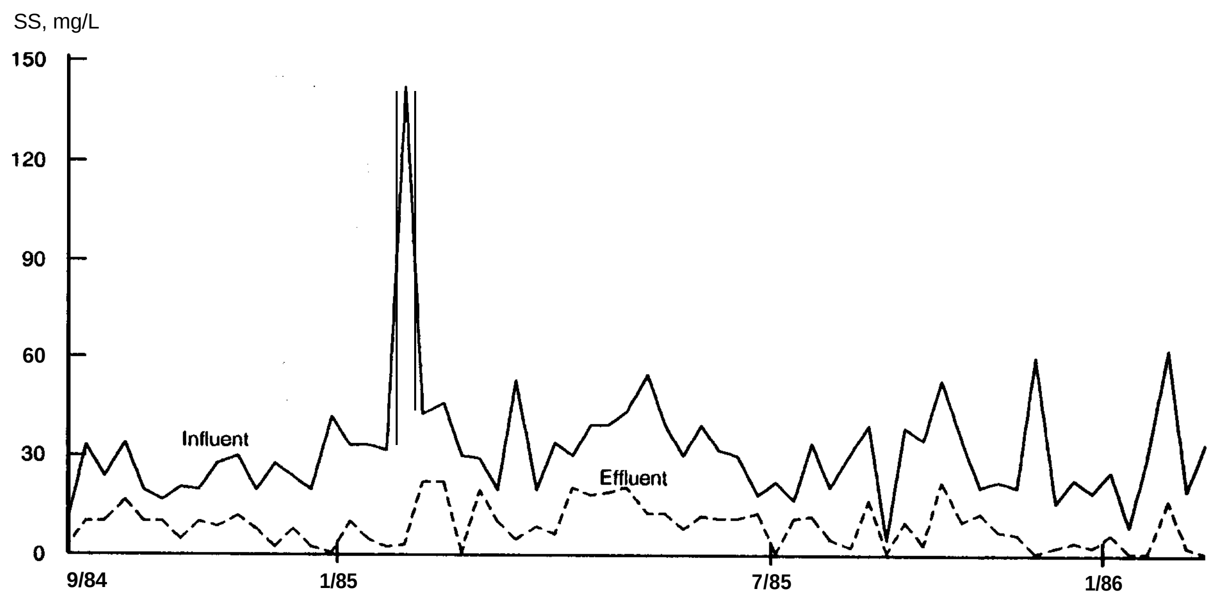


Figure 3-10. TSS performance data for Emmitsburg, MD SFS (19).



control is the second major concern. Mosquito production has been identified as a major drawback to the use of an aquatic plant treatment system. The need to control mosquito production affected the design of the facility, and will affect operating procedures as well.

3.8.3.3 Pilot Plant Results

a. Description of the Pilot Facility
A one-year pilot testing program using a 0.4-ha (1-ac) cattail marsh was initiated to develop design criteria for a full-scale system. The pilot marsh was 15 m (50 ft) wide by 270 m (875 ft) long. There was a healthy stand of cattails *(Typha* spp.) growing on the site prior to application of wastewater.

Earth berms enclosed the marsh on all sides. Wastewater was pumped to the marsh through plastic piping and distributed across the influent end of the marsh through a manifold with nine valved outlets. Effluent was collected at the lower end and discharged with the normal plant effluent.

The condition of the marsh bottom grading was not known. An average depth between 0.15 and 0.3 m (0.5 and 1 ft) was estimated but an actual average depth could not be determined.

b. Experimental Design
The two variables adjusted during the pilot study were influent source and detention time. Water depth in the marsh was kept constant so flow rate was used to vary detention time. Flow rates ranged from 136 to 380 m^3/d (36,000-100,800 gpd), corresponding to actual detention times of 1.3-3.8 days, and hydraulic surface loading rates of 340-1,000 m^3/ha-d (36,600-108,900 gpd/ac).

Selection of the influent source was based on the assumption that algae entering the marsh would penetrate it and would be measured as SS in the final effluent. There is a visible transition from the first ponds in the series without significant algal growth, to ponds (in the latter half of the series) with algal growth. It is believed that the main mechanism limiting growth in the first cells is restricted light penetration due to high turbidity and scum formation. Five of the 14 oxidation ponds in service at Gustine were alternately used as an influent source, with visual observation being the primary method of selection. The pond farthest downstream without significant algal growth was selected with the goal of avoiding high concentrations of algae in the marsh influent.

Marsh influent and effluent levels of BOD_5, SS, pH, and temperature were measured twice per week. In addition, two dye tests were performed to measure the time of flow through the marsh. Routine effluent total coliform measurements were made, but detailed bacterial testing was not conducted. (It is assumed that disinfection of the final effluent will be required.) Eleven sampling stations were used to monitor mosquito larva production during the latter portion of the pilot study.

c. Experimental Results
During a 2-l/2 month "start up and acclimation" period, both marsh influent and effluent BOD_5 and SS levels were high, at one point exceeding 400 mg/L and 250 mg/L, respectively. The very high influent BOD_5 was probably due to insufficient pretreatment. To reduce the influent BOD_5 and SS loadings the source pond was changed from the eighth pond in the flow sequence to the tenth, farther downstream in the process. The initial detention time in the marsh system was 2.1 days.

Influent and effluent levels of BOD_5 and SS for the period December 1982-October 1983 are illustrated in Figures 3-11 and 3-12. The influent source pond and marsh detention time for each time period is shown at the top of the figures. Effluent levels were generally below 30 mg/L from May through October 1983. The removal of BOD_5 was particularly good in the latter part of the summer and fall, averaging 74 percent. The rise in effluent BOD_5 in late July and early August corresponds with high effluent SS levels. These increases could be the result of concentration due to loss of water through evapotranspiration (calculated to be up to 45 percent in the summer). SS removal was particularly good following startup, averaging 80 percent during April, May, and June, and increasing to 89 percent from July through August.

There was some suspicion that nitrogenous oxygen demand was affecting BOD_5 test results. In an evaluation performed at the end of the study (summarized in Table 3-13) it was found that nitrification increased the BOD_5 readings by up to 16 mg/L. This additional oxygen demand often made the difference between meeting or exceeding 30 mg/L effluent BOD_5.

The effect of detention time on removal efficiency was difficult to establish because relatively short detention times were used. Removal as a function of detention time is reported in Table 3-14. Because the data were collected at different times of the year and at different loading rates, direct conclusions can not be made. In general it appears that a detention time of 2.7-3.8 days is the minimum necessary for adequate treatment during warm weather.

Bacteriological testing consistently showed levels greater than 2400 MPN/l00 mL. It is assumed that disinfection of the final effluent will be required.

The marsh was sampled for mosquito larvae by the Merced County Mosquito Abatement District from

Figure 3-11. BOD_5 performance data for Gustine, CA pilot marsh system.

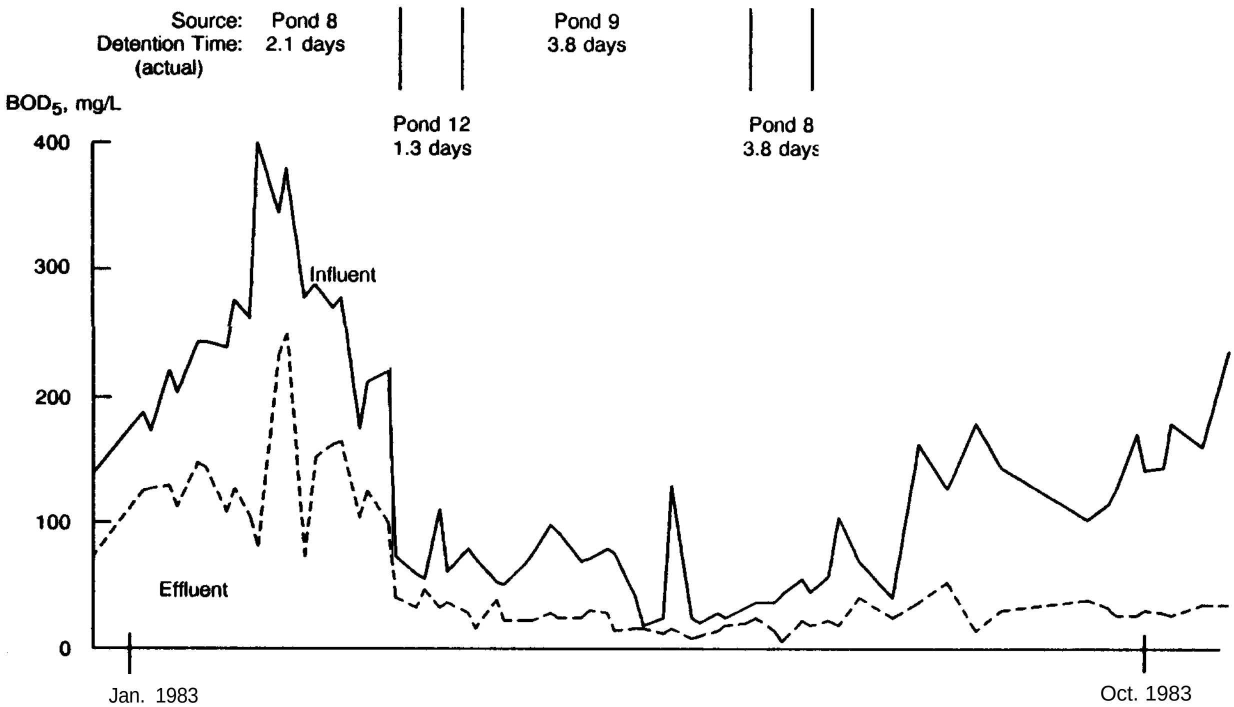


Figure 3-12. SS performance data for Gustine, CA pilot marsh system.

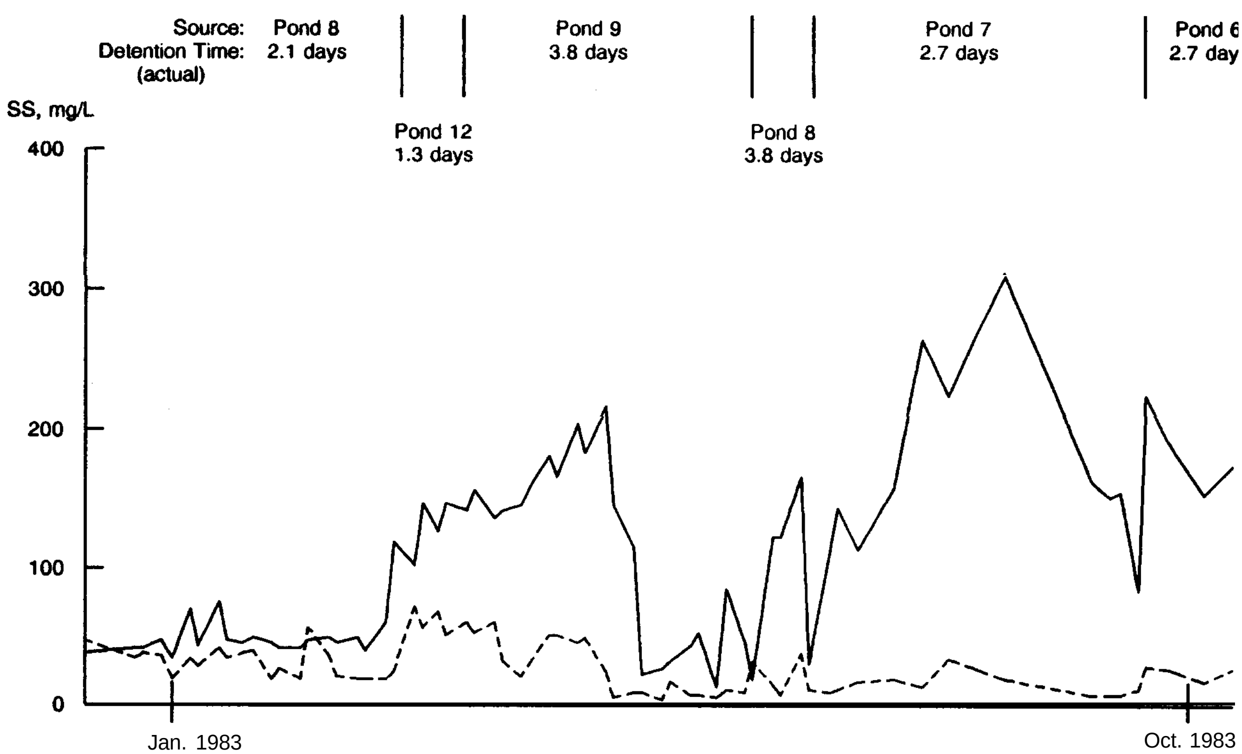


Table 3-13. Determination of Nitrification Component in BOD_5 Test - Gustine, CA (201)

Test Date	Station[a]	Water Temp.°C	BOD_5, mg/L Standard	With Nitrification Inhibitor	Difference
10/13/83[b]	Influent	19	251	244	7
	1+00		93	81	12
	2+00		50	48	2
	3+00		48	39	9
	4+00		21	11	10
	5+00		22	20	2
	6+00		13	10	3
	7+00		22	19	3
	8+00		14	7	7
	Effluent		30	25	5
10/6/83[C]	Effluent	20	33	17	16
11/3/83[C]	Effluent		20	14	6

[a] Stationing measured from effluent end of marsh, each station 30.5 m (100 ft) apart.
[b] Tests performed by UC Davis Environmental Engineering Laboratory.
[c] Tests performed by California Water Lab, Modesto, CA.

Table 3-14. BOD_5 and SS Removal Efficiencies As a Function of Detention Time - Gustine, CA (20)

Actual Detention Time, d	Removal Efficiency*, % BOD_5	SS	Time Period
1.3	49	61	3/10-4/4
2.1	48	28	12/23-3/9
2.7	74	89	7/7-10/13
3.8	68	80	4/12-7/6

* Removal efficiencies based on average inftuent and effluent concentrations over the time period covered.

June 10 through October 20, 1983. The average number of mosquito larvae at each of the 11 sampling stations ranged from 3.0 to 7.8 larva per dip. Both *Culex pipiens* and *Culex tarsalis* larva were found in about equal numbers. Based on experience and data of the abatement district, it was concluded that a marsh of the type tested may represent a mosquito breeding source which must be subject to control measures.

3.8.3.4. Design Factors

Based on research conducted at the University of California, Davis (21) it has been shown that low winter temperatures will control system sizing. Longer detention time is required for BOD_5 removal due to reduced biological activity.

It is expected that the lowest water temperatures will occur in January or February and be about 5°C (40°F). At this temperature and a BOD_5 loading rate of 112 kg/ha-d (100 Ib/ac-d), using data from U.C.D. research, it appears that a maximum detention time of about 11 days is required. At the design flow of 3,785 m^3/d (1 mgd), a marsh area of about 9.3 ha (23 ac) at a water depth of 0.45 m (1.5 ft) would be required. The corresponding hydraulic loading is 407 m^3/ha-d (43,500 gpd/ac). Detention time can probably be reduced to as little as 4 days during the warmest summer months.

The primary method of varying detention time will be depth control. The ability to control water depth, and to drain cells completely, is necessary to facilitate harvesting of the plants, and other maintenance activities. Such operational flexibility is a key design factor.

Annual burning of the dormant marsh vegetation will be practiced to enhance treatment by maintaining plug flow characteristics, and to control mosquito production. Individual cell width is limited to 12-15 m (40-50 ft) by the access requirements. Levees separating cells must be capable of accommodating service vehicles.

Stocking of the mosquito larva eating fish, *Gambusia affinis,* is the primary method of mosquito control. High mass loading leads to low oxygen levels produced by increased biological activity. Low oxygen levels inhibit the movement of fish so loading rates should be maintained between 112 and 168 kg/ha-d (100 and 150 Ib/ac-d). This influent is to be distributed to avoid organic “hot-spots.” Levee side slopes are steep, and vegetation is managed to allow penetration of fish throughout the system. Bottom slopes are designed to facilitate rapid draining of the cells, if required, to interrupt the reproductive cycle of the mosquitoes.

The above factors were used to develop the design criteria summarized in Table 3-15.

3.8.3.5 Description and Operating Characteristics of the Treatment System

A schematic of the completed marsh treatment system is shown in Figure 3-13. Pretreatment is accomplished in up to 11 of the existing oxidation

Table 3-15. **Design Criteria for Constructed Wetland at Gustine, CA (22)**

Item	Value
Effluent Criteria, mg/L	
BOD_5,	30
SS	30
Design Flow, m^3/d	3,785
Area, ha	9.7
Surface Hydraulic Loading, ma/ha-d	380
Depth, m	0.1-0.45
Detention Time, d	4-11
Inlets	Head end of channels, and one-third point
Outlets	Adjustable weirs

ponds operated in series. Following the ponds, 24 marsh cells, each about 0.4 ha (1 ac) in size, operate in parallel. The operator can draw wastewater from any one of the last seven oxidation ponds. This method of operation allows the operator to control the detention time in the ponds from 28 to 54 days, and to adjust the degree of pretreatment. The operator can thus avoid applying heavy concentrations of algae which develop in the latter ponds throughout the summer.

Pond effluent flow is split into six parts in a distribution structure and each portion of the flow is directed to a group of four marsh cells. Each of the 24 cells is 11.6 m (38 ft) wide, 337 m (1,107 ft) long and has an adjustable water depth of 10-45 cm (4-18 in). Levees, 3 m (10 ft) wide, separate the cells from one another.

Flow is introduced across the width of the marsh cells at the head end and also at a point one third of the total length from the head end. The initial flow split will be 67 percent at the head, and 33 percent at the one-third point. Overloading of the inlet zone of the cell is thus avoided. The reverse arrangement (33 percent at the head and 67 percent at the one-third point) can also be used with flow from the first third used to dilute the flow applied to the second two thirds.

Effluent from each cell flows over an adjustable weir used to control water depth in the cell. The effluent is then pumped to a disinfection process prior to discharge.

Hydraulic detention time is controlled by varying the number of cells in service, and by varying the water depth in each cell. The operator is offered great flexibility in attaining the desired detention time in the marsh which varies from about four days in the summer to 11 days in the winter. This operational flexibility allows the cells to be taken out of service sequentially each summer for vegetation management and other maintenance requirements.

Up to 12 cells may be taken out of service at any one time. The initial operating schedule listing the number of cells and the hydraulic detention time for each month is presented in Table 3-16.

In September 1986, six of the marsh cells were seeded with locally acquired hardstem bulrush rhizomes and six cells were seeded with locally acquired cattail rhizomes. The specified minimum planting density was 11 rhizomes/m^2 (1/sq ft for bulrush rhizomes and 5 rhizomes/m^2 (0.45/sq ft) (18 in center-to-center) for cattail rhizomes. For both species, rhizomes were distributed in the marsh cells at a density greater than specified using a manure spreader and then were disked into the soil with a disk-harrow. The contractor was responsible for assuring that the rhizomes germinated and that a healthy crop was established. However the early winter rainfall which the contractor had planned on for germination was very low in 1986 and the rhizomes did not germinate.

The marsh cells were replanted in June 1987. Both bulrush and cattail rhizomes were purchased from a nursery in Michigan and were planted using a tomato planter.

Several methods of vegetation management are under consideration, including mechanical harvesting and burning. Most management techniques require that the cell be taken out of service and allowed to dry. A ramp was constructed into each cell to allow access of harvesting equipment, should the mechanical harvest option be selected.

Six marsh cells have been planted in bulrush. Stands of bulrush are generally less dense than stands of cattail and therefore allow greater movement of mosquito fish. If treatment in the bulrush cells is comparable to that in the cattail cells, replanting of the marsh in bulrush may be considered.

3.8.3.6 Costs

Bids for the Gustine treatment plant improvements were received in August 1985. Approximate costs for the marsh system portion of the project were extracted from the lump sum bid and are summarized in Table 3-17.

City-owned land for the Gustine project was available. Land requirements for this system were 9.7 ha (24 ac) net for the area actually planted and about 14.5 ha (36 ac) gross for the whole marsh system, including all interior cell divider levees and an outer flood protection levee.

3.8.4 Fabius Coal Preparation Facility

3.8.4.1 History

The Tennessee Valley Authority (TVA) processed coal at the Fabius Coal Preparation Plant, located in

Figure 3-13. Gustine, CA marsh system flow schematic.

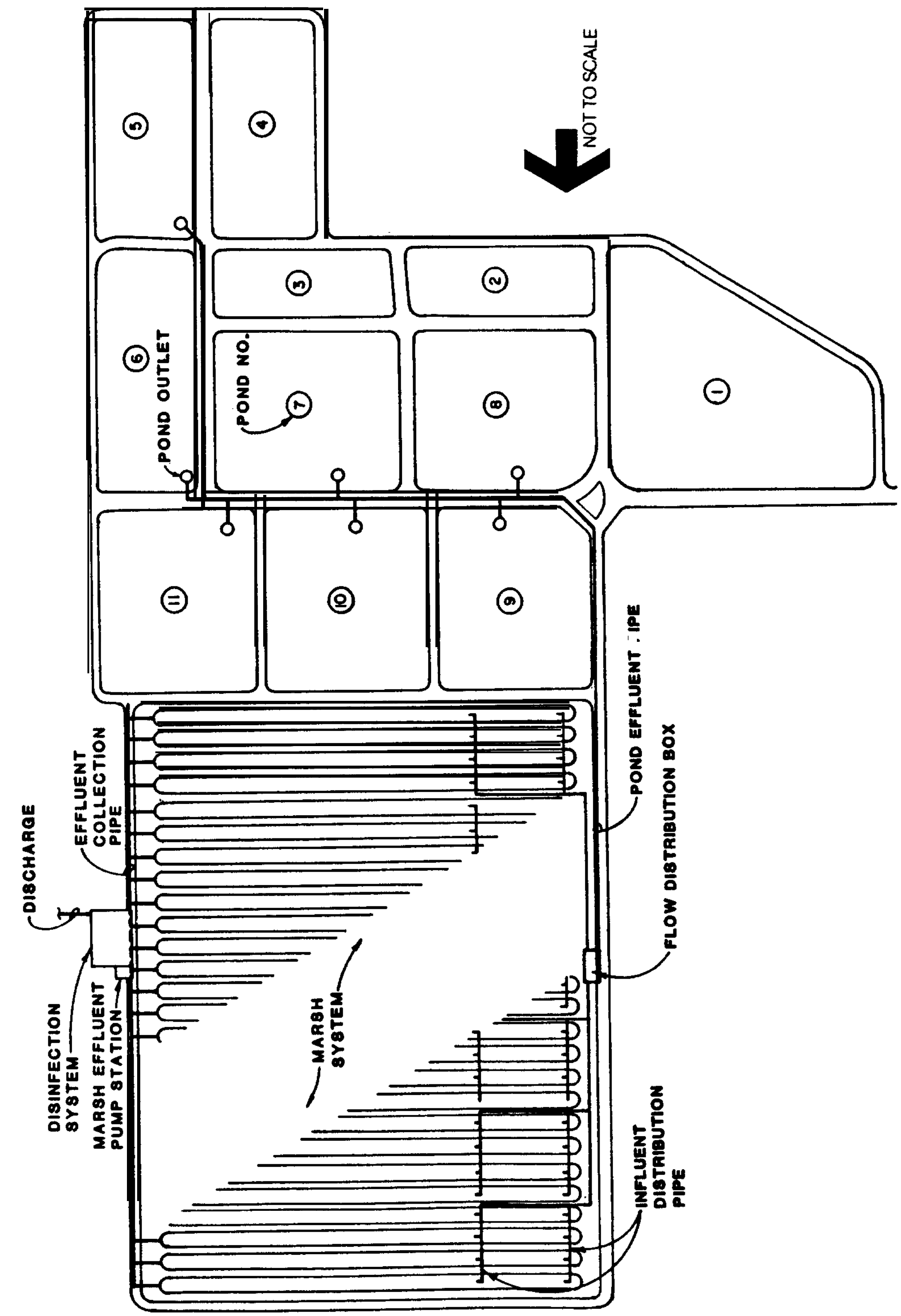


Table 3-16. Initial Operating Schedule of the Gustine, CA Marsh System (23)

Month	No. Cellis in Service,	Hydraulic Detentron Time, d
January	24	11
February	24	11
March	20	10
April	16	8
May	16	6
June	12	5
July	12	4
August	12	4
September	16	6
October	20	8
November	24	10
December	24	11

Table 3-17. Capital Costs for Gustine, CA Marsh Project (23)

Item	cost, $ (August 1985)
Pond effluent piping[a]	192,000
Earthwork[b]	200,000
Flow distribution structure[c]	16,000
Flow distribution piping in marsh[d]	205,000
Marsh cell water level control structure[e]	27,000
Marsh effluent collection piping[f]	83,000
Planting[c]	69,000
Paving[h]	90,000
Total	882,000

[a] Includes 790 m (2,600 H) Of 53-cm (21-in) PVC gravity piping. five manholes, seven pond outlet control pipes with wooden access platformss.

[b] Total earthwork volume, approx. 334,000 m^3 (45,000 cu yd). Cost includes clearing and grubbing, extra effort to work in area of very shallow ground water and to construct a 2-m (6.5-H) high outer levee to enclose the marsh area and protect it from the 100-year flood.

[c] A concrete structure with V-notch wears, grating, access stairs, and handrail.

[d] Approximately 850 m (2,800 H) of 20-cm (8-in) PVC gravity sewer pipe, 760 m (2,500 H) of 20-cm (8-in) gated aluminum pipe, and wooden support structures with concrete base slabs for the gated pipe installed at the one-third of length point.

[e] Small concrete structures in each cell with weir board guides and 60-mm (0.24-in) mesh stainless steel screen.

f Approximately 460 m (1,500 ft) of 10-38 cm (4-5 in) PVC gravity sewer pipe plus manholes.

e Based on mechanical planting of bulrush and cattail rhizomes on 45 and 90-cm (18 and 36-in) grid, respectively. Total bulrush area of about 2.4 ha (6 ac); 7.2 ha (18 ac) for cattails.

h Aggregate base paving of the outer levee and selected inner levees of the marsh area.

Jackson County, Alabama, from 1971 to 1979. In 1979 the facility was closed and in 1984 reclamation efforts were started. One of the main reclamation efforts was to involve the two coal refuse (coal slurry) disposal ponds which have a combined water surface area of 17 ha (42.5 ac) (see Figure 3-14). The coal slurry water stored in the ponds is treated and discharged but until recently seepage from the toe of the impoundment dam was not treated. Seepage flows range from 45 to 150 m^3/d (11,900-39,600 gpd) and contain high concentrations of iron and manganese. DO is less than 2.0 mg/L, SS exceed 98 mg/L, and pH averages 6.0.

In April 1985, it was decided to experiment with a marsh/pond wetland system for treating the two large and several small seeps (seepage flows) emanating from the impoundment dam.

3.8.4.2 Project Description

A series of four wetland areas were created in June 1985 by clearing 1.2 ha (3 ac) of woodlands, constructing four dikes with overflow spillways in the drainage path of the combined seepage flows, and transplanting a number of wetlands plant species in the diked areas (see Figure 3-15). Transplanted species, selected from nearby acid seeps, included bulrush (Scirpus), rush (Juncus), spikerush *(Eleocharis),* cattails *(Typha),* and scouring rush *(Equisetum).*

The water surface area of all the wetlands areas is approximately 0.6 ha (1.48 ac), and water depth varies from 0 to 1.5 m (0-5 ft) in the larger ponds. Based on seepage flows of 45-150 m^3/d (8-27 gpm), the surface hydraulic loading rate on the system is 75-250 m^3/ha-d (8,000-26,700 gpd/ac). After the clearing and dike construction were completed, it was discovered that there are additional seeps entering the wetlands system. One large and one small seep emerge at Pond 3 and two smaller seeps emerge at Pond 4. The four large wetland areas were stocked with mosquitofish and fathead minnows.

In July 1985, water quality sampling of the two major influents, the final effluent and at four locations in the wetlands system was initiated. Samples were collected biweekly and analyzed for pH, redox potential (Eh), DO, total iron, total manganese, and total SS.

An experiment to determine the capacity of the wetlands system for treating coal slurry water in addition to the seepage was performed in December 1985.

During a four-week period, supernatant from the coal slurry ponds was fed into the wetlands system at a flowrate of 110-220 m^3/d (29,000-58,000 gpd). Effluent quality dropped below discharge requirements at the next sampling and the experiment was stopped two weeks later. Starting in May experiments with treating supernatant flows were resumed but at much lower flow rates (5.4 m^3/d [1,400 gpd)

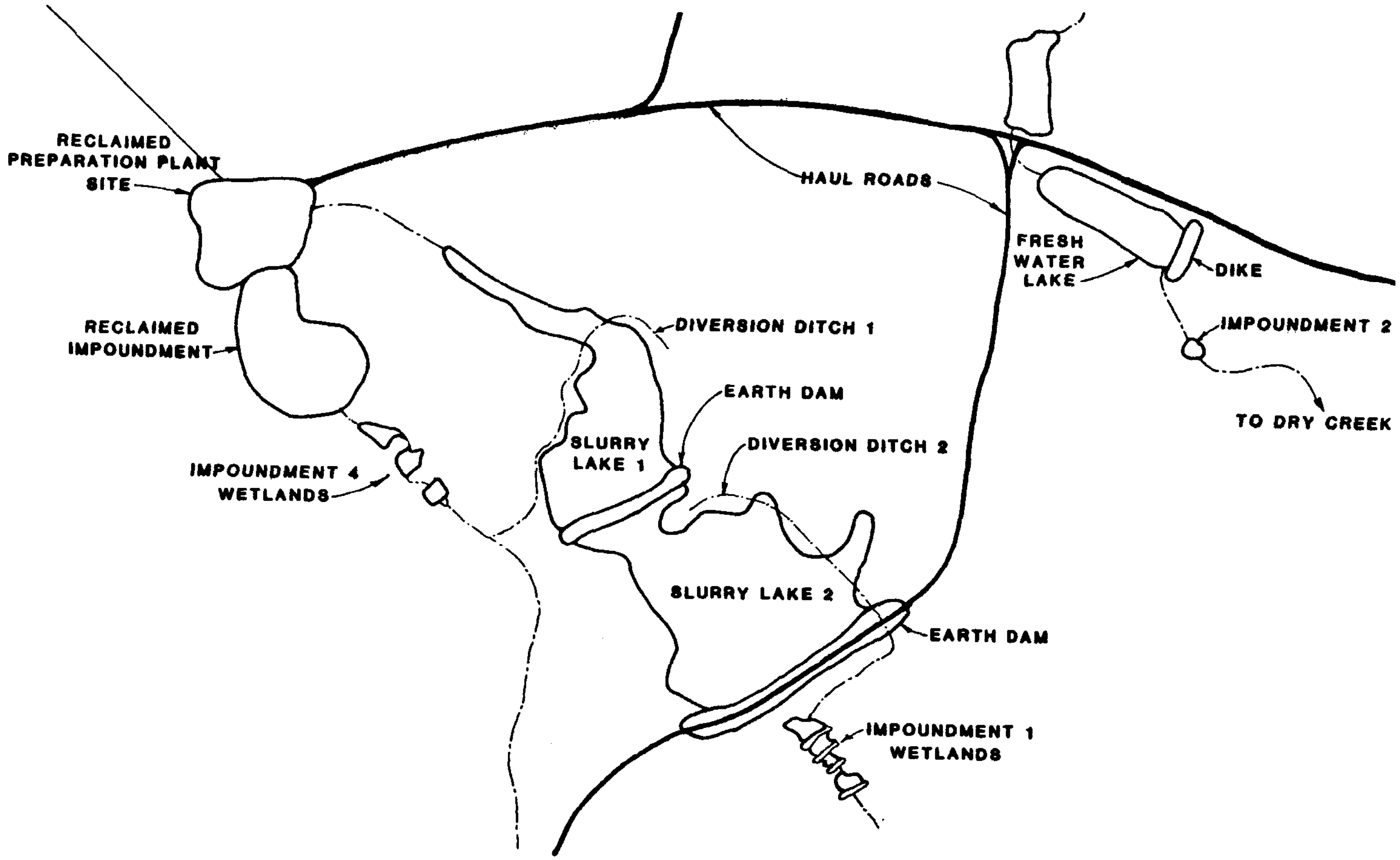
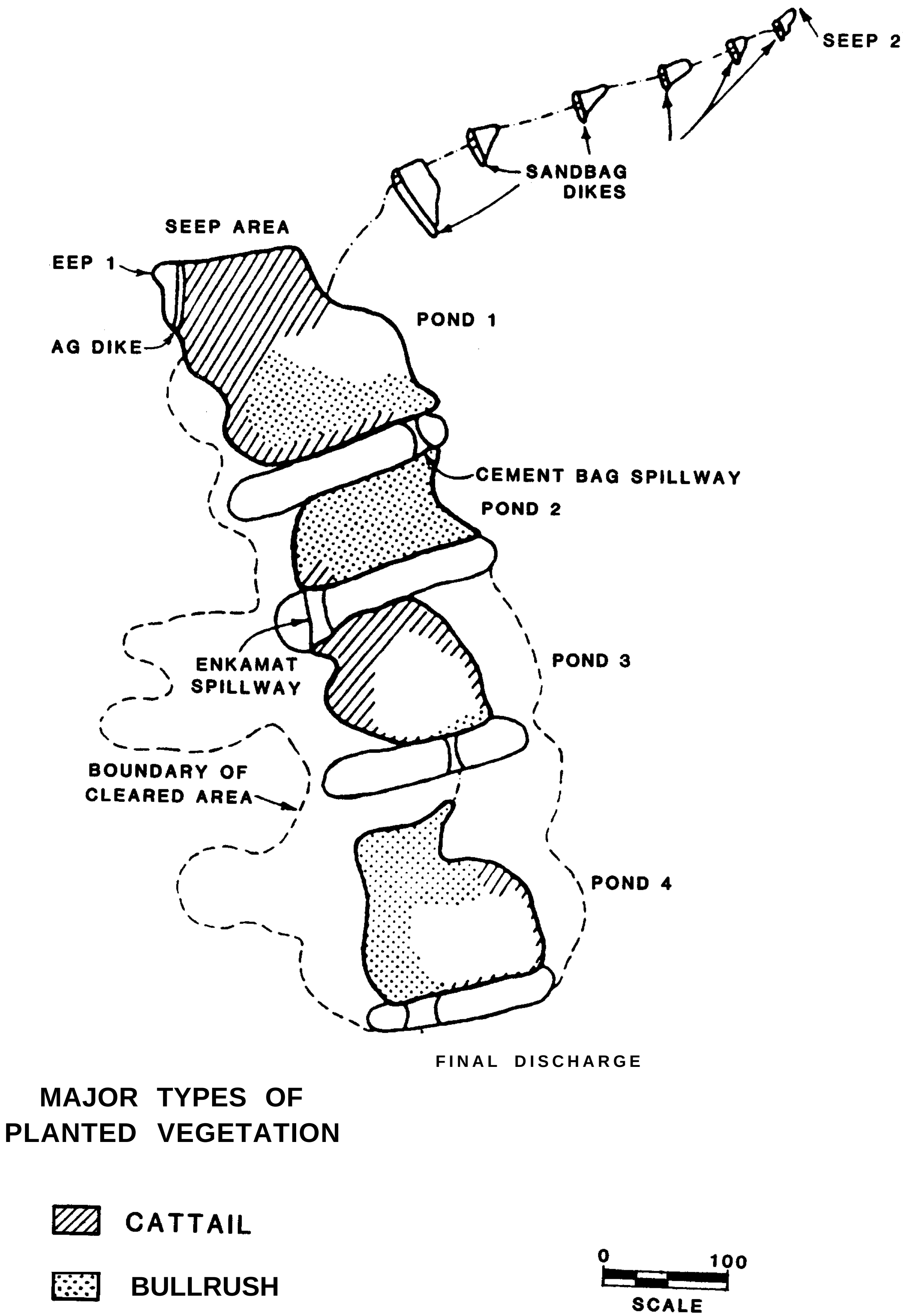

RECLAIMED PREPARATION PLANT SITE
HAUL ROADS
FRESH WATER LAKE
DIKE
IMPOUNDMENT 2
TO DRY CREEK
RECLAIMED IMPOUNDMENT
DIVERSION DITCH 1
EARTH DAM
DIVERSION DITCH 2
SLURRY LAKE 1
IMPOUNDMENT 4 WETLANDS
SLURRY LAKE 2
EARTH DAM
IMPOUNDMENT 1 WETLANDS

Figure 3-15. Fabius Coal Facility Impoundment 1 wetlands.



3.8.4.3 Operating Characteristics

The range and average water quality values for the influent, pond 1 effluent and final effluent with the wetlands system during a 12-month period treating coal slurry seepage and supernatant are summarized in Table 3-18. The average values include results during the four-week period when a relatively large flow of coal slurry supernatant was treated. Wetlands effluent water quality during periods when only seepage was being treated was always better than the discharge requirements. Compared with the alternative, chemical treatment, the wetlands system is much simpler in operation and maintenance and would appear to be more stable in terms of effluent quality.

3.8.4.4 Costs

The construction of the wetlands system at Fabius was performed by TVA personnel and cost approximately $28,000.

3.8.5 Summary

Although the four case studies presented in this chapter cover only portions of the range of possible applications of constructed wetlands, they represent four different approaches to the use of a constructed wetlands system for wastewater treatment. A comparison of the four systems is difficult but a summary of each system's design and operating characteristics and costs is provided in Table 3-19.

Constructed wetlands systems offer several potential advantages as a wastewater treatment process. These potential advantages include simple operation and maintenance, process stability under varying environmental conditions, lower construction and operating costs, and in the case of free water surface systems, the possibility to create a wildlife habitat. The potential problems with free water surface constructed wetlands include mosquitoes. Startup problems in establishing the desired aquatic plant species can be a problem with FWS and SFS wetlands alike.

Table 3-18. Fabius Coal Preparation Facility Marsh System Performance (24)

Period	Pond 4 Effluent Flow, m^3/d	pH			DO, mg/L			Fe, mg/L			Mn, mg/L			SS, mg/L		
		Inf.	Eff1	Eff4	Inf.	Eff1	Eff4	Inf.	Eff1	Eff4	Inf.	Eff1	Eff4	Inf.	Eff1	Eff4
7/85-9/85	52.3	6.0	6.4	6.6	0	6.2	-	80	2.6	0.64	8.7	1.4	0.43	95	8.9	2.2
10185-12/85	53.4	6.0	-	6.5	0	-	7.2	97	-	0.79	9.9	-	0.48	74	-	4.0
1/86-3/86	91.6		6.5	6.5	-	10.9	11.2		9.3	0.94	-	11.2	5.9	-	33	2.8
4/86-6/86	62.7		6.1	6.3	-	10.9	7.4	-	3.5	0.71	-	3.1	2.1	-	19.3	4.7
7/86-9/86	26.7	4.7	6.4	7.0	-	5.3	7.3	59	14.7	0.70	18	2.6	1.1	155	46.7	3.0
10/86-12/86	107.4	6.3	6.4	6.6	-	8.2	9.7	40	4.3	0.63	8.6	6.2	1.6	48	18.3	2.0

Table 3-19. Constructed Wetlands Case Studies Summary

Type	Arcata, CA	Emmitsburg, MD	Gustine, CA	Fabius Coal Facility
Aquatic Plants	Hardstem bulrush Cattails	Cattails	Cattails Hardstem bulrush	Bulrush Cattails Rush Spikerush
System Type	Free Water Surface	Subsurface Flow	Free Water Surface	Free Waler Surface
Influent	Oxidation Pond Effluent	Tricking Filter Effluent	Oxidation Pond Effluent	Coal Slurry Pond Seepage
Special Design Features	Intermediate Wetlands System Wildlife Sanctuary		Variable Source of Influent, Step Feed	
Design Flow, m^3/d	11,150	130	3785	227
Wetlands Surface Area, ha	12.6	0.07	9.3	0.6
Influent/Effluent BOD_5 mg/L	36.1/13.7	61.5/18.0	~ 150/- 24[a]	
Influent/Effluent SS, mg/L	42.9/31.3	30.2/8.3	~ 140/- 19[a]	
Hydraulic Surface Loading, $m^3/ha\text{-}d$	907	1,540	412	374
Capital Cost, $\$/m^3/d$	45	- 264[b]	232	
Capital Cost, $/ha	41,000	- 495,000[b]	94,000	

[a] Pilot plant results.
[b] Costs are not representative of full-scale system costs.

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National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
(703) 487-4650

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CHAPTER 4
Design of Aqua tic Plant Systems

4.1 Background

Aquatic plant systems are engineered and constructed systems that use aquatic plants in the treatment of industrial or domestic wastewater. They are designed to achieve a specific wastewater treatment goal. Aquatic plant systems can be divided into two categories:

1. Systems with floating aquatic plants such as water hyacinth, duckweed, pennywort; and

2. Systems with submerged aquatic plants such as waterweed, water milfoil, and watercress

Until recently, most of the floating aquatic plant systems have been water hyacinth systems. Use of water hyacinth for wastewater treatment in the United' States can be traced back to field-scale experiments in Texas and laboratory research by NASA researchers at the Bay St. Louis Experimental Station in Mississippi carried out in the early 1970s. Water hyacinths have been used in a variety of experimental and full-scale systems for treating various quality wastewaters.

However, use of water hyacinth has been limited, in geographic location, to warm weather regions because of the sensitivity of water hyacinth to freezing conditions. Water hyacinth systems have been most often used for either removing algae from oxidation pond effluents or for nutrient removal following secondary treatment. Since a conference on aquaculture systems for wastewater treatment at the University of California's Davis campus in September 1979, additional data have been accumulated on the use of aquatic plants in wastewater treatment (1,2).

Since 1970, aquatic treatment systems have been used successfully in a variety of treatment applications including secondary, advanced secondary, and tertiary treatment. Most of the performance data reported in the literature for these systems have, however, been observational rather than quantitative. Hydraulic detention time, hydraulic loading rate, and organic loading rate are the most common parameters used and needed to size aquatic plant systems.

4.7.7 Characteristics of Aquatic Treatment *Systems*

Aquatic treatment systems consist of one or more shallow ponds in which one or more species of water tolerant vascular plants such as water hyacinths or duckweed are grown (3). The shallower depths and the presence of aquatic macrophytes in place of algae are the major differences between aquatic treatment systems and stabilization ponds. The presence of plants is of great practical significance because the effluent from aquatic systems is of higher quality than the effluent from stabilization pond systems for equivalent or shorter detention times. This is true, particularly when the systems are situated after conventional pond systems which provide greater than primary treatment.

In aquatic systems, wastewater is treated principally by bacterial metabolism and physical sedimentation, as is the case in conventional trickling filter systems. The aquatic plants themselves, bring about very little actual treatment of the wastewater (3). Their function is to provide components of the aquatic environment that improve the wastewater treatment capability and/or reliability of that environment (4).

4.1.2 History

General reviews of the use of water hyacinth and several other aquatic plants for wastewater treatment, including duckweed, are presented elsewhere (2,5-7). The locations of several pilot- and full-scale tests which were significant in developing methods and performance data for aquatic treatment systems are presented in Table 4-1. The systems in Mississippi and Texas (presented in Table 4-1) received facultative pond effluent as their influent source. Primary effluent was the influent wastewater for the systems at Walt Disney World, San Diego, and Hercules. All other locations in Table 4-1 received secondary effluent into the floating aquatic plant system.

Research at Walt Disney World in Florida (8) has, since 1978, been directed toward an integrated system including: 1) aquaculture treatment of wastewater to meet federal, state and local standards, 2) biomass management for achieving optimum yields, and 3) anaerobic digestion of harvested

Table 4-1. History of Use of Floating Aquatic Treatment Systems (Water Hyacinths, except as noted)

Location	Scale	Objective	Date	Status
University of Florida	Experimental	Research	1964-1974	Completed
Bay St. Louis, MS[a]	Full	Secondary	1976	Ongoing
Lucedale, MS	Full	Secondary	1970s	Abandoned
Orange Grove, MS	Full	Secondary	1970s	Abandoned
Cedar Lake (Biloxi), MS[b]	Full	Secondary	1979	Ongoing
Williamson Creek, TX	Pilot	Secondary	1975	Abandoned
Austin-Hornsby, TX	Pilot/Full	Secondary	1970s	Ongoing
Alamo-San Juan, TX	Full	Secondary	1970s	Abandoned
San Benito, TX	Full	Secondary	1976	Ongoing
Rio Hondo, TX	Full	Secondary	1970s	Abandoned
Lakeland, FL	Full	Tertiary	1977	Ongoing
Waft Disney World, FL	Pilot	Secondary	1978	Completed
Coral Springs, FL	Full	Tertiary	1978	Abandoned
Orlando, FL	Full	Tertiary	1985	Ongoing
University of California Davis, CA	Experimental	Research	1978-1983	Completed
Hercules, CA	Full	Advanced Secondary	1980-1981	Abandoned
Roseville, CA	Pilot	Nitrification	1981	Abandoned
San Diego, CA	Pilot	Advanced Secondary	1981	Ongoing

[a] Frost killed hyacinths; pennywort and duckweed are now used.
[b] Duckweed.

aquatic vegetation to produce methane for energy recovery.

4.1.3 Climatic Constraints

The water hyacinth systems that are currently used to treat wastewater in the United States are located in the warm temperate climates of the southern states. The optimum water temperature for water hyacinth growth is 21-30°C (70-96°F). Air temperatures of -3°C (-26°F) for 12 hours will destroy the leaves and exposure at -5°C (-23°F) for 48 hours will kill the plants. If a water hyacinth system were to be used in a colder climate, it would be necessary to house the system in a greenhouse and maintain the temperature in the optimum range (9). Based upon the limited data available, it would be uneconomical to attempt to develop a water hyacinth wastewater treatment system in cold regions (9). Duckweed *(Lemna* spp.) is more cold tolerant than water hyacinths and can be grown practically at temperatures as low as 7°C (45°F) (10).

4.2 Vegetation

Aquatic plants have the same basic nutritional requirements as plants growing on land and are influenced by many of the same environmental factors. The treatment responses in an aquatic plant system are due to the presence of the plants in the water system altering the physical environment of the systems **(11).** Water hyacinth plant roots act as a living substrate for attached microbial organisms, which provide a significant degree of treatment (11).

4.2.1 Floating Plants

Floating plants have their photosynthetic parts at or just above the water surface with roots extending down into the water column. In photosynthesis, floating aquatic plants use atmospheric oxygen and carbon dioxide. Nutrients are taken up from the water column through the roots. These roots are an excellent medium for the filtration/adsorption of suspended solids and growth of bacteria. Root development is a function of nutrient availability in the water and nutrient demand (i.e., growth rate) of the plant. Thus, in practice, the density and depth of treatment medium (i.e., plants roots) will be affected by wastewater quality/pretreatment and factors affecting plant growth rate such as temperature and harvesting.

With floating plants, the penetration of sunlight into water is reduced and the transfer of gas between water and atmosphere is restricted. As a consequence, floating plants tend to keep the wastewater nearly free of algae and anaerobic or nearly so, depending on design parameters such as BOD_5 loading rate, detention time, and the species and coverage density of floating plants selected for use (4). An observation of interest is that some molecular oxygen produced by photosynthetic tissue is translocated to the roots and may keep root zone microorganisms metabolizing aerobically, though the surrounding water is anaerobic/anoxic (4).

4.2.1.1 Water Hyacinths

Water hyacinth *(Eichhornia crassipes)* is a perennial, freshwater aquatic vascular plant with rounded, upright, shiny green leaves and spikes of lavender flowers (11) (See Figure 4-1). The petioles of the plant are spongy with many air spaces and contribute to the buoyancy of the hyacinth plant. When grown in wastewater, individual plants range from 0.5 to 1.2 m (20 to 47 in) from the top of the flower to the root tips (11). The plants spread laterally until the water surface is covered and then the vertical growth increases. Hyacinths are very productive photosynthetic plants. Their rapid growth is a serious nuisance problem in many slow flowing southern waterways. These same attributes become an advantage when used in a wastewater treatment system.

In the United States, this plant is widely distributed in Alabama, California, Florida, Mississippi, Louisiana, and Texas (5). After years of using expensive physical and chemical control measures, the water hyacinth problem has been generally reduced to manageable levels through the use of the hyacinth weevil *(Neochetina eichhomiae* and N. *bruchi)* and hyacinth mite *(Orthogalumna terebrantis).* Both of these biological control agents were imported from South America, the native location of the water hyacinth. The mite probably was introduced accidentaly with the original water hyacinth plants at the Cotton States Centennial Exposition in New Orleans, Louisiana, in 1884 (12,13). These biological control agents have reduced water hyacinth populations to manageable levels so the hyacinth is no longer considered a major concern for maintenance of open waterways.

Water hyacinth is a rapid growing aquatic macrophyte and is ranked eighth among the world's top 10 weeds in growth rate (5). It reproduces primarily by vegetative propagation, but seeds may be a major source of reinfestation once the parent plants have been removed. Water hyacinth also develops a large canopy, which may provide a good competitive edge over other floating aquatic plants growing in the same system. Growth of water hyacinth is influenced by: 1) efficiency of the plant to use solar energy, 2) nutrient composition of the water, 3) cultural methods, and 4) environmental factors (5).

Plant growth is described in two ways. The first is to report the percentage of pond surface covered over a period. The second more useful method is to report the plant density in units of wet plant mass per unit of surface area. Under normal conditions, loosely packed water hyacinth can cover the water surface at relatively low plant densities (10 kg/m^2 [20 Ib/sq ft] wet weight). It can reach a maximum density of 50 kg/m^2 (100 Ib/sq ft) wet weight (5), before growth ceases.

As in other biological processes, growth rates in water hyacinth systems depend on temperature. Both air and water temperature are important in assessing plant vitality. Water hyacinths are reported to survive 24 hour exposure at temperatures of 0.5 to -5°C (33 to 31°F) but die at temperatures of -6 to -7°C (21 to 19°F) and cannot become established in regions where winter temperatures average 1 ^{o}C (34°F) (14). Growth is rapid at 20-30°C (68-96°F) and nearly stops at 8-15°C (46-59°F) (14). Suitable areas for growing water hyacinths include the southern portions of California, Arizona, Texas, Mississippi, Alabama, Georgia, and Florida. Areas within the continental United States where cultivation of water hyacinth systems is possible are shown in Figure 4-2.

Hyacinth systems can be used to advantage in correcting algal bloom problems in oxidation ponds. Use of hyacinths in summer only is a technically feasible solution for some rural systems that experience discharge problems with high SS (from algae).

4.2.1.2 Pennywort

Pennywort *(Hydrocotyle umbellata)* is not a free floating plant; it tends to intertwine and grows horizontally, and at high densities the plants tend to grow vertically. Unlike water hyacinth, photosynthetic leaf area of pennywort is small, and at dense plant stands, yields are significantly reduced as a result of self shading (15). Pennywort exhibits mean growth rates greater than 10 g/m-d (73 Ib/ft-d) in central Florida (15). Although rates of N and P uptake by water hyacinth drop sharply during the winter, nutrient uptake by pennywort is approximately the same during both warm and cool seasons. Nitrogen and phosphorus uptake during the winter months is greater for pennywort than for water hyacinth (16).

Although annual biomass yields of pennywort are lower than water hyacinth, it offers a great potential as a cool season plant that can be integrated into water hyacinth/water lettuce biomass production systems (15).

4.2.1.3 Duckweed

Duckweeds are small, green freshwater plants with leaflike frond from one to a few millimeters in width. *Lemna* and *Spirodela* have a short root usually less than 10 mm (0.4 in) in length (Figure 4-3). Duckweed such as *Lemna* spp., *Spirodela* spp., and Wolffia spp., have all been tested for pollutant removal or used in wastewater treatment systems (11). Potential growth areas for duckweed in the United States are shown in Figure 4-3 for various seasons of the year.

Figure 4-1. **Morphology of the hyacinth plant [Reprinted with permission of McGraw-Hill Book Company (11)).**

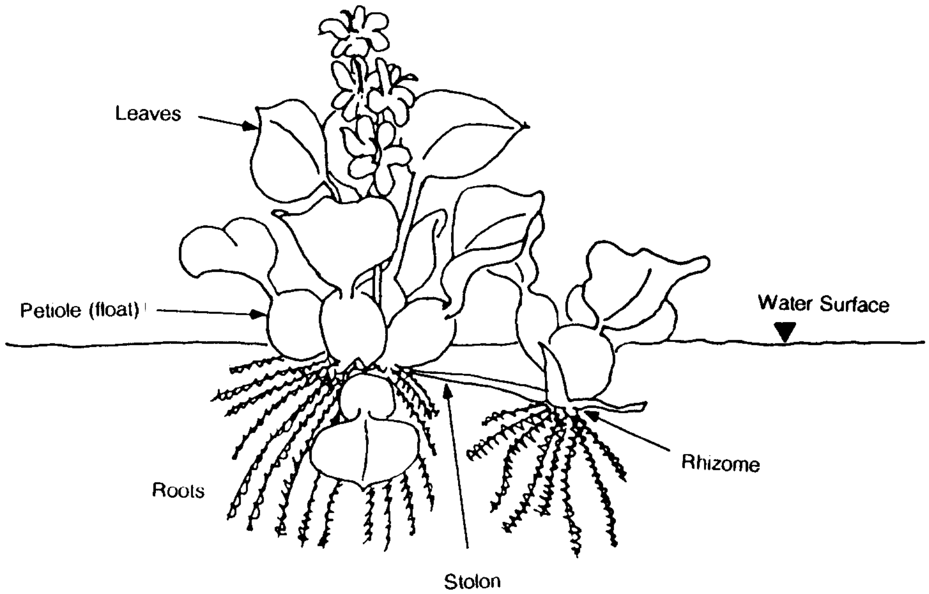
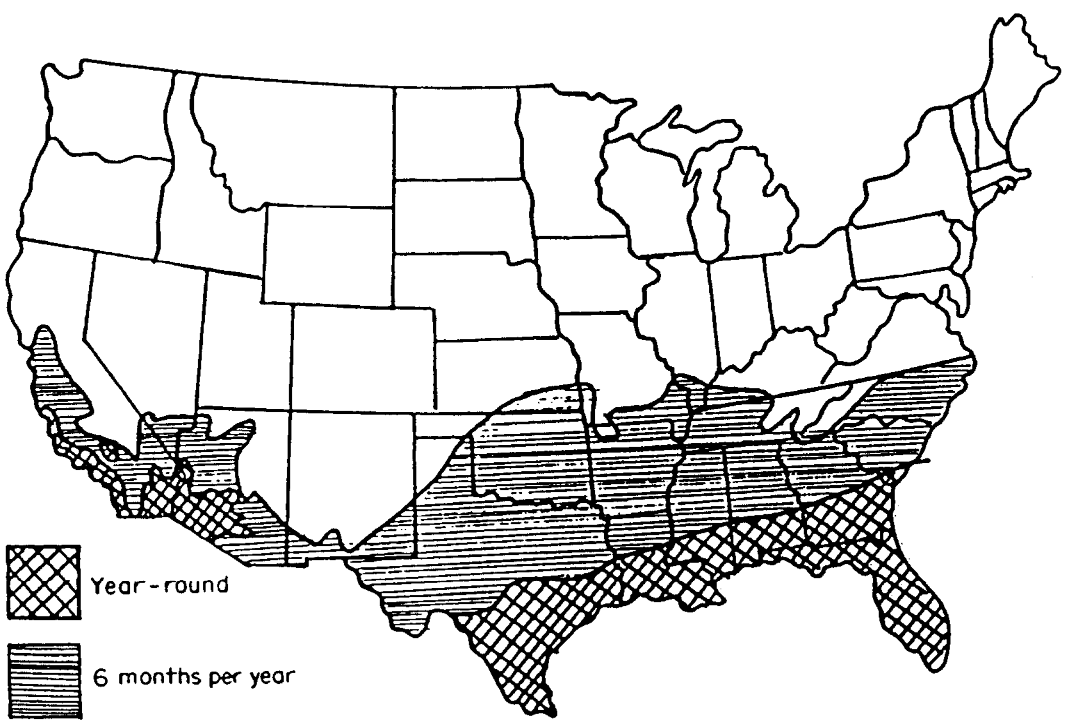


Figure 4-2. **Suitable areas for hyacinth systems (10).**



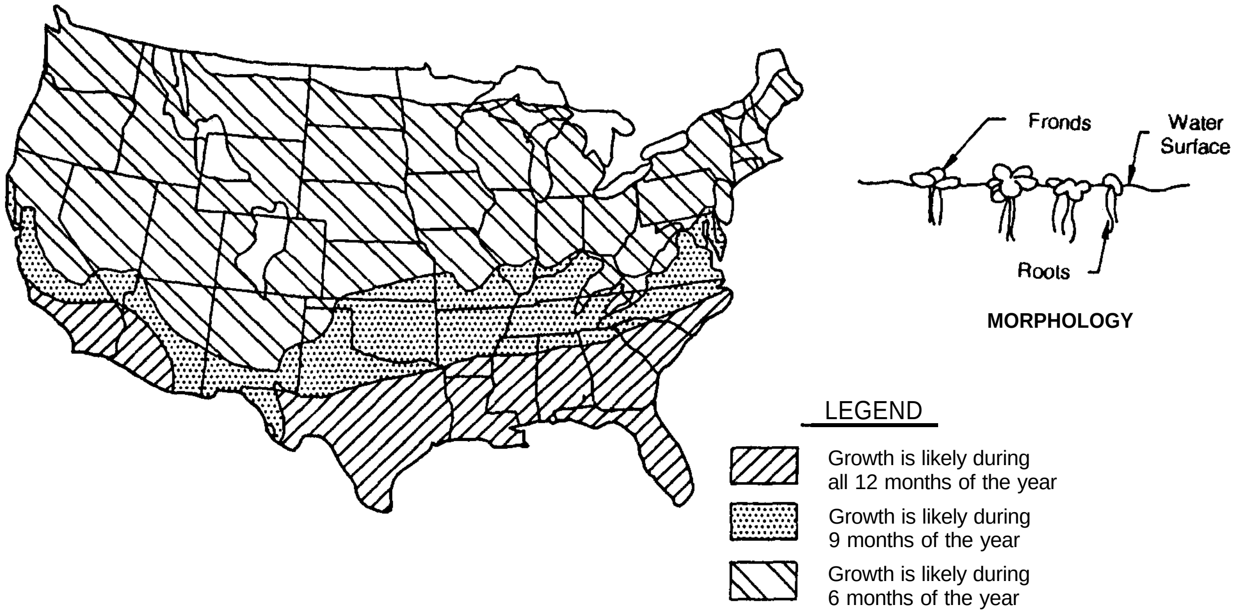


Figure 4-3. Morphology of and potential growth areas for duckweed plants (7).

Duckweeds are the smallest and the simplest of the flowering plants and have one of the fastest reproduction rates. A small cell in the frond divides and produces a new frond; each frond is capable of producing at least 10-20 more during its life cycle (9). *Lemna* sp. grown in wastewater effluent (at 27°C [81 ^{o}F]) doubles in frond numbers, and therefore in area covered, every four days. It is believed that duckweed can grow 30 percent faster than water hyacinths. The plant is essentially all metabolically active cells with very little structural fiber **(11).**

Performance of some existing duckweed systems is summarized in Table 4-2. Duckweed systems are developed by following the conventional design procedures for faculaltive lagoons. Effluent from a duckweed covered system should exceed performance of conventional facultative lagoons for BOD_5, SS and nitrogen removal (11). The effluent from a duckweed system is likely to be anaerobic and post aeration may be necessary. The advantage of duckweed systems over a similar additional facultative lagoon cell is lower algae concentrations in the effluent. This is due to extensive shading of the water by the mat of surface duckweed.

Duckweed, like hyacinths, contains about 95 percent water; the composition of the plant tissue is given in Table 4-3 (4). Duckweed contains at least twice as much protein, fat, nitrogen, and phosphorus as hyacinth. The value of duckweed as a food source for a variety of birds and animals has been confirmed by several nutritional studies **(17).**

Small floating plants, particularly duckweed, are sensitive to wind and may be blown in drifts to the leeward side of the pond. Redistribution of the plants requires manual labor. If drifts are not redistributed, decreased treatment efficiency may result due to incomplete coverage of the pond surface. Also piles of decomposing plants can result in the production of odors.

4.2.2 Submerged Plants

Submerged plants are either suspended in the water column or rooted in the bottom sediments. Typically, their photosynthetic parts are in the water column, but certain vascular species may grow to where their photosynthetic parts are at or just below the water surface.

The potential for use of submerged aquatic plants for treatment of primary or secondary effluent is severely limited by their tendency to be shaded out by algae and their sensitivity to anaerobic conditions. The mechanism by which submerged plants are able to remove ammonia from the water column is related to their photosynthetic processes which remove carbon dioxide from the water (unlike hyacinths) thus raising the pH and driving ammonia to the gaseous form which can diffuse into the atmosphere. Ammonia gas is the most toxic form of nitrogen for fish. This

Table 4-2. **Performance of Existing Duckweed Systems (7)**

Location	Influent	BOD_5 mg/L		TSS, mg/L		Depth, m	Detention Time, days
		Influent	Effluent	Influent	Effluent		
Biloxi, MS	Facultative Pond Effluent[a]	30	15	155	12	2.4	21
Collins, MS	Facultative Pond Effluent	33	13	36	13	0.4	7
Sleep Eye. MN (Del Monte)	Facultative Pond Effluent	420	18	364	34	1.5	70
Wilton, AR	Facultative Pond Effluent[a]	-	6.5	-	7.4	2.7	0.7
NSTL, MS	Package Plant Effluent	35.5	3.0	47.7	11.5	0.4	8

[a] Partially aerated.
[b] Theoretical hydraulic detention time for duckweed cell only.

Table 4-3. **Composition of Duckweeds Grown in Wastewater (after 11)**

Constituent	Percent of Dry Weight	
	Range	Average
Crude protein	32.7-44.7	38.7
Fat	3.0-6.7	4.9
Fiber	7.3-13.5	9.4
Ash	12.0-20.3	15.0
Carbohydrate		35.0
TKN	4.59-7.15	5.91
Phosphorus, as P	0.5-0.7	0.6

mechanism is of some concern for healthy populations of mosquito fish which are generally encouraged in aquatic treatment ponds for mosquito control.

At night these plants respire (i.e., use oxygen) in competition with the mosquito fish. It is generally considered that this category of plant will not have widespread usage *in* aquatic systems because of its pronounced diurnal effect on the aquatic environment, tendency to be shaded out by nuisance algae, and sensitivity to anaerobic conditions (2). No pilot- or full-scale systems using submerged plants are known and therefore none are reported in this manual.

4.3 Process Design Criteria for Water Hyacinth Systems

Water hyacinth systems represent the majority of aquatic plant systems that have been constructed. Organic loading is a key parameter in the design and operation of water hyacinth systems. Three types of hyacinth systems can be described based on the level of DO and the method of aerating the pond.

Aerobic hyacinth systems without supplemental aeration will produce secondary treatment or nutrient (nitrogen) removal depending on the organic loading rate. This type of system is most common of the hyacinth systems already constructed. Its advantages include few mosquitoes or odors.

For a system location in which no mosquitoes or odors can be tolerated, an *aerobic system with supplemental aeration* is required. The added advantage of such a system is that, with aeration, higher organic loading is possible and reduced land area is required. The characteristics of these two systems are summarized in Tables 4-4 and 4-5.

The third configuration for a hyacinth system is to operate it under high organic loading. The purpose is to achieve secondary treatment, and these systems are capable of producing consistent treatment without aeration under high organic loading. Disadvantages include increased mosquito populations and potential for odors. The early systems at Disney World were this type (called *facultative/anaerobic* in this manual). Facultative/anaerobic systems are not commonly being designed any more because it has been recognized that organic loading rates of up to 100 kg/ha-d (89 Ib/ac-d) produce consistent results without the disadvantages of high loading.

4.3.1 Organic Loading Rates

BOD_5 loading rates for water hyacinth systems can range from 10 to 300 kg/ha-d (9-268 Ib/ac-d) (see Table 4-5). For primary effluent loading at Disney World, Florida, the basins were loaded at 55-440 kg/ha-d (50-400 Ib/ac-d), without significant odor problems except at the higher loadings. Average loadings on the entire system without aeration should not exceed 100 kg/ha-d (89 Ib/ac-d).

4.3.2 Hydraulic Loading Rate

Hydraulic loading rate, expressed in units of m^3/ha-d, is the volume of wastewater applied per day divided by the surface area of the aquatic system. The hydraulic loading rates applied to water hyacinth facilities have varied from 240 to 3,570 m^3/ha-d (25,650-381,650 gpd/ac) when treating domestic wastewaters (9). For secondary treatment objectives (BOD_5 and SS<30 mg/L), the hydraulic loading rate is typically between 200 and 600 m^3/ha-d (21,600-64,600 gpd/ac). For advanced secondary treatment with supplemental aeration, hydraulic loading rates of 1,000 m^3/ha-d (107,000 gpd/ac) have been used successfully. However, organic loading rates will generally control hydraulic loading.

Table 4-4. Types of Water Hyacinth Systems

Type	Purpose	Typical BOD_5 Loading, kg/ha-d	Advantages	Disadvantages
Aerobic Non-aerated	Secondary Treatment	40-80	Limited mosquitoes; limited odors	More land area required; harvesting may be more dffficult (depends on pond configuration)
Aerobic Non-aerated	Nutrient Removal	**10-40**	Limited mosquitoes; limited odors nutrient removal	More land area required; harvesting may be more difficult (depends on pond configuration)
Aerobic Aerated	Secondary Treatment	150-300	No mosquitos; no odors; higher organic loading rates; reduced land area	Additional harvesting required; supplemental power required
Facultative/Anaerobic*	Secondary Treatment	220-400	Higher organic loading rates; reduced land area	Increased mosquito population; potential for odors

a Only suitable where odors and mosquitoes may not be a problem.

Table 4-5. Design Criteria for Water Hyacinth Systems

Factor	Type of Water Hyacinth System: Aerobic Non-aerated	Aerobic Non-aerated	Aerobic Aerated
Influent Wastewater	Screened or Settled	Secondary	Screened or Settled
Influent BOD_5, mg/L	130-180	30	130-180
BOD_5 Loading, kg/ha-d	40-80	10-40	150-300
Expected Effluent, mg/L			
BOD_5	<30	<10	<15
SS	<30	<10	<15
TN	415	< 5	<15
Water Depth, m	0.5-0.8	0.6-0.9	0.9-1.4
Detention Time, days	10-36	6-18	4-8
Hydsraulic Loading, m^3/ha-d	> 200	< 800	550-1,000
Harvest Schedule	Annualy	Twice per Month	Monthly

4.3.3 Water Depth

The recommended depth of hyacinth ponds is 0.4-1.8 m (1.2-6 ft) with the majority of investigators recommending a depth of 10.9 m (3 ft) (9). The critical concern is to provide adequate depth for the root system to penetrate through the majority of the liquid flowing through the hyacinth pond. A greater depth is sometimes recommended for the final cell in a series of hyacinth ponds since the hyacinth roots will be longer when fewer nutrients are present in the water (11). Recommended depth from the San Diego project (with aeration) is 1.07-1.37 m (3.5-4.5 ft) (18). For duckweed systems, operating depths of 1.5-2.5 m (58.2 ft) have been used.

4.3.4 Vegetation Management

The literature on water hyacinths as a wastewater treatment process contains considerable speculation on the use of the water hyacinth upon harvesting (8). Composting, anaerobic digestion for the production of methane, and the fermentation of the sugars into alcohol are techniques proposed as a means to partially recover the costs of wastewater treatment. These digestion techniques may have use in a large scale operation; however, it is unlikely that a typical small wastewater treatment production system will approach the economic break-even point from methane gas production.

The need for harvesting depends on the water quality objectives for the project, the growth rates of the plants, and the effects of predators such as weevils. Harvesting of aquatic plants is needed to maintain a crop with high metabolic uptake of nutrients. For example, frequent harvesting of hyacinths (every three to four weeks) is practiced in Florida to achieve nutrient removal. Nitrogen and phophorus removal by the plants is achieved only with frequent harvesting. In areas where weevils pose a threat to healthy hyacinth populations, selective harvesting can theoretically be used to keep the plants from being infected. The State of Texas recommends an annual draining and cleaning of each basin instead of regular plant harvesting (11). Duckweed harvesting for nutrient removal may require frequencies of at least one week during warm periods.

The harvested plants are typically dried and landfilled. The drying process may be a source of significant odors. At Kissimmee, Florida, the hyacinths are vermicomposted. Ground duckweed can be used as animal feed without air drying.

4.3.5 Mosquitoes and Their Control

The objective of mosquito control is to suppress the mosquito population below the threshold level required for disease transmission or nuisance tolerance level. Strategies that can be used to control mosquito populations include (from [3]):

1. Stocking ponds with mosquito fish *(Gambusia afinis).*

2. More effective pretreatment to reduce the total organic loading on the aquatic system to help maintain aerobic conditions.

3. Step feed of influent waste stream with recycle.

4. More frequent harvesting.

5. Application of man-made control agents.

6. Diffusion of oxygen (with aeration equipment).

Effective mosquito control is based on two very difficult operational parameters: the maintenance of DO at 1 mg/L and the frequent harvesting and thinning of the water hyacinths. Supplemental aeration has been employed at San Diego to maintain this goal.

In many parts of the United States, the growth of mosquitoes in aquatic treatment systems may be the critical factor in determining whether the use of such systems will be allowed (3). Fish used for control of mosquitoes (typically *Gambusia affinis)* will die in anaerobic conditions caused by organically overloaded ponds. In addition to inhibited fish populations, mosquitoes may develop in dense hyacinth systems when plants have been allowed to grow tightly together. Pockets of water form within the plant body and are accessible to the mosquito larvae but not the fish.

4.3.6 Suggested Design Parameters

Design parameters used to size aquatic systems include hydraulic detention time, organic loading rate, and less frequently nitrogen loading rate. Design parameters based on the required level of treatment have been summarized in Table 4-5. Design criteria for effluent polishing using duckweed in facultative ponds are summarized in Table 4-6.

4.3.7 Sludge Management

Sludge consists of both wastewater solids and plant detritus. It must eventually be removed from aquatic plant system ponds. The quantities of sludge that accumulate were estimated at Williamson Creek, Texas, to be 1.5 to 8 x 10^{-4} m^3 of sludge/m^3 of wastewater treated (150-800 gal/mgd) (1). This compares to 1.8 x 10^{-3} m^3 of sludge/m^3 of wastewater treated (1,800 gal/mgd) for conventional primary stabilization ponds. Generally the rate of sludge accumulation in a pond containing water hyacinths is a function of the pretreatment provided. Very little information is available regarding sludge accumulation for ponds with aquatic plants other than water hyacinths. A cleaning frequency for hyacinth ponds based on the degree of treatment and the frequency of plant harvesting has been suggested (11). Suggested cleaning frequencies are shown in Table 4-7.

Table 4-6. Design Criteria for Effluent Polishing With Duckweed Treatment Systems

Factor	Secondary Treatment
Wastewater Input	Facultative Pond Effluent
BOD_5 Loading, kg/ha-d	22-28
Hydraulic Loading, m^3/ha-d	<50
Water Depth, m	1.5-2.0
Hydraulic Detention Time, days	15-25
Water Temperature, ^oC	>7
Harvest Schedule	Monthly

Table 4-7. Recommended Sludge Cleanout Frequency for Water Hyacinth Ponds (11)

Pond Type	Cleaning Frequency
Primary Cells in Shallow High-Rate Systems	Annual
Secondary Cells	2-3 years
Tertiary Cells	2-3 years
Deep Secondary Cells (regularly harvested)	5 years
Secondary Cells (irregularly harvested)	Annual
Systems Used Only Seasonally	Annual

4.4 Physical Features of Aquatic Treatment Systems

4.4.1 System Configurations

Most of the early hyacinth systems involved rectangular basins operated in series similar to stabilization ponds. Long, narrow channels were used in the Disney World research in Florida.

The San Diego Aquaculture Project, as an example, is a pilot-scale water hyacinth project for treatment of primary effluent to secondary effluent quality. The current configuration of this system has evolved to solve earlier problems with hydrogen sulfide odors, and presence of mosquito larvae in the ponds. The solution to the above two major problems is reflected in the unique system configuration and influent distribution system.

Early operating experience at the San Diego facility indicated that hydrogen sulfide odors and mosquito larvae were a problem. Because of the urban setting, this pilot plant had stringent requirements of no odors and no mosquito larvae being allowed. Initial solutions included lower organic loading and recycle flow from the effluent end of the pond to the front end to dilute the influent flow and distribute the organic load more completely throughout the pond. This solution was only partly successful and organic loading rates had to remain low to prevent anaerobic conditions at the head end of the pond.

A series of tests of BOD_5 concentration along the length of the pond indicated that most of the BOD_5 removal occurred in the first 15 m (50 ft) of the 120-m (400-ft) pond. The most recent system configuration includes recycle of effluent and step feed of influent at eight locations approximately 15 m (50 ft) apart along the length of the pond. Supplemental aeration has also become a regular part of the pond configuration.

The evolution of the distribution system experiments which have resulted in the choice of the step feed with recycle is shown in Figure 4-4. Step feed and recycle should be used as operational tools to control organic loading in the pond. With these tools, and a pond with high length-to-width ratios (>10:1), the operator can control the treatment process for best performance. Pattern C represents the current San Diego system and pattern D represents the wraparound pattern planned for future facilities. The wraparound design shortens recycle lines and step feed lines.

4.4.2 Inlet and Outlet Structures

Shallow, rectangular basins with a high length to width ratio are usually designed for aquatic treatment systems to reduce the potential for short circuiting and to simplify harvesting operations. The use of baffles and influent distribution manifolds helps to maximize the retention time. Influent manifolds and multiple inlet (step feed) systems can also be used effectively for recycling treated effluent to reduce the influent concentrations of wastewater constituents. An effluent manifold across the basin will maintain a low velocity into the manifold which serves to maintain quiescent conditions near the outlet. If variable operating depths are planned, it should be possible to remove effluent at a depth of 0.3 m (1 ft) below the most shallow operating depth.

4.4.3 Supplemental Aeration

The need for aeration is derived from the strict need for mosquito control and odor control. Aeration of the ponds helps maintain DO> 1 mg/L for the mosquitoe fish in the system and minimizes H_2S gas production. A successful configuration of the aeration system at San Diego uses fine bubble diffusers. Fine bubble diffusers produced DO levels 0.5-1.0 mg/L higher than coarse bubble diffusers in similarly configured ponds with the same BOD_5 loading rate and total air flow (Figure 4-5). The capacity of the aeration system was equal to two times the BOD_5 load. [A method for sizing the aeration system is shown in Sample Problem No. 2.] During daylight hours an automated system will cycle on and off as required to maintain DO> 1 mg/L When water hyacinths are actively photosynthesizing, they transport oxygen to their roots and at the same time to the microbes attached to the roots. This process lowers the supplemental aeration equipment and associated energy costs for aeration.

One method of supplemental aeration cited is spray irrigation. In this method, wastewater is recycled through spray heads onto the hyacinths. This technique is also often cited for frost control in climates where winter temperatures are marginal for hyacinths. A spray recycle system in which more temperature tolerant plants are used in order to function as a living trickling filter has also been proposed (19).

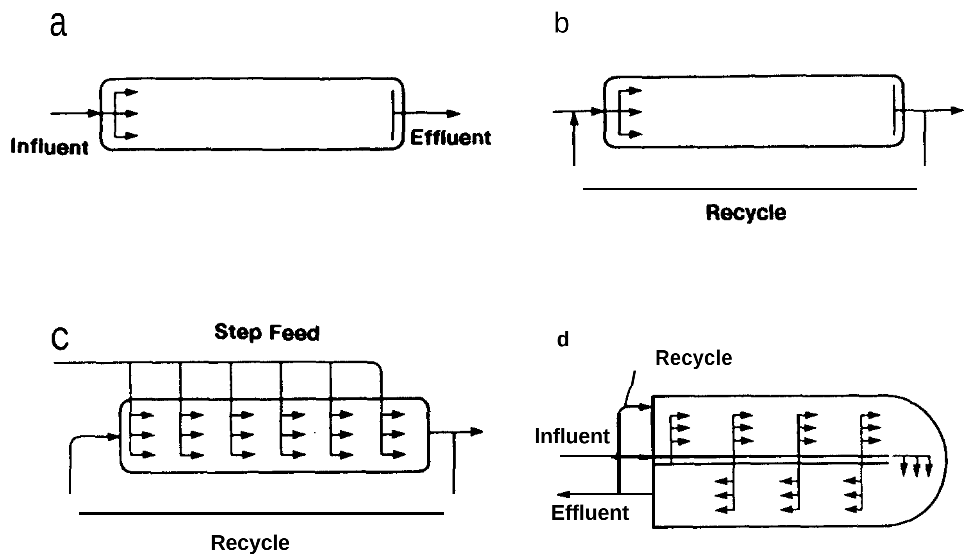
The San Diego project experimented with spray irrigation for supplemental aeration and found both effective aeration and lower mosquito larvae populations (18). The lower vector population was probably due to the disruption of the water/air interface by the simulated rain effect during the nighttime when the mosquitoes are actively breeding (19).

An important negative effect of spraying was related to hyacinth plant health. The plants in the San Diego project which were sprayed began to show stress and yellowing while plants just outside the spray area flourished (16). Plant health was improved by limiting spray period to 12 evening hours. Although spray irrigation effectively raises dissolved oxygen levels, and limits mosquito larvae populations, concerns over increased TDS due to excessive evaporation and cost of pumping tend to minimize the value of this approach (18).

4.4.4 Operation and Maintenance of Aeration

DO should be measured at least twice per day. The goal should be to maintain an average **DO** concentration of 1-2 mg/L along the pond length. If the DO falls below 1 mg/L, additional aeration should be added, or the influent flow should be reduced, until the pond recovers. This operation can be automated and optimized with DO probes. Fine bubble diffusers can develop a thick biological slime buildup, after several months of operation, especially if aeration is intermittent (18). Monthly inpond cleaning with a coarse brush can be effective in at least temporarily controlling the biological slime growth.

Figure 4-4. Evolution of flow pattern through San Diego, CA water hyacinth treatment ponds: a)origianl plug-flow, b) plug-flow with recycle, c) step-feed with recycle, d) step-feed with recycle in wraparound pond (18).



4.5 Performance Expectations

4.5.1 Design Equations

The San Diego water hyacinth project examined a series of time sequenced profile tests with various recycle flows. The tests were done to determine 1) the maximum allowable organic loading rate and 2) the optimum recycle ratios (18). Based on the results of the testing program, it was concluded in the San Diego Aquaculture Project that the modified step feed system could be modeled as a series of continuous flow stirred tank reactors (18). [This flow diagram is shown in Figures 4-8 and 4-13.1

4.5.1.1 BOD_5 Removal

The steady state materials balance for the first reactor in the series of eight reactors assuming first order BOD_5 removal kinetics is (18):

$$\text{accumulation} = \text{inflow} - \text{outflow} + \text{generation} \qquad (4\text{-}1)$$

$$0=Q_r(C_8)+0.125\ Q(c_0) - (Q_r+0.125\ Q)(c_1) - k_T(C_1)v_1 \qquad (4\text{-}2)$$

Where,

Q_r = recycle flow, m^3/d
C_8 = BOD_5 concentration in effluent from reactor number 8 in series, mg/L
0.125Q = inflow to each individual cell (Q÷8),
C_o = BOD_5 concentration in influent, mg/L
C_1 = BOD_5 concentration in effluent from reactor number 1 in series, mg/L
k_T = First order reaction rate constant at temperature, T, d-t
V_1 = Volume of first reactor in series, m^3

The estimated k_T value to be used in Equation 4.2 is 1.95 d-t at 20°C (68°F). An important aspect of the recycle system as shown in Figure 4-8a is that the recycle ratio is 16:1 for the first reactor in series and 23:1 for the last reactor in series. If the recycle flow had been mixed directly with the influent before being applied to the pond, the recycle ratio would have been 2:1. The difference between these two modes of operation is significant with respect to the performance of the pond.

4.5.1.2 Temperature Effect

Based on the results of the daily testing program, the value of the temperature coefficient, 0, in the following equation is estimated to be about 1.06 (18).

$$k_T = k_{20}\ 0^{(T-20)} \qquad (4\text{-}3)$$

Where,

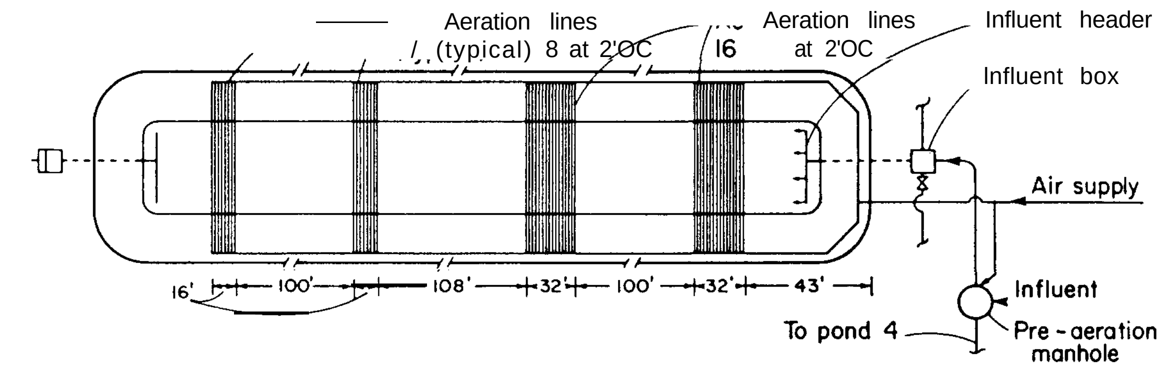
0 = empirically derived temperature coefficient
T = operating water temperature, ^oC

4.5.2 Nitrogen Removal

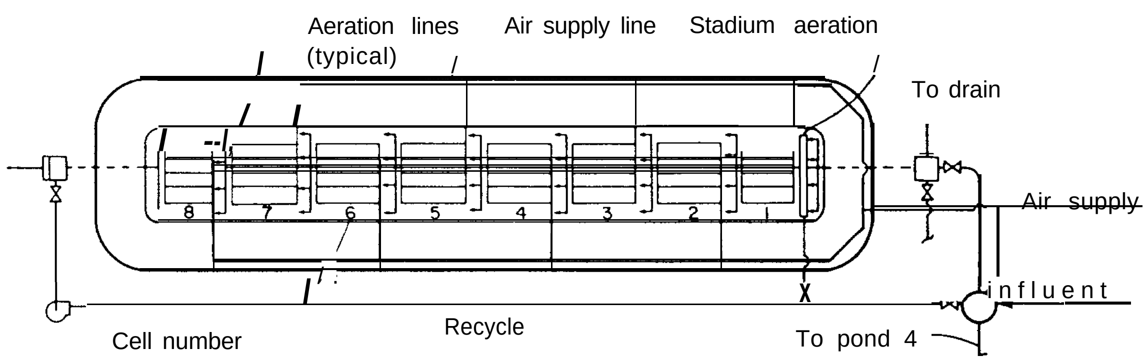
Nitrogen removal by plant uptake can only be accomplished if the plants are harvested. Nitrate, produced through nitrification, is removed by denitrification and plant uptake. In the past, there has been some question as to whether nitrification or plant uptake is the principal ($NH\ +_4$-N) ammonia-nitrogen conversion mechanism that ultimately leads to nitrogen removal. Based on data collected for a

Figure 4-5. Evolution of Pond 3 flow and aeration system configurations at San Diego, CA: a) plug-flow with air diffusion tubing (Hinde), b) step feed with recycle and coarse bubble aeration system, c) stepfeed with recycle and fine bubble aeration system (18).

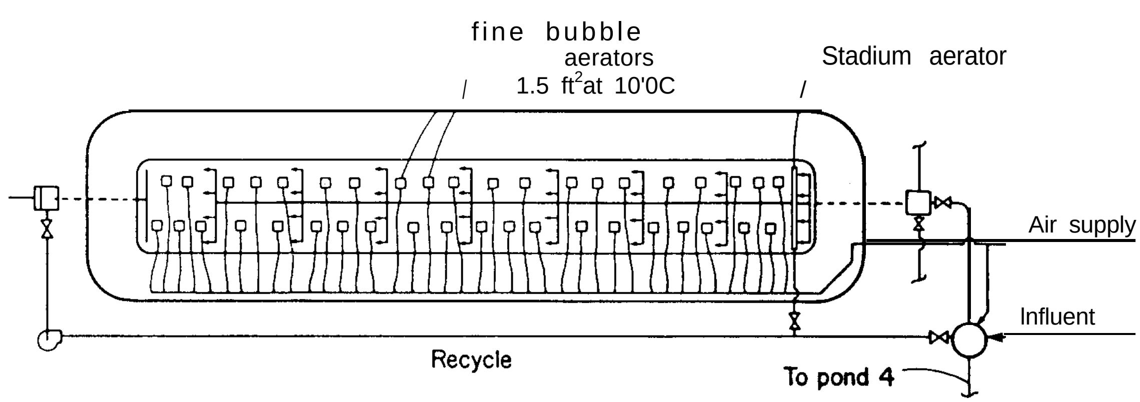
a. In operation May 84 - April 86



b. In operation May 86-October 87



c. In operation November 87-Present



review of existing water hyacinth treatment systems, Weber concluded that nitrification followed by denitrification was the principal nitrogen removal mechanism (20). Only when water hyacinth systems received low nitrogen loadings and significant harvesting was conducted did plant uptake become the principal nitrogen removal mechanism (20).

The nitrogen removal for 54 data points from case studies including locations at Coral Springs, FL; Williamson Creek, MS; and University of Florida, FL have been summarized (21). The results of these studies are presented in Table 4-8 as the percent of expected nitrogen removal for a particular surface loading rate.

Table 4-8. Nitrogen Removal - Water Hyacinth Tertiary Treatment (21)

Hydraulic Loading, m^3/ha-d	Total Nitrogen Reduction, %
9,350	10-35
4,675	20-55
2,340	37-75
1,560	50-90
1,170	65-90
$\leq$ 5935	70-90

4.53 Phosphorus Removal

Phosphorus removal from aquatic macrophyte systems is due to plant uptake, microbial immobilization into detritus plant tissue, retention by the underlying sediments, and precipitation in the water column. Since P is retained by the system, the ultimate removal from the system is achieved by harvesting the plants and dredging the sediments (22).

Phosphorus uptake in Florida marshes averaged 11 percent with signs of net export of phosphorus from the marsh in the winter (23). Reddy and Tucker (24) studied the productivity of water hyacinths grown with various nitrogen sources. The optimum N/P ratio in the water medium should be 2.3-5 to achieve maximum biomass yields (24). This ideal range can be used to estimate whether nitrogen or phosphorus is limiting to water hyacinths in a particular pond environment.

Phosphorus removal by precipitation/adsorption in aquatic systems not involving plant harvesting was found to be approximately 2 kg P/ha-d (1.8 Ib/ac-d) in one study (4). Phosphorus may be removed prior to applying wastewater to an aquatic system by a chemical addition and precipitation reaction. Precipitation may be the cost effective method of removal depending on the degree of phosphorus removal required.

4.6 Sample Design Problems

The following two sample design problems indicate how the design criteria in Tables 4-4 and 4-7 can be applied. Example No. 1 is also used to show the use of Table 4-8 in estimating nitrogen removal.

4.6.1 Sample Problem No. 1:

Design a hyacinth system to produce secondary effluent with screened, raw municipal wastewater as influent.

Assume:
Design flow rate = 730 m^3/d;
BOD_5 = 240 mg/L
SS = 250 mg/L
TN = **20** mg/L
TP = 10 mg/L
critical winter temperature > 20°C.

Effluent requirements:
BOD_5 <30 mg/L
SS < 30 mg/L.

Solution:

1. Determine BOD_5 loading:

   $(240\ mg/L)\ (730\ m^3/d)\ (10^3\ L/m^3)\ (1\ kg/10^6\ mg)$
   $= 175\ kg/d$

2. Determine basin surface areas required based on criteria in Table 4-4:

   50 kg/ha-d BOD_5 for entire area
   100 kg/ha-d BOD_5 for first cell

   Total area required = (175 kg/d) ÷ (50 kg/ha-d)
   = 3.5 ha

   Area of primary cells = (175) ÷ (100)
   = 1.75 ha

3. Use two primary cells, each 0.88 ha in area; with L:W =3:1, the dimensions at the water surface will be:

   $$\text{Area of primary cells} = L \div W = (L)(L/3) = L^2 \div 3$$

   $$(0.88\ ha)\ (10{,}000\ m^2/ha) = L^2 \div 3$$

   $$8{,}800\ m^2 = L^2 \div 3$$

   L = 163 m
   W = 163÷3 = 54 m

4. Divide the remaining required area (3.5 ha - 1.75 ha = 1.75 ha) into two sets of two basins (four cells - 0.44 ha each) to produce a total system with two parallel sets with three basins each.

Area of final cells = L ÷ W = (L)(L/3) = $L^2 \div 3$

(0.44 ha) (10,000 m^2/ha) = $L^2 \div 3$

4,400 m^2 = $L^2 \div 3$

L= 115 m
W = 115 m÷3 = 38 m

5. Allow 0.5 m for sludge storage and assume a 1.2 m "effective" water depth for treatment; total pond depth = 1.7 m. Use 3:1 sideslopes, and use the equation below (approximate volume of a frustum) to determine the treatment volume.

V = [(L) (W) + (L - 2sd) (W - 2sd)
+ 4 (L - sd) (W - sd)] d÷6

Where,

v = volume of pond or cell, m^3
L = length of pond or cell at water surface, m
W = width of pond or cell at water surface, m
s = slope factor (e.g., 3:1 slope, s = 3)
d = depth of pond, m

Primary cells:
V=[(163) (54) + (163 - 20301.2) (54 - 20301.2)
+4 (163 - 2•1.2) (54 - 2Ž1.2)] 1.2÷6

v = 9,848 m^3

Final cells:
V=[(115) (38) + (115 - 2Ž3•1.2) (38 - 2•3•1.2)
+ 4(115 - 2 x 1.2) (38 - 2•1.2)] 1.2÷6

V = 4,745 m^3

6. Determine the hydraulic detention time in the "effective" treatment zone:

Primary cells:
t = (2) (9,848 m^3) ÷ (730 m^3/d) = 27 days

Final cells:
t = (2) (4,745 m^3) ÷ (730 m^3/d) = 26 days

Total detention time = 27 + 26
= 53 days > 40 days, OK

7. Check hydraulic loading:

(730 m^3/d) ÷ (3.5 ha) = 209 m^3/ha-d
>200 m^3/ha-d, OK

8. Estimate nitrogen removal with Table 4-8 to be sure sufficient nitrogen is present to sustain growth in the final cells and to determine harvest frequency. Hydraulic loading is:

209 m^3/ha-d

From Table 4-8 essentially 90 percent removal is predicted at a hydraulic loading <935 m^3/ha-d. Since the hydraulic loading for this example is 250 m^3/ha-d it is reasonable to expect 5 mg/L of nitrogen in the final effluent or less. Because the nitrogen will not be at optimum growth levels in this system an annual harvest is suggested. An influent flow diffuser in each of the primary cells is recommended to properly distribute the untreated influent.

4.6.2 Sample Problem No. 2:
Design an aerated hyacinth system with recycle to produce secondary effluent on a site with limited available area.

Assume:
Design flow = 730 m^3/d
BOD_5 = 240 mg/L
SS = 250 mg/L
TN = 20 mg/L
TP = 10 mg/L
winter water temperature = 20°C.

Effluent requirements:
BOD_5 <30 mg/L
SS<30 mg/L

Assume 80 percent plant coverage is maintained on the basins and routine monthly harvests are included.

Solution:
1. Since the site area is limited, space is not available for preliminary treatment in a pond unit. Use Imhoff tanks for primary treatment and supplemental diffused aeration in the hyacinth ponds to minimize area requirements. The Imhoff tank has the added advantage for this relatively small flow in that separate sludge digestion is not required.

2. Design the Imhoff tank.

<u>Typical criteria</u>:
Sedimentation detention time = 2 hr
Surface loading = 24 m^3/m^2-d
Overflow weir loading = 600 m^3/m-d
Surface area for scum = 20% of total surface
Sludge digestion volume = 0.1 m^3/capita for the population served, or about 33% of total tank volume

Minimum sedimentation area needed
= (760 m^3/d) ÷ (24 m^3/m^2-d) = 31.7 m^2

Surface area needed for scum
= (0.20) (31.7 m^2) = 6.3 m^2

Total surface area needed
= sedimentation area + scum area
=31.7 + 6.3 = 38 m^2

A typical tank might be 8 m long and 5 m wide. In this case the central sedimentation chamber might be 4 m wide with open channels on each side, about 0.5 m wide, for scum accumulation and gas venting. The slotted, sloping bottom (bottom walls sloped at 5:4) would have to be about 3 m deep to provide the necessary 2-hour detention time. The total depth of the hopper bottomed tank might be 6-7 m including an allowance for freeboard and the sludge digestion volume.

A properly maintained Imhoff tank can achieve about 47 percent BOD_5 removal and up to 60 percent SS removal. Assuming no nitrogen or phosphorus losses the primary effluent for this example would be:

BOD_5 = (240 mg/L) (0.53) = 127 mg/L
SS = (250 mg/L) (0.40) = 100 mg/L
TN = 25 mg/L
TP = 15 mg/L

3. The BOD_5 loading on the hyacinth basins would be:

$$(127 \text{ mg/L})(730 \text{ m}^8\text{/d})(10^3 \text{ L/m}^3)(1 \text{ kg}/10^6 \text{ mg}) = 92.7 \text{ kg/d}$$

4. Determine the basin volume using Equation 4-2. Assume a recycle ratio of 2:1 as in the San Diego case. Also, design the system with step feed at eight points as shown in Figure 4-5. In order to solve Equation 4-2, the concentration of the effluent from the eight sections of the basin can be estimated from the recycle ratio as shown in Figure 4-13 in the case studies.

$$0=Q_r(C_8)+0.125\ Q(C_0) - (Q_r+0.l25\ Q)(C_1) - k_T(C_1)V_1 \quad (4\text{-}2)$$

Where,

Q_r = recycle flow, m^3/d
= 2Q = 2(730) = 1,460 m^3/d
C_8 = BOD_5 concentration in effluent from reactor number 8 in series, mg/L
= $C_o \div 8$ = 127 ÷ 23 = 5.52 mg/L
0.125Q = inflow to each individual cell (Q÷8), m^3/d
= 730÷8 = 91.25 m^3/d
C_o = BOD_5 concentration in influent, mg/L
= Imhoff tank effluent = 127 mg/L
CI = BOD_5 concentration in effluent from reactor number 1 in series, mg/L
= $C_O \div 16$ = 127÷16 = 7.94mg/L
k_T = first order reaction rate constant at temperature, T, d-t
= 1.95 d^{-1} at 20°C
V_1 = volume of first reactor in series, m^3
= total Volume ÷ 8, m^3

$$0 = (1,460)(5.52) + (91.25)(127) - (1,460 + 91.25) - (1.95)(7.94)(V_1)$$

$$0 = 8,059 + 11,589 - 12,317 - 15.5\ V_1$$

$$V_1 = 7,331 \div 15.5 = 473 \text{ m}^3$$

Total Basin Volume = 8 (V_1) = 8 (473) = 3,784 m^3

5. Calculate the number of ponds required. Refer to Table 4-5 for pond dimensions. Length, width and depth should be 122 m x 8.5 m x 1 m (400 ft x 28 ft x 3.3 ft), respectively. These pond dimensions result in a volume of 745 m^3 (196,000 gal). For the total basin volume required, 3,784 m^3 (1 Mgal), five ponds will be needed.

Assume that the required oxygen is double the organic loading, the air contains about 0.28 kg/m^3 oxygen, and the aeration efficiency (E) in the shallow basins is about 8 percent.

Total air required
= [2 (BOD_5, mg/L) (Q, L/d) (10^{-6} mg/kg)] ÷ [E (0.28 kg/ma)]
= [(2) (127) (730 x 10^3)(10-^{6}] ÷ [(0.08) (0.28)]
= 8,260 m^3/d = 5.73 m^3/min

From Table 4-5, maximum air flow per aerator is 0.028 m^3/min. Since there are five ponds, the number of aerators required per pond is:

Number Aerators
= (5.73 m^3/min) ÷ [(5 ponds) (0.028 m^3/min)]
= 40.9 aerators/pond

Divide the aerators into eight sections within the ponds as illustrated in Figure 4-5C. Each aerator should have a surface area of 0.14 m^2 (1.5 sq ft).

6. An inlet step feed system is essential for the ponds to ensure uniform distribution of influent. The use of Gambusia fish or other biological or chemical agents are necessary for mosquito control. Plants should be harvested about every three to four weeks. No more than 20 percent of the plant cover removed at any one time.

7. The treatment system designed in this example will provide better performance than the system developed in Example No. 1 on one-half to one-third of the land area. The major reasons are the use of the Imhoff tank for primary treatment, step feed, and aeration. In locations where land is limited or very expensive this approach to treatment might be cost effective when secondary level treatment is required.

The added cost of aeration equipment may be cost effective where land area is at a premium. An aerated hyacinth system becomes a hybrid system that is more complex than a natural aquatic system as described in this manual and less complex than conventional treatment with trickling filters or rotating biological contactors.

4.7 Case Studies

The purpose of this section is to provide a view of the state of the art in the design and operation of aquatic plant systems by providing case study summaries of three systems which are representative of current knowledge and practice. The three systems are in San Diego, California; Austin, Texas; and Orlando, Florida. The San Diego pilot scale water hyacinth system was chosen as a case study because it attempts to treat primary effluent to secondary effluent quality. The Austin water hyacinth system was chosen because it utilizes a cover for frost protection. The Orlando water hyacinth system was chosen because it attempts to remove BOD_5, SS, nitrogen and phophorus from an effluent that has undergone advanced secondary treatment.

4.7.7 San Diego, California

4.7.1.1 History

The City of San Diego depends on imported water for at least 90 percent of its water supply. Recognizing that its available water supply sources will fall short of the projected needs by the year 2000, San Diego has been working since the 1950s on ways to meet future water demands. Early attempts at using secondary treated wastewater for irrigation and distilling ocean water into a potable supply were unsuccessful.

In 1964, San Diego began work on reclaiming water by using reverse osmosis (RO) to remove salt. Primary treated effluent was passed through RO units for use in low pressure steam boilers. This 76-m^3/d (20,000-gpd) pilot plant successfully produced high purity boiler feedwater. In a cooperative program sponsored by the California Department of Water Resources, it was found that the RO units at San Diego also removed viruses. Based on that finding, the use of reclaimed water to meet the City's water requirements was first given serious consideration.

In 1974, the RO pilot plant was moved from Point Loma to a site adjacent to the Jack Murphy Stadium. At this location, the objective was to reclaim water for irrigation of the stadium sod farm (25).

The demonstration wastewater reuse project known as Aqua I, was operated from September 1981 to June 1986. The complete pilot plant included the following treatment processes: secondary treatment with hyacinths, lime stabilization, ultrafiltration, pressure sand filtration, reverse osmosis, carbon adsorption, ozone and ultraviolet light disinfection, and digestion of harvested hyacinths for methane production. The capacity of the Aqua I treatment facility was 114 m^3/d (30,000 gpd).

The current San Diego pilot plant, described in this case study summary, is an extension and expansion of the previous facility. An advisory board was formed to advise the San Diego researchers, to review results, and to make recommendations for operation of the pilot facility.

4.7.1.2 Project Description

Conceptually, the overall water reclamation program in San Diego can be divided into four parts: aquatic wastewater treatment using water hyacinths; advanced water treatment using reverse osmosis to produce raw potable water; anaerobic digestion of hyacinth biomass and wastewater sludge to produce methane; and a health effects study to compare the risks of using reclaimed water to those using the current water supply. The aquatic treatment portion of the project consists of four separate phases and will be completed in 1989.

Phase 1, completed in 1984, included the design and construction of two alternative 1,890-m^3/d (0.5-mgd) primary facilities and four alternative 380-m^3/d (0.1l-mgd) secondary facilities, including six water hyacinth treatment ponds.

Phase 2, completed in 1986, included operation and evaluation of the pilot plant under alternative treatment schemes.

Phase 3, to be completed in 1989, will include construction of the Water Reclamation Plant using the aquatic treatment scheme selected on the basis of the results from Phase 2. The pilot plant from Phase 2 will be scaled up to 3,785 m^3/d (1 mgd) capacity, with a 1,890-m^3/d (0.5-mgd) advanced treatment system added to reduce salt concentrations and to further remove pollutants. An anaerobic reactor will be included to produce methane gas from the water hyacinths.

Phase 4 will include operation and evaluation of the 3,785-m3/d (1-mgd) facility.

4.7.1.3 Pilot Plant Results

The overall goal of the pilot program was to demonstrate an innovative/alternative water reclamation process with cost-effective recovery of energy. The program was intended to provide a firm basis for preparing the engineering design of a large-scale system. Note that the original funding for the program covered only the demonstration of wastewater treatment using aquatic plants. Under the original grant, the objective of the aquatic treatment system was to meet 30 mg/L each for BOD_5 and SS. With an additional grant for the evaluation of advanced treatment and health effects, the objectives for the pilot aquatic treatment system became: 1) to supply suitable water to the advanced water treatment system for further processing, and 2) to supply hyacinth biomass and wastewater sludge to the anaerobic digester for energy recovery through methane production. The goals of the program remained the same. Utilization of a natural biosystem, coupled with low energy systems and energy recovery has been the goal. The additional goal is reclamation of water for useful purposes such as irrigation and raw potable water supplies.

Phase II Studies (Early Developments)
The two primary and four secondary treatment processes were operated in various combinations to form seven different treatment trains for comparison and evaluation of overall system efficiencies (see Figures 4-6 and 4-7). Primary facilities consisted of a sedimentation basin and a rotary disk filter, each 1,890 m^3/d (0.5 mgd) in capacity. Secondary facilities consisted of a pulsed bed filter (PBF), a sludge blanket/fixed film reactor (SB/FF), a hybrid rock filter (HRF), and water hyacinth ponds. The six water hyacinth ponds were each 8.5 m x 126 m long x 1.2 m deep (28 ft x 416 ft x 4 ft). The ponds were constructed with earthen berms and a clay lining. The hyacinth ponds were operated in three sets of two ponds each, with piping and slide gate arrangements permitting operation in parallel or in series, and at varying depths. The hyacinth ponds were utilized both as a secondary treatment process and as a polishing treatment following the other secondary treatment processes.

The complete treatment trains evaluated in the Phase 1 portion of the program included:

a. Primary Sedimentation Basin - Hybrid Rock Filter - Hyacinth Ponds.

b. Rotary Disk Filter - Sludge Blanket Fixed Film Reactor - Hyacinth Ponds.

c. Primary Sedimentation Basin - Sludge Blanket Fixed Film Reactor - Hyacinth Ponds.

d. Primary Sedimentation Basin - Pulsed Bed Filter - Hyacinth Ponds.

e. Primary Sedimentation Basin - Hyacinth Ponds.

f. Rotary Disk Filter - Hyacinth Ponds.

g. Rotary Disk Filter - Pulsed Bed Filter - Hyacinth Ponds.

Data collection for the treatment trains began in September 1984 and continued through September 1985. Data collected for each treatment train included BOD_5, SS, nutrients and the concentrations of sulfur compounds throughout the system. BOD_5 and SS concentrations were measured to determine if the final effluent met secondary treatment discharge standards. Nutrient data, including measurement of the various forms of nitrogen and phosphorus, were included for evaluation of microbial processes and nutrient uptake by the water hyacinths. Measurement of sulfur compounds was included because of the potential for formation of hydrogen sulfide and odor problems. Based on a detailed analysis of the performance data for the alternative process trains cited above, it was concluded that the most cost-effective system was train F (rotary disk filter-hyacinth ponds) (27). The flow sheet involving the hybrid rock filter was rejected because of clogging. The anaerobic reactor was rejected because of odor generation.

Experiments conducted since September 1985 were with the selected process flowsheet. To determine how BOD_5 and SS were removed in the pond, profile tests along the length of the ponds were undertaken in the fall of 1985. From profile testing, it was found that most of the treatment for BOD_5 and SS occurred in the first 50 ft of the hyacinth ponds. Based on this finding, flow was introduced in intervals or "steps" along the entire length of the ponds. This presents organic overloading of the head-end of the pond.

Phase // *Studies (Step-Feed Hyacinth Ponds)*
Based on the findings from the profile testing program, Ponds 3 and 5 were modified to test the effect of effluent recirculation and of step feeding the influent at several locations along the length of the ponds. Each pond was divided into eight cells, each 15.2 m (50 ft) long, with influent fed at the front end of each cell (see Figure 4-8). The existing recirculation system was utilized. The bulk of the recycle flow was pumped to the cascade aerators. The remaining portion of the recycle flow was returned to the aeration manholes where it was combined with the influent and reintroduced to the ponds through the influent step feed piping. An aeration system covering the entire length of each pond was constructed using PVC pipe with holes drilled at 0.3-m (1-ft) intervals. Aeration was also provided to the aeration manhole. Installation of the aeration system was necessary to overcome the problems associated with the presence of high sulfate levels in the influent wastewater.

The step-feed system was put into operation in March 1986. The system was monitored to determine: 1) the treatment capability of the pond and individual cells, 2) air requirements for different influent feed rates, 3) the maximum feed rate at which a DO concentration of 1 mg/L could be maintained, 4) the effect of recirculation *on* DO concentrations and pond chemistry, and 5) the effect of total coverage by the aeration system.

Performance Data for Step-Feed Hyacinth Ponds
Design criteria for the planned expansion of the water hyacinth system, as well as criteria for the original system, are summarized in Table 4-9. Performance data for the various treatment processes that

Figure 4-6. Site plan for San Diego, CA aquaculture pilot plant (26).

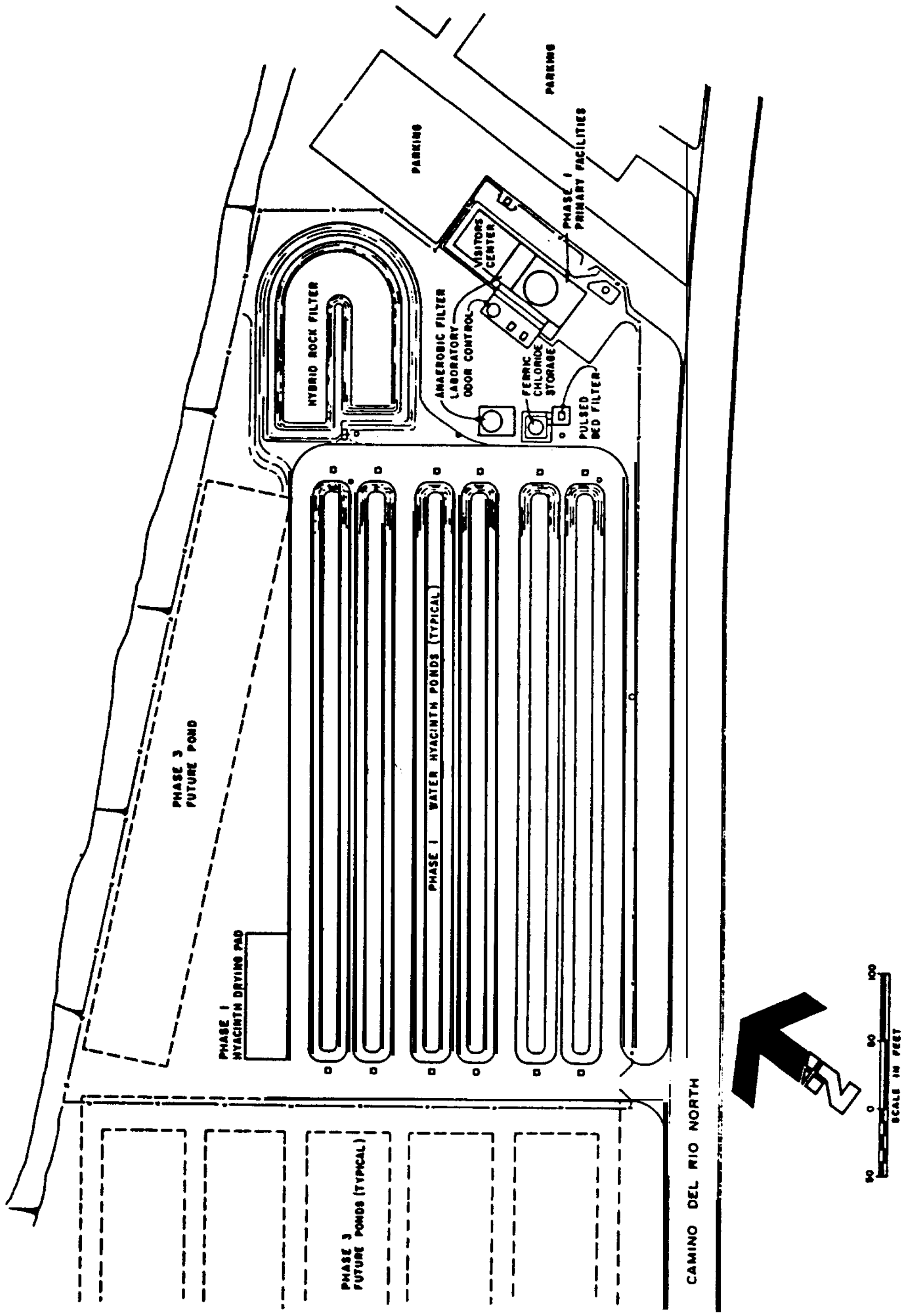


Figure 4-7. Schematic diagram of primary and secondary facilities - San Diego, CA aquaculture pilot plant (25).

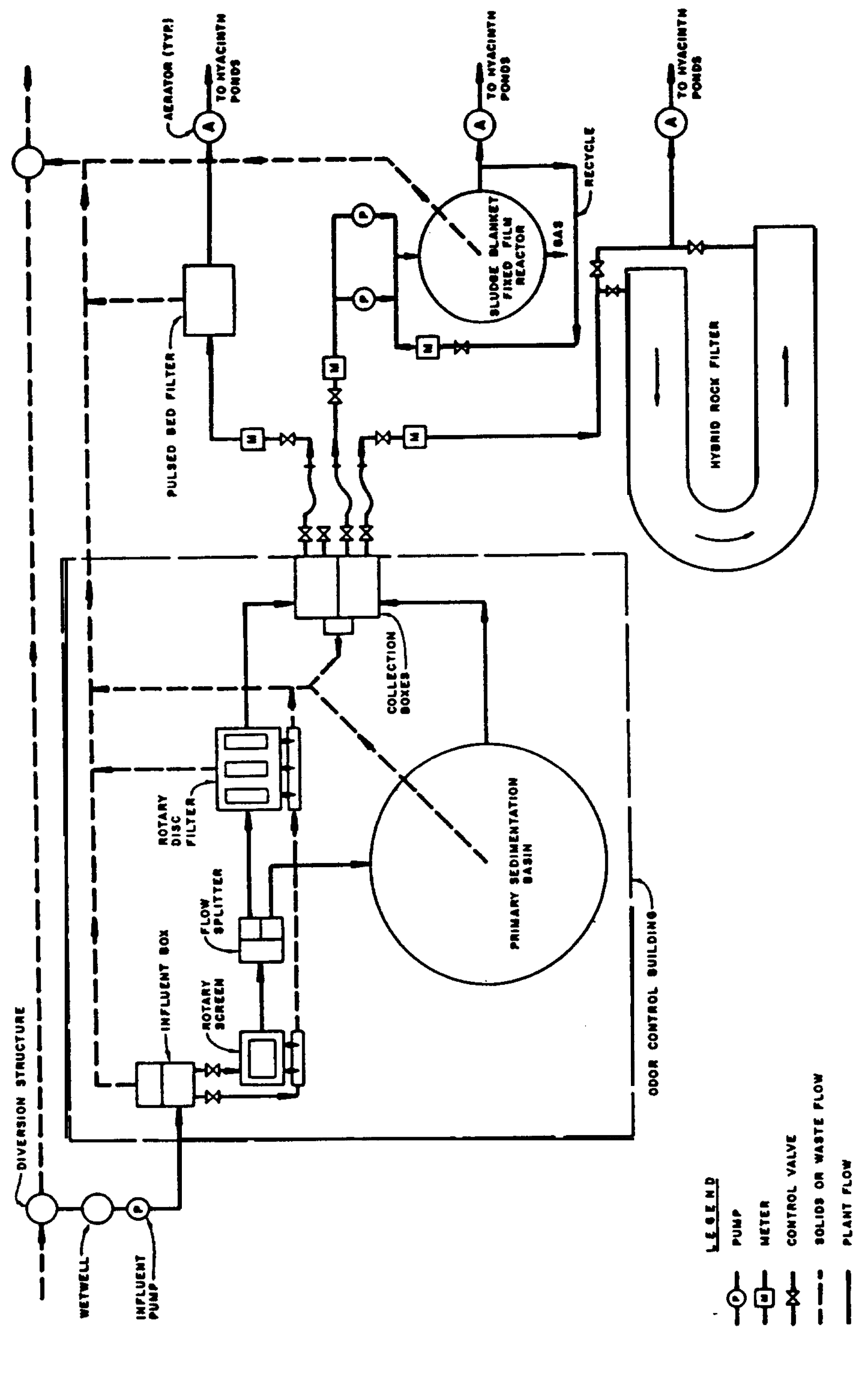
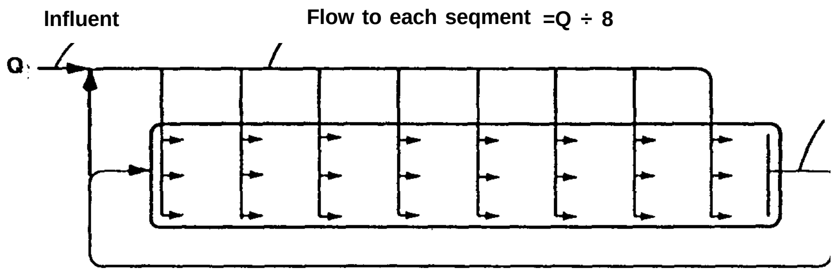


Figure 4-6. Schematic of hyacinth pond step-feed system with recycle - San Diego, CA (26).



comprise the aquatic treatment system are presented in Figures 4-9 and 4-10, for December, 1982 through October, 1983. As shown, the aquatic pond effluent BOD_5 values were consistently well below 30 mg/L regardless of the significant variation in the influent BOD_5 (125 to 375 mg/L) with the exception of a single value, all of the SS values were also below 30 mg/L.

Profile testing for BOD_5, SS, and DO was conducted to determine treatment efficiencies throughout the pond. Time sequenced samples were taken at the influent of each cell and approximately 3 m (10 ft) before the influent of the next cell. Results of a typical profile test for BOD_5, SS and DO are shown on Figure 4-11. The profiles show the results of dilution from the recycle flow at the head of the pond. Loading appears to be consistent throughout each cell, with adequate treatment achieved throughout the entire pond. DO showed the greatest variation, with a general decline throughout the last four cells to about 1 mg/L.

Harvesting and Hyacinth Productivity

Harvesting was accomplished at the pilot facilities primarily to provide open water surfaces and low plant densities to allow for more effective control of mosquito larvae by mosquito fish. Hyacinths were removed from the ponds during harvesting using a truck mounted, articulating clam shell bucket and loaded into an emptiable box also attached to the truck.

Hyacinth productivity for the first year of operation was significantly higher than reported at similar facilities in Florida. Average productivity for the second year, 67 dry metric tons/ha-yr (30 t/ac-yr), was typical of other installations. The lower productivity during the second year was probably the result of maintaining a lower plant density in the ponds by systematic harvesting. There was no attempt to correlate hyacinth productivity with treatment performance since the main purpose of the harvesting was to provide for mosquito control.

Odors and *Odor Control*

The design of the pilot plant included provisions to control odors from the various treatment processes. The odor control provisions included: 1) enclosing the primary settling basin and the rotary disk filter in a separate building and routing exhaust air from the building through a carbon adsorption unit; 2) precipitating sulfides with ferric chloride in the anaerobic filter sludge blanket fixed-film reactor (SBFFR) and hybrid rock filter (HRF); and 3) providing carbon canisters to adsorb hydrogen sulfide and other odors at each of the aeration manholes. Aeration manholes, located downstream from each of the three secondary processes, contain aerators to increase the DO concentration of the processed wastewater before being introduced to the ponds.

Odor control measures provided for the primary facilities successfully prevented odors in the vicinity of the pilot plant. Carbon canisters at the SBFFR and aeration manholes also controlled odors, except for an incident at the SBFFR when the carbon canister became depleted and had to be replaced. Several incidents of odor were associated with the HRF. Most of the problems occurred during the first few months of operation. The unit was taken out of service in June 1984, one month after startup, because of the odor problems. When ferric chloride was added to the HRF influent in late June, odors became less intense and less frequent. However, isolated incidents of odor were reported, mostly when ponding occurred on the surface of the HRF as a result of clogging of the medium.

The most serious odor problems were associated with the hyacinth ponds. Hydrogen sulfide odors were noticed at the effluent boxes and at the aeration tubing. The principal cause of the odors is the reduction of the sulfates in the wastewater to

Figure 4-9. **BOD_5 performance data for San Diego, CA Pond #3 with 200 percent recycle (27).**

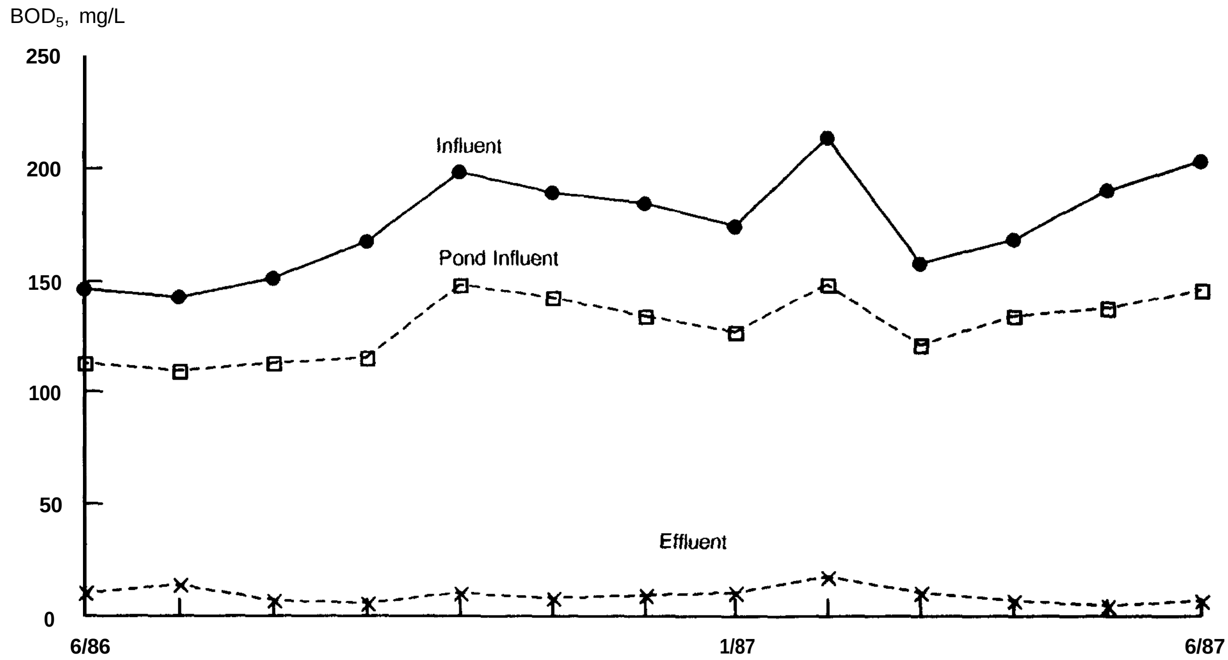


Figure 4-10. **SS performance data for San Diego, CA Pond #3 with 200 percent recycle (27).**

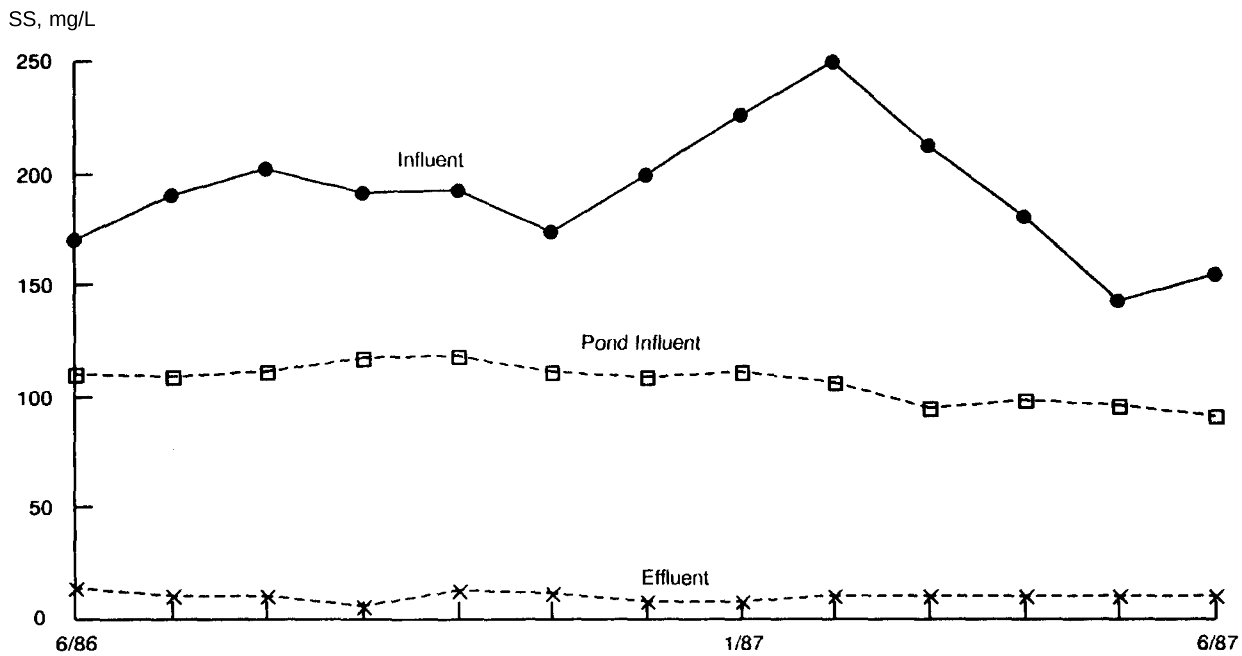


Table 4-9. Design Criteria for Modified Plug-Flow Water Hyacinth Ponds for Expanded San Diego, CA Aquatic Treatment Facility (18)

Item	Original	Expanded
Pond Configuration		
Cross-Section	Trapezoidal	Trapezoidal
Flow Scheme	Plug-Flow	Step-Feed with Recycle[a]
Pond Dimensions		
Max. length, m	122	122
Base width, m	3.55	3.66
Side slopes	2:1	2:1
Max. height, m	1.22	1.52
Top width at 1.5 m		9.76
Surface Area, ha		
at 1.07 m	0.097	0.097
at 1.22 m		0.105
at 1.37 m		0.113
Process Design and Operation		
BOD_5 loading (BOD_5/COD = 0.45). kg/ha-d	123b	359[c]
Influent flow per pond, ma/d		313
Operating depth, m	98	1.37[c]
Recycle ratio	Variable	2:1
Max. airflow per aerator[d], m^3/min	0	0.028
DO in pond, mg/L		1.2
Expected effluent, mg/L (% of time)		
BOD_5		120 (90)
		≤ 10 (50)
SS		≤ 25 (90)
		11(50)

[a] Wrap around pond design is to be used (see Figure 4-4d).
[b] Based on an assumed BOD_5/COD ratio of about 0.7.
[c] Tentative based on completion of depth tests.
[a] Aeration system (see Figure 4-4c).

hydrogen sulfide under the anaerobic conditions in the bottom sludge deposits. The solution to the odor problem was to change the method of operating the ponds, as discussed previously, and to raise the DO concentration sufficiently to satisfy the oxygen requirements of the wastewater and produce a DO residual of at least 1 mg/L in the remainder of the ponds.

Vectors and Vector Control
The primary objective of the vector control program was to evaluate the mosquito breeding potential of the hyacinth ponds and to identify effective measures for controlling mosquito populations. Observations were made of the changing populations of larval mosquitoes and mosquito fish *(Gambusia),* adult mosquitoes, midges, and invertebrate mosquito predators. Incidental observations concerning the ecology of the ponds were also made.

Mosquitoes were controlled adequately when a sufficient population of *Gambusia* was maintained in the ponds. However, the low DO levels throughout the ponds during much of the testing period, together with low water temperatures in the winter, significantly reduced the fish populations and required use of other mosquito control measures. Two man-made agents (BTI *(bacillus thurengensis israulis)* and Golden Bear Oil 1111) were used successfully, but continued applications were necessary.

Performance Summary
Based on the performance of Pond 3 it was concluded that a step feed system with recirculation greatly increases the treatment capacity of the pond. Introduction of influent at 15.2-m (50-ft) intervals resulted in a nearly uniform loading distribution and effective treatment throughout the pond, with effluent BOD_5 and SS concentrations well below the limits for secondary treatment. However, continuous aeration throughout the pond is required to maintain aerobic conditions so as to eliminate the development of odors. Air requirements are proportional to the pond BOD_5 loading, with approximately 2.5 standard L of air required per second to treat 1 kg of BOD_5 (2.4 scfm/lb). Recirculation provided initial dilution of the incoming wastewater and helped in distributing the loading throughout the pond. At higher recirculation rates, effluent turbidity increased. High turbidity can cause excessive chlorine demand and thus increase the cost of chlorination. However, SS levels were generally within the limits of secondary treatment standards, even at recirculation ratios as high as 51.

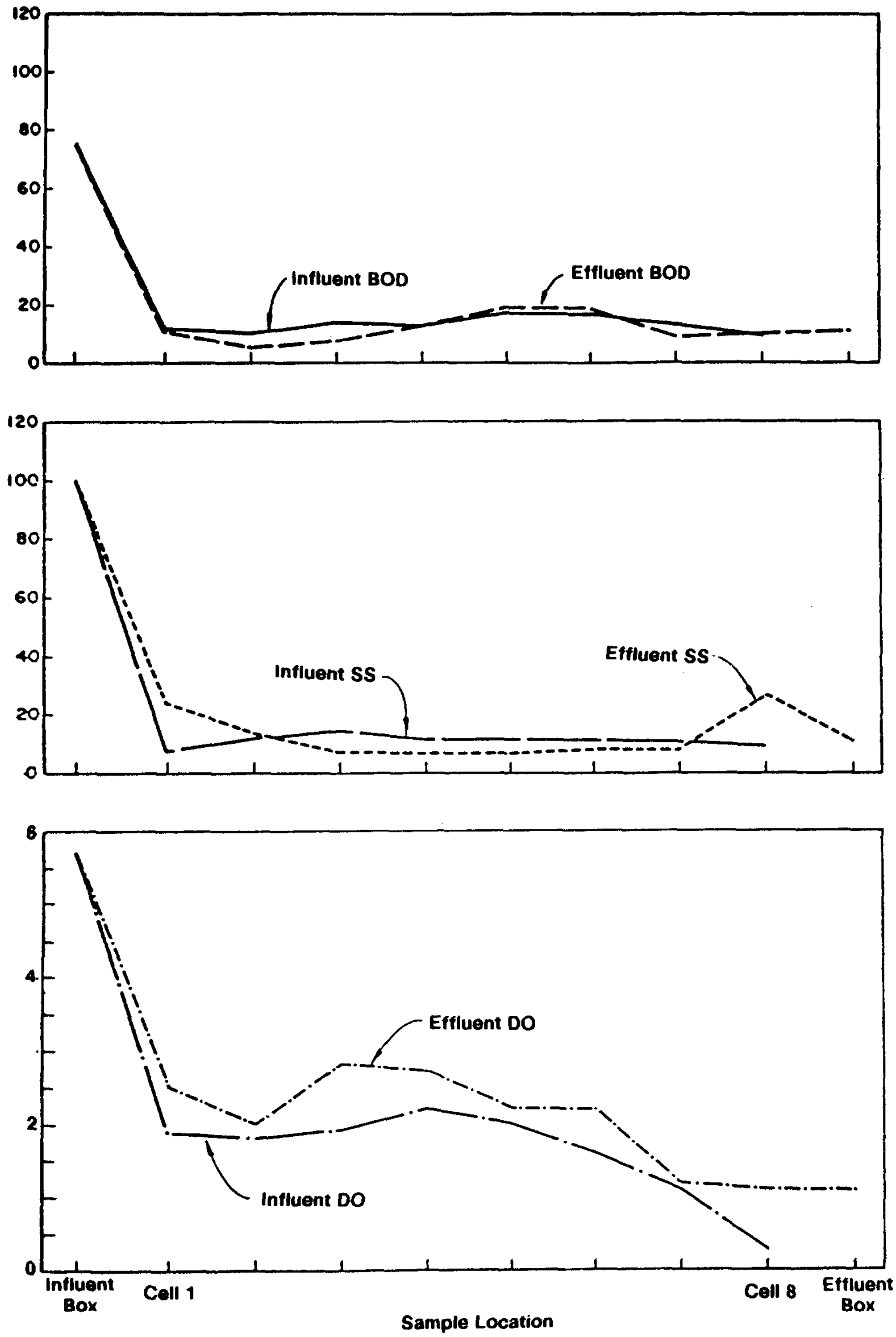
4.7.1.4 Design Factors

Process design factors for the hybrid aquatic system used at San Diego involve consideration of: 1) pollutant surface loading rates, 2) operating water depths, 3) process kinetics, and 4) temperature effects. The aquatic system is considered to be a hybrid because of the need to aerate due to the specific characteristics of the local wastewater. Although the final design factors have not been selected for a 3,785-m^3/d (1-mgd) facility, the values given below are consistent with the findings to date.

Pollutant Surface Loading Rates
A commonly used loading parameter for aquatic plant systems is based on surface area and is expressed as mass $CBOD_5$/area-d. Loading rates, based on using a step-feed system with recycle and supplemental aeration, of 200-250 kg $CBOD_5$/ha-d (180-225 lb/ac-d) are recommended by the San Diego researchers.

Operating Water Depths
The San Diego researchers believe that operating water depths for aquatic systems are extremely important with respect to process performance and in defining the hydraulic detention time and the mixing conditions within the pond system. Recommended operating water depth for a hybrid step-feed water hyacinth system with aeration is 0.9-1.2 m (30-42 in).

Figure 4-11. Influent and effluent BOD, SS, and DO for step-feed hyacinth pond - San Diego, CA (26).



Hydraulic Surface Loading Rates
During the Phase II pilot studies, the hydraulic surface loading rate was held at 0.058 m^3/m^2-d (62,000 gpd/ac). The resultant hydraulic detention time was 21 days.

Process Kinetics
The San Diego step-feed hyacinth system with recycle has been modelled, as shown in Figure 4-12, as a series of CFSTRs (continuous-flow stirred-tank reactors) (28). Using the cascade flow model, the treatment performance of the pond system was described adequately assuming first-order kinetics (see Figure 4-13). The corresponding first order reaction rate constant k was found to be about 1.95 d-t.

Temperature Effects
The performance of all aquatic treatment systems is temperature dependent. Based on both experimental studies and an analysis of data presented in the literature, it appears that a modified van't Hoff-Arrhenius temperature relationship can be used to estimate the effect of temperature on wastewater treatment using aquatic systems. Based on experimental studies with water hyacinth and emergent plant systems, it is estimated that the value of the temperature coefficient is about 1.09.

4.7.1.5 Operating Characteristics
The performance of the hybrid step-feed hyacinth system with recycle and supplementary aeration has proven to be stable with respect to the effluent quality (see Figures 4-9 and 10). Even before the step-feed system was developed, the effluent quality was good (both BOD_5 and SS less than 30 mg/L) regardless of the condition of the pond (whether the DO levels were low or nonexistent and the pond was odorous).

There are two constraints to the operation of a hyacinth system in San Diego that dictate operating practices that may not be factors in other locations. A hyacinth system must be odorless and free of mosquitoes. These constraints are backed by requirements for a minimum dissolved oxygen of 1 mg/L in the ponds and zero mosquito larvae per dip. The mosquito requirement can only be met by maintaining a large and healthy mosquito fish population in the ponds and low plant densities so that mosquito fish have access to breeding locations. It has been recommended that the DO in the ponds be maintained above 1 mg/L for the mosquito fish.

The climate in San Diego is such that cold weather stress on the hyacinths was not a factor in effluent quality. Another problem common to the southern United States, introduced weevil and mite species for biological control of hyacinths, has not been a problem in San Diego primarily because these species have not been introduced in the area.

4.7.1.6 Costs
In addition to the costs associated with conventional hyacinth pond construction, costs for hybrid step-feed hyacinth facility include the capital and O&M costs for the step feed distribution piping, recirculation pumps and piping, and a complete in-pond aeration system. The costs of all these features were included in the cost analysis developed for the hyacinth ponds.

Based on an applied wastewater BOD_5 concentration of 175 mg/L, and a pond loading rate of 225 kg BOD_5/ha-d (200 Ib/ac-d), a 3,785-m^3/d (1-mgd) facility would require a pond surface area of 2.9 ha (7.3 ac). Capital costs for the ponds would be approximately $2.18 million with an annual O&M cost of $494,000 (mid 1986 dollars). Anaerobic digestion of the harvested hyacinths has the potential to generate methane having an energy equivalent of about 2 billion BTU/yr. Use of this energy to generate electricity could significantly reduce the outside power costs for the entire treatment facility.

4.7.2 Austin, Texas

4.7.2.1 History
The State of Texas has been gathering information on the use of water hyacinths to improve the quality of stabilization pond effluent since 1970. Field-, pilot-, and full-scale studies of hyacinth systems have taken place at various locations, including the City of Austin. The use of a water hyacinth system in wastewater treatment has been shown to be feasible but winter freezing is a recurring problem.

The city's Hornsby Bend Sludge Treatment Facility receives excess activated sludge from area wastewater treatment plants. It was placed into operation in the 1950s and is undergoing a major expansion and renovation program.

Original plant design called for supernatant from three sludge holding lagoons to be passed through a chlorine contact basin and then discharged to the Colorado River. The quality of the treated supernatant was not meeting the discharge requirements established for the facility.

Water hyacinths were introduced into the 1.2-ha (3-ac) chlorine contact basin in 1977 and they served as a seasonal upgrade to the treatment process for several years. Basin configuration was not well suited to hyacinth treatment and the hyacinths were usually damaged by freezing conditions each winter. A greenhouse structure was proposed to protect the hyacinth and offer year round treatment.

Figure 4-12. Definition sketch for the analysis of a hyacinth pond with step-feed and recycle (28).

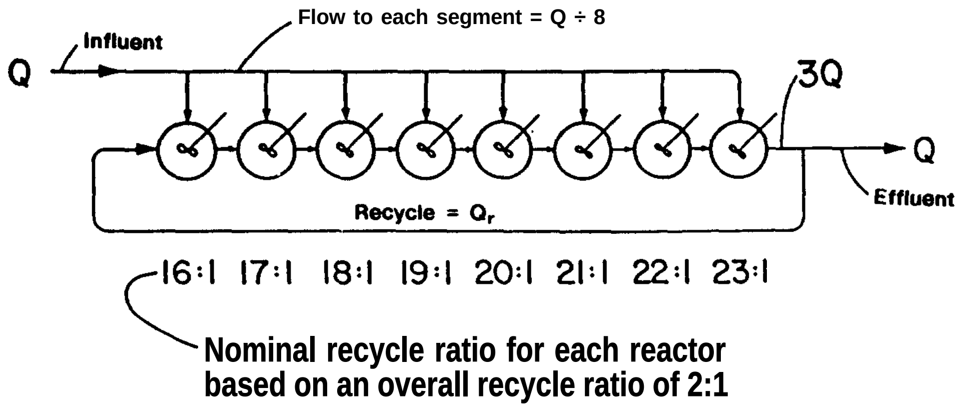
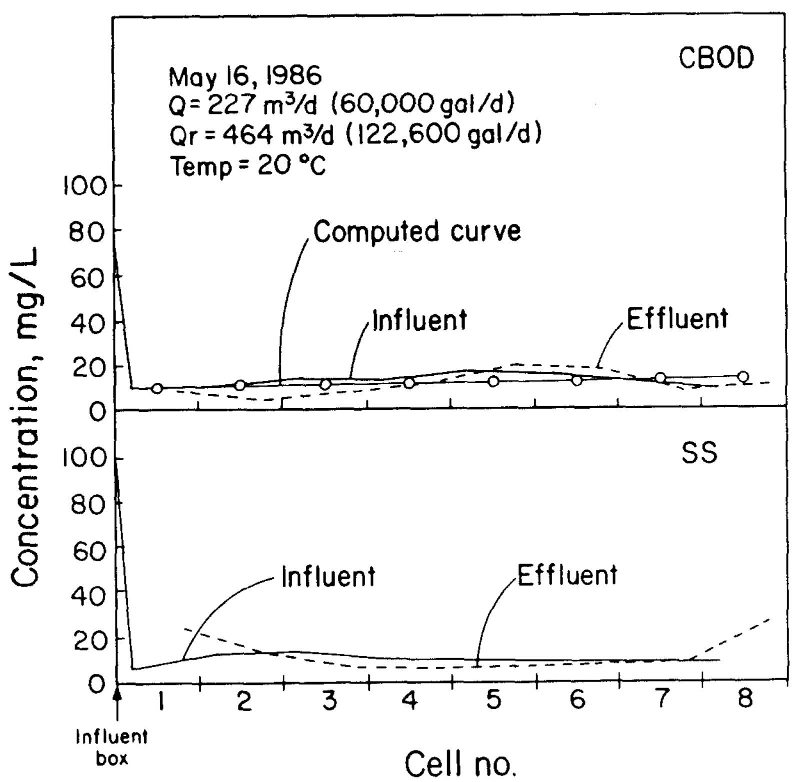


Figure 4-13. Analysis of performance data for hyacinth pond 3, San Diego, CA, with step-feed and recycle (18).



Typical Removal Curves For BOD And SS Along Pond Length For Pond 3 When Operated In The Step-Feed Mode With Recycle.

A new water hyacinth facility with three basins covered with a permanent greenhouse structure was included in the Hornsby Bend expansion and renovation plans. The Hornsby Bend Hyacinth Facility (HBHF) qualified for funding under the EPA Construction Grants Program as an innovative wastewater treatment process. It was the first hyacinth facility with a permanent greenhouse structure funded by the USEPA.

4.7.2.2 Design Objectives
The design objective is to provide year-round upgrading of sludge lagoon supernatant quality to meet 30 mg/L BOD_5, and 90 mg/L SS discharge limits.

4.7.2.3 Design Factors

Basin Design
The Texas Department of Health specifies a maximum design surface hydraulic loading rate of 1,870 m^3/ha-d (0.2 mgd/ac) for water hyacinth wastewater treatment basins (29). Loading rates up to 4,680 m^3/ha-d (0.5 mgd/ac) are permitted on a case-by-case basis. Austin's Hornsby Bend Hyacinth Facility (HBHF) incorporates three basins that have a total surface area of 1.6 ha (4.0 ac) when filled to their 17,000-m^3 (4.5-Mgal) capacity. The basins were designed to receive a maximum daily flow of 7,570 m^3/d (2 mgd); equivalent to a surface loading rate of 4,680 m^3/ha-d (0.5 mgd/ac).

The center basin has an area of 0.64 ha (1.6 ac) and the two outer basins have areas of 0.48 ha (1.2 ac) each (see Figure 4-14). All three basins are 265 m (870 ft) long. The center basin is 24.2 m (80 ft) wide and the outer basins are 18.1 m (60 ft) wide. Basin depths vary from 0.9 m (3 ft) at the upstream end to 1.5 m (5 ft) at the downstream end. The middle basin receives roof runoff during storms. The investigators at HBHF believe temperature changes due to runoff entering the basin have caused stress to some species stocked in the pond, and plans are underway to divert roof drainage out of the facility.

Influent flow to the basins is distributed uniformly across the width of each basin at the upstream end via a 30-cm (12-in) diameter perforated pipe. Two secondary distribution pipes at 63.9 m (210 ft) and 127.8 m (419 ft) downstream of the primary inlet in each basin are available for experimental step application of influent.

Maintenance of the basins will include harvesting of plants and removal of detritus accumulation. The basin slope facilitates cleaning. A drain valve at the bottom of the outlet structure is separate from the adjustable telescoping valve used to set water depth. Capacity of the facility is adequate to treat design flows with one of the three basins out of service for cleaning. Berms separating the basins accommodate a 3-m (10-ft) wide unsurfaced roadway used during harvesting.

Mosquito control was a major consideration in the design of the basins. The primary method of control is stocking of predators of mosquito larva and adults. These include mosquito fish *(Gambusia affinis),* grass shrimp *(Palemonetes kadiakensis),* and leopard, tree, and cricket frogs. Eight open areas are incorporated into the design of each basin to maintain oxygen levels adequate for survival of the *Gambusia* and grass shrimp. The openings consist of either a 55.7-m^2 (600-sq ft) or a 74.2-m^2 (800-sq ft) area protected from water hyacinth intrusion by chain-link fence fabric. Light is allowed to penetrate the water surface and sponser growth of algae on the gravel lined bottom of the aerators. The open areas help insure mosquito fish survival. After leaving the hyacinth facility, the polished secondary effluent passes over a two step cascade aerator with a total drop of 3.4 m (11 ft). DO concentration of the effluent has exceeded 5 mg/L at the discharge.

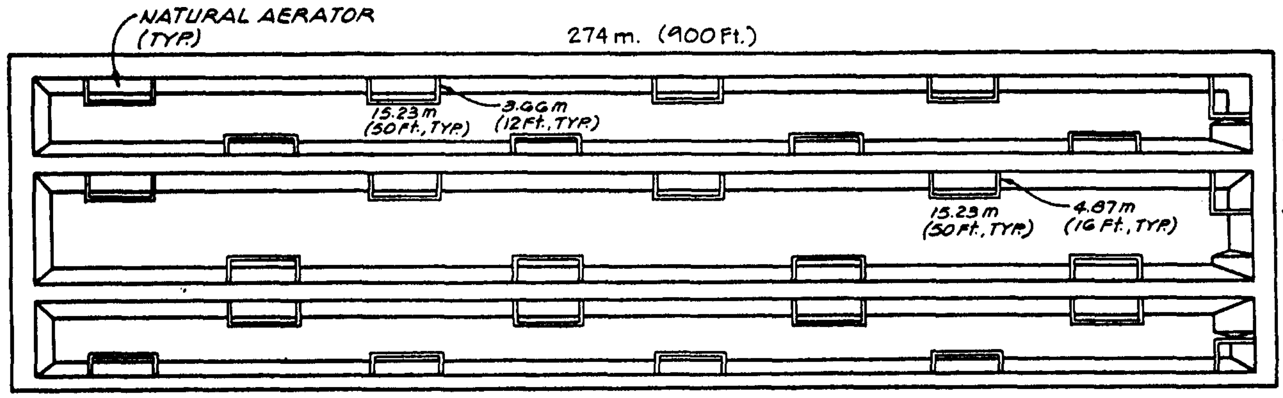
Greenhouse Design
A 2-ha (5-ac) greenhouse structure covers the three hyacinth basins to prevent winter freezing of the plants. The three bays of the concrete and steel structure are completely enclosed in clear, reinforced fiberglass decking with a light transmission value of 65 percent. Light transmission of the fiberglass is critical to plant growth so the performance of the panels is being monitored over time. A section view of the greenhouse structure is provided in Figure 4-15.

Sidewalls are 3.4 m (11 ft) high to permit maneuvering of maintenance vehicles and equipment. Seven overhead doors at each end of the building originally provided access for both personnel and equipment. Separate personnel doors were recently added. Moveable barriers are placed across open doorways to exclude snakes and other predators of organisms stocked for mosquito control.

The barriers will also prevent the return of Nutria (a large pond dwelling rodent) which inhabited the facility for several months but have since moved out. Both the doors and roof ridge vents running the entire length of the building provide ventilation. The ridge vents are screened to reduce immigration of adult mosquitoes.

4.7.2.4 Operating Characteristics
Biological stability of the water hyacinth basins is the prime requirement for successful wastewater treatment. As a result of maintenance work on one of the sludge lagoons that feed the hyacinth basins, influent loading levels were erratic and, subsequently, so were treatment levels during the first six months of operation. Influent and effluent BOD_5, SS, NH3-N, and N03-N values are presented in Table 4-10 for

Figure 4-14. Hornsby Bend, TX hyacinth facility basin configuration (30).



PLAN VIEW

Figure 4-15. Hornsby Bend, TX hyacinth facility pond and roof section (30).

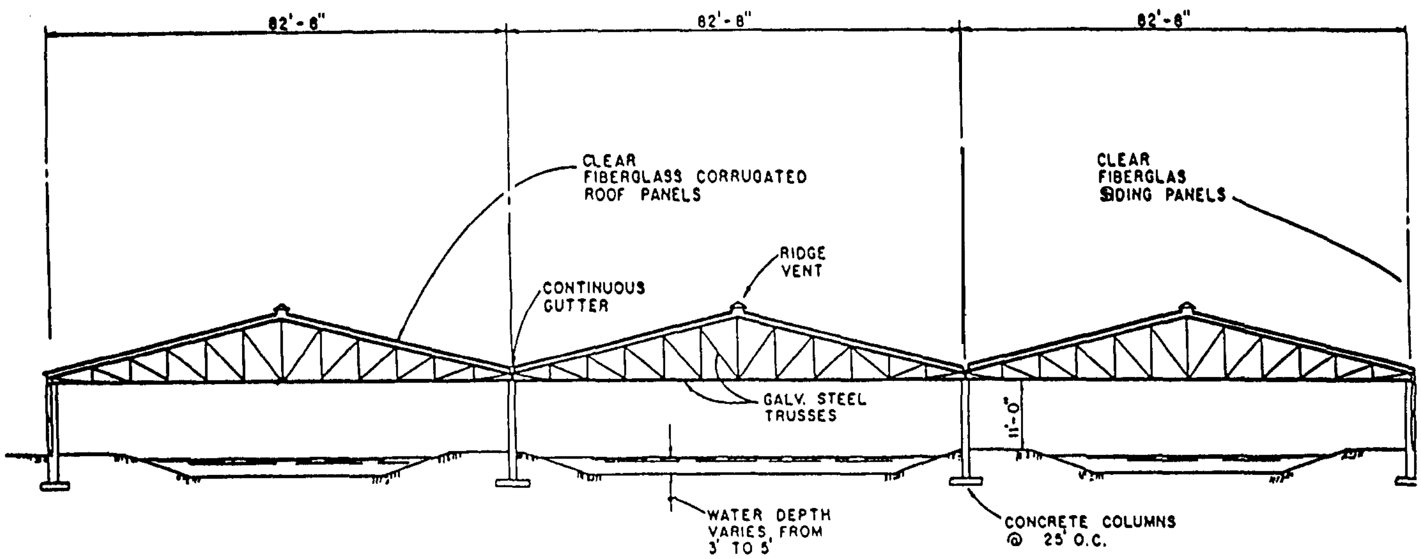


Table 4-10. Performance Data - Hornsby Bend, TX Hyacinth Facility' (31)

	pH		BOD_5, mg/L		TSS, mg/L		VSS. mg/L		NH_3-N, mg/L	
Date	Influent	Effluent	Influent	Effluent	Influent	Effluent	Influent	Effluent	Influent	Effluent
9/87	8.4	7.1	97	30	140	31	90	28	22.9	38.6
10/87	8.3	7.8	39	11	120	19	169	22	26.5	43.0
11/87	8.3	7.8	153	9	245	21	240	17	26.1	39.3
12/87	8.2	7.7	106	14	142	24	111	14	41.9	39.1
1/88	8.1	7.6	79	18	127	17	96	16	121.1	31.0
2/88	8.1	7.7	84	45	84	36	71	12	95.6	36.4
3/88	8.1	7.6			155	41	91	37	77.6	42.0
4/88	7.9	7.6	357	139	162	47	160	49	76.8	42.5
5/88	7.9	7.4	143	34	121	26	68	8	43.5	21.9
5/88	8.0	7.7	156	30	117	30	79	23	47.0	33.9
7/88	8.1	7.7	99	28	132	19	104	12	24.7	37.4

* Monthly average of approximately 12 samples (composites) per month.

1987 and 1988. The primary method for assuring relatively constant loading rates in the future will be maintaining a constant influent flow rate. The HBHF operates under 30 mg/L BOD_5 and 90 mg/L SS discharge requirements, with a maximum 30-day average flow of 7,570 m^3/d (2 mgd). By June, 1989 no discharge of pond effluent to the Colorado River will be permitted. Plans for future disposal include using HBHF effluent to irrigate approximately 80 ha (200 ac) of agricultural land near the facility. When the facility was placed into operation in February of 1986, the basin effluent BOD_5 concentration was at or near 10 mg/L.

Mosquito control measures have been effective. In addition to the species stocked, dragonflies have inhabited the facility. Dragonfly larva feed on mosquito larva and the adults prey on the mosquito adults. There was a noticeable increase in the mosquito population, believed to be due to immigration of adults, when the weather became cooler.

DO concentration within the natural aerators has been measured as high as 5 mg/L. Small plants and debris are removed daily from each aerator to maintain a constant light source for the oxygen producing algae attached to the rock at the bottom.

No harvesting was necessary during the first five months of operation but was needed constantly during July and August. Harvesting was much less frequent during the following winter. A modified tractor mounted backhoe is used to remove hyacinth from a 1.2-1.8 m (4-6 ft) strip along the perimeter of each basin. In addition to acting as temporary aerators, the cleared areas facilitate movement of mosquito larvae predators. Harvested plant material is first dried on an asphalt pad, then mixed with thickened waste activated sludge and recycled by the city's Department of Parks and Recreation. The recycling program was implemented in January of 1987.

Based on operating experience at other hyacinth facilities in the Austin area it is known that humus accumulation will occur at a relatively fast rate, and that most accumulation will take place near the inlet end of the basin. It is hoped that partial draw-down of a basin will be adequate for cleaning, without requiring restocking of plants and other organisms. There are several unanswered questions regarding the operating characteristics of the HBHF under extreme weather conditions. Of primary concern is survival of the hyacinth plants during very cold weather. Outside temperatures during the 1985-86 winter were mild and did not provide an indication of the greenhouse's ability to retain heat entering the system. Outside air temperatures rose to above 37°C (98°F) during the summer of 1986 without causing heat stress damage to the plants within the greenhouse; inside temperatures were approximately 55°C (131 °F) on those days. Another concern is the potential decreased light transmissivity of the fiberglass over time. Deterioration of the fiberglass, and algal growth brought on by condensation on the inside surfaces may inhibit light transmission. Roadways inside the facility have been subject to moisture and are deteriorating. Condensation dripping onto the road surfaces and capillary rise weaken the road structure. Installation of a permanent road surface on the berms is planned.

4.7.2.5 Costs

Total engineering design and construction cost of the facility was estimated to be $1,200,000. A more detailed accounting is not yet available.

4.7.2.6 Monitoring Programs

Under the requirements of the HBHF discharge permit and the need to evaluate other aspects of basin performance, influent and effluent levels of the following contaminants are being monitored: BOD_5, SS, VSS, NH_3-N, NO_3-N, and TP. Research work during 1986 included efforts to develop a mathematical model of BOD_5, SS and nutrient removal, and study of the nitrification process within the hyacinth system. A consistent effort to monitor and maintain the biological structures of the treatment system will be necessary during the formative stages of its unique ecosystem. Biological maturity and stability will not occur overnight, but it is ultimately essential to dependable treatment performance.

4.7.3 Orlando, Florida

4.7.3.1 History

The City of Orlando's Iron Bridge Wastewater Treatment Facility (IBWTF) was constructed in 1979 to provide regional wastewater treatment. It was designed to achieve tertiary treatment standards using primary clarification and RBCs for carbonaceous BOD_5 removal and nitrification, submerged RBCs for denitrification, chemical addition and sedimentation facilities for phosphorus removal, and rapid sand filters for final polishing. The discharge permit for the plant required an effluent of 5 mg/L BOD_5, 5 mg/L SS, 3 mg/L TN, and 1 mg/L TP and allowed a maximum discharge of 90,000 m^3/d (24 mgd).

By 1982, flows to the plant were increasing but the city was faced with meeting the existing waste load allocation for the Iron Bridge discharge to the St. Johns River. The city of Orlando started looking for ways to achieve higher levels of treatment for a portion of the total flow. One proposal was to use a water hyacinth system to treat 30,000 m^3/d (8 mgd) to achieve an effluent quality of 2.5 mg/L BOD_5, 2.5 mg/L SS, 1.5 mg/L TN, and 0.5 mg/L TP. This level of treatment would allow for a maximum influent flow of 106,000 m^3/d (28 mgd). The city of Orlando decided in 1983 to test the feasibility of this proposal by building and operating a pilot hyacinth facility.

Based on the results of the pilot study it was decided to build the full scale water hyacinth system. The full-scale system was completed in the summer of 1985 and has been in operation since.

4.7.3.2 Design Objective

The major design objective for the water hyacinth system at IBWTF was to treat a portion of the total plant flow to a higher effluent quality to allow for an increased effluent discharge flow without violating the waste load allocation for the discharge. The specific goal was to remove 50 percent of the major pollutants in 350 L/s (8 mgd) of effluent, allowing for an increase of 175 Us (4 mgd) in discharge flow.

4.7.3.3 Pilot Plant Results

Pilot Facilities Description

The hyacinth pilot facility consisted of five ponds built in series, each 5.2 m x 9.8 m (17 ft x 32 ft) providing a total pond area of 253 m^2 (2,720 sq ft). The required pond surface area was determined using a computer model (HYADEM) developed by Amasek, Incorporated after assuming a wet crop density of 12.2 kg/m^2 (2.5 Ib/sq ft) and an influent flow of 54.5 m^3/d (14,400 gpd). The pond depth was set at 0.6 m (2 ft) resulting in a nominal hydraulic detention time of 2.8 days. The nominal surface loading rate was 2,240 m^3/ha-d (0.24 mgd/ac).

Experimental Design

The stated goals of the pilot study (25) were:

1. Demonstrate the ability of the hyacinth system to achieve the desired effluent concentrations on an average monthly basis with nitrogen being the major concern.

2. Demonstrate the ability of the hyacinth system to perform during the winter months.

3. Demonstrate the ability of the hyacinth system to recover following a freezing event.

4. Determine the need for micronutrient addition.

5. Determine the applicability and degree of reliability of Amasek design and operational models.

6. Reveal specific operational adjustments required.

The pilot system was operated under steady state conditions. Influent and effluent samples were analyzed twice weekly during November and December 1983 and daily during the period from January 1 to March 15, 1984 for BOD_5, SS, TN, and TP. Additionally there was periodic determination of standing crop densities, total crop biomass, and micronutrient concentrations in the influent and effluent.

Experimental Results

The five ponds were stocked with water hyacinth in September 1983. Problems with influent quality control made it difficult to evaluate pilot plant performance for the following three months. Plant growth during this adjustment period was below expected rates. Factors which may have caused poor growth were a possible micronutrient deficiency and activity of the hyacinth weevil *(Neochetina eichhorniae).*

By December the wet standing hyacinth crop had increased from 455 kg (1,000 lb) to 1,650 kg (3,636 lb), approximately 6.5 kg/m2 (1.34 lb/sq ft). On December 25 and 26 a freeze occurred that produced a noticeable effect on the plants but did not kill them. Treatment efficiencies decreased in January. A meaningful evaluation of the effect of the freeze was not possible due to the instability of the system.

Actual loading rates were not as had been planned. Flow was reduced to 21.2 m^3/d (5,600 gpd) during the second week in January 1984 to accommodate the higher nitrogen loading. Initially, iron, potassium and phosphorous were added as a micronutrient supplement to the influent. In January, zinc, copper, manganese, molybdenum, boron, and sulfur were added to the supplement program, and the last two ponds were covered with a portable greenhouse structure in order to assess their performance during freeze events.

Pollutant removal from February 15 to March 15 was stable and the system did not have any major operating problems. Removal of BOD_5, SS, TN, and TP during this one-month period averaged 60, 43, 70, and 65 percent respectively.

In a Amasek report assessing the performance of the pilot facility, it was concluded that covering a water hyacinth system for freeze protection at the Iron Bridge plant was not cost effective considering "the ability of hyacinths to recover from even severe Florida freeze events, and considering some of the negative features associated with a covered system (32).

4.7.3.4 Design Factors

The areal requirements and standing crop density of the system were determined using the same computer model that had been used in the design of the pilot hyacinth system. The premise of the model is that nutrient removal is tied directly to plant growth. Plant growth is modelled using Monod kinetics and the van't Hoff-Arrhenius temperature relationship, and apparently assuming that growth is occurring in a reactor with a constant concentration of the limiting nutrient. Growth rate is then related to plant density and surface area coverage, and the average daily rate of nutrient uptake is calculated. The calculation of effluent nutrient content is made with the following relationship:

$$C_n = (Q_iC_i - N_u - N_l) \div Q_o$$

where,

- C_n = effluent nutrient concentration
- C_i = influent nutrient concentration
- Q_i = daily flow in
- Q_o = daily flow out
- N_u = daily mass nutrient removal by plant uptake
- N_l = daily mass nutrient removal by incidental processes.

In general, most researchers have concluded that nitrogen removal is by nitrification/denitrification with only incidental removal by the plant biomass.

Results of the pilot-scale system were used to determine the necessary constants for the growth relationships.

The system consists of two ponds each having a surface area of 6 ha (15 ac) and hyacinth digesting facilities (see Figure 4-16). Each pond is further divided into five basins 67 m long x 183 m wide (220 ft x 600 ft) using berms.

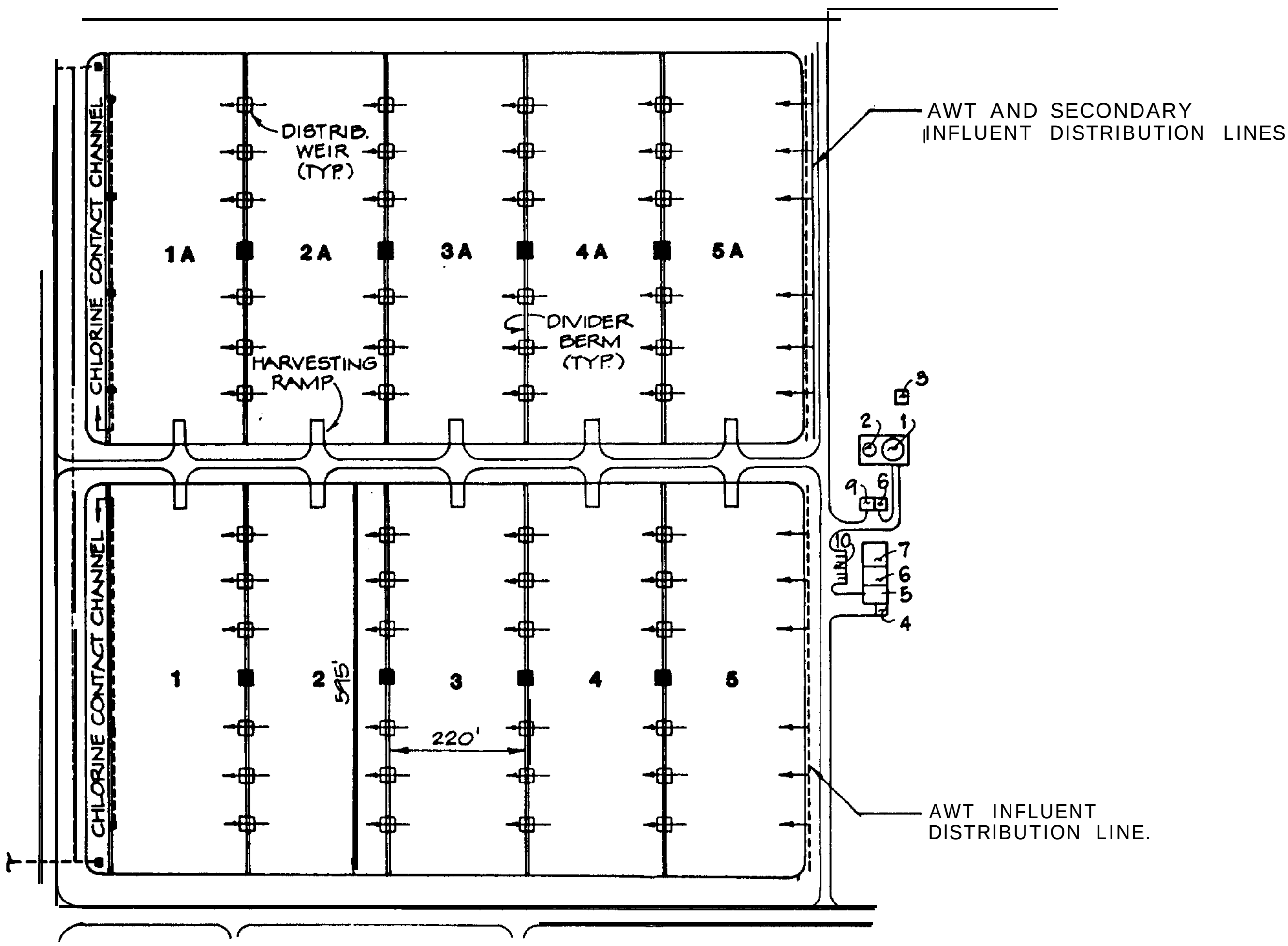
Weirs are located at six points in the dividing berms to distribute flow evenly across the full width of the berms to prevent short-circuiting. AWT effluent is fed to both ponds through an influent manifold. The west pond has an influent line from the secondary facilities in addition to the AWT influent line. Supplementary nutrient addition is provided by chemical dosing and mixing facilities, and chemical feed pipes to the influent lines and to the weirs in each dividing berm. Pond depth is 0.9 m (3 ft) resulting in a hydraulic detention time of approximately 3.5 days.

4.7.3.5 Operating Characteristics

The Iron Bridge hyacinth facility was initially stocked with water hyacinth in late 1984. Until July 1985 the system was operated in a start-up mode. During this time the system met nutrient removal requirements. In July 1985 Amasek took over operation of the system. In a report to the City of Orlando (33), Amasek summarized the process problems encountered from July 1985 to February 1986:

1. At the time Amasek took over operations, the crop had developed extensive weevil populations and there was considerable encroachment of alligator-weed.
2. Amasek attempted to improve crop viability by selective harvesting. Growth of the remaining crop, however, was not as projected, and extensive algae development resulted in violation of SS limits.
3. As weevil populations developed, a spraying program (Sevin) was initiated. Also new hyacinth stock was brought in to enhance crop development.
4. Improved crop viability was noted as a result of the spraying. However, crop growth was inconsistent, and coverage was not being achieved as designed. This resulted in a continuation of algae development and solids violations. However, adequate nutrient removal continued.
5. By January, 1986, it had become evident that the crop was experiencing serious growth problems. Nutrient removal was still being observed, although there was a considerable decline in the rate of removal.
6. Several potential causes for the growth problems were identified during a series of meetings with the city. These were as follows:

Figure 4-16. Iron Bridge, FL hyacinth facility basin configuration.



Key to Numbered Structures:

1. Methane Generation Tank
2. Equalization lank
3. Compressed Methane Gas Storage Tanks
4. Equipment Wash Pad
6. Covered Maintenance Work Area
6. Maintenance Storage Room
7. Control Room
8. Heater Equipment Room
9. Chemical Feed System
10. Parking Area

a. Metal toxicity, with aluminum as the primary suspect.

b. Biological interferences or competition, principally from the algae populations.

c. Macronutrient deficiencies, with phosphorus the principle concern.

d. Micronutrient deficiencies.

7. In mid-January, 1986, the system was shut down in an attempt to restore crop health and to facilitate solids control. The east pond was fertilized to bring levels of nitrogen, phosphorus, iron and calcium to excess concentrations. A series of experiments were established to test impacts of various additives. Extensive testing of plant and water quality was conducted to identify toxic or deficient levels.

8. By late January plant morphology indicated a very serious growth problem, and the standing crop began to decline significantly. The east pond showed no response to the added nutrients, indicating that either a toxic influence or a micronutrient deficiency was the problem.

9. In February, 1986, flow to the west side was reinstated, and an improvement in crop health was noted almost immediately. This verified the suspicion that there were no chronic toxic influences from the Iron Bridge effluent. This had been noted also within the set of contained experiments. A micronutrient deficiency therefore became the principal suspect. In evaluating this concern more closely, the Iron Bridge plants and water were compared to plants and water in Amasek's other systems.

In summary, the growth problems have been assessed as follows:

A molybdenum deficiency has developed as a result of: 1) precipitation and filtration of aluminum molybdate prior to discharge to the hyacinth lagoons, 2) interference of molybdenum uptake by sulfates which are put into the system as ferrous sulfate, and 3) low sediment pH and poor system buffering because of low alkalinity which inhibits molybdenum uptake.

To correct the hyacinth growth problems at the Iron Bridge hyacinth facility, molybdenum and boron are added as part of the supplementation program, ferric chloride is used instead of ferrous sulfate, and lime or soda ash is added to increase influent alkalinity to 60 mg/L as $CaC0_3$.

From February to May 1986, the hyacinth system was operated in a start-up mode to establish a healthy crop. Starting in June the west pond was operated as designed except that the influent nitrogen levels were approximately 13 mg/L rather than 3 mg/L. In September the east pond was also placed in service. Influent and effluent concentrations of BOD_5, SS, TN, and TP for six months of relatively steady operation (June to November) are presented in Table 4-11. During this steady operation period, the hyacinth system did not meet its treatment goals for either BOD_5 or SS. The BOD_5 and SS concentrations were reduced on average from 4.87 and 3.84 mg/L in the influent to 3.11 and 3.62 mg/L in the effluent. In terms of mass of nitrogen removed, the system did achieve the removal rates predicted. Effluent phosphorus levels were always below the design goal of 0.5 mg/L, although it was necessary to add supplemental phosphorus to the influent to assure phosphorus was not limiting plant growth.

4.7.3.6 Costs

The construction costs of the hyacinth system at the Iron Bridge plant were $1,200,000 for the hyacinth digester, and $2,000,000 for the basins and piping. Operation and maintenance is performed under contract by the Amasek Corp. for a yearly fee of $550,000 which covers all O&M costs associated with the hyacinth system, such as pumping and sludge disposal.

4.7.3.7 Monitoring Programs

Amasek is performing extensive monitoring of the hyacinth facility as part of their O&M contract with the city of Orlando. A summary of the monitored parameters and frequency of monitoring is provided in Table 4-12. In addition to the influent and effluent water quality parameters, standing crop biomass is monitored to allow for control of harvesting operations. Monitoring of hyacinth predators and micronutrient contents in the influent is also performed to assure the hyacinths remain healthy.

4.7.4 Summary

The three case studies provided in this chapter represent a broad range of the potential uses of aquatic plant systems. A comparison of the three systems is difficult but a summary of each system's design and operating characteristics and costs is provided in Table 4-13.

What is clear from these case studies is that aquatic plant systems can be designed and operated to accomplish a variety of wastewater treatment tasks, but the designs and the operation are not always simple. Hyacinth systems are susceptible to cold weather and particularly in the southern states, can be affected by biological controls introduced to help control water hyacinths in the natural environment. Concerns of health agencies for mosquitoes can play a very big factor in the design and operation of

Table 4-11. Iron bridge, FL Water Hyacinth System Performance Summary

Date	Wastewater Flow, m^3/d	BOD_5, mg/L		SS, mg/L		TN, mg/L		TP[a]	
		Influent	Effluent	Influent	Effluent	Influent	Effluent	Influent	Effluent
6/86	16,680[b]	3.24	4.58	**3.06**	**6.31**	**12.52**	8.09	0.37	0.24
7/86	**17,450[b]**	4.12	**1.73**	3.85	**1.86**	**12.44**	8.06	0.33	**0.11**
8/86	**16,850[b]**	3.33	**3.70**	**3.58**	4.28	**12.77**	**7.62**	0.55	0.19
9/86	**32,500[c]**	6.16	2.66	**5.23**	**2.91**	**12.66**	7.96	0.75	0.15
10/86	**31,190[c]**	4.43	**3.11**	**2.70**	**3.56**	**14.49**	9.66	0.89	0.22
Average	23,250	4.87	**3.11**	**3.84**	**3.62**	**13.00**	8.16	**0.61**	0.22

[a] Phosphorus is added to the hyacinth system Influent as a nutrient supplement.
[b] West hyacinth pond in operation.
[c] Both hyacinths ponds in operation.
[d] Both ponds in operation for portions 01 the period

aquatic plant systems. Finally although water hyacinth systems may be useful in nutrient removal, there are limits to the treatment capacity and dependability of hyacinth systems in terms of meeting very low effluent values.

4.8 References

When an NTIS number is cited in a reference, that reference is available from:

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
(703) 487-4650

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Table 4-12. Iron Bridge, FL Water Hyacinth System Monitoring

Parameter	Frequency
Influent Flow	Daily
Air Temperature	5 days/week
Wastewater Temperature	5 days/week
pH	5 days/week
Conductivity	5 days/week
DO	5 days/week
Rainfall	Daily
Wind Velocity	5 days/week
Wind Direction	5 days/week
Chlorine	Twice/week
TKN	Twice/week
NH_4-N	Twice/week
NO_3-N	Twice/week
NO_2-N	Twice/week
TN	Twice/week
OP	Twice/week
TP	Twice/week
BOD_5	Twice/week
TSS	Twice/week
TDS	Once/week
Na	Once/week
K	Once/week
Fe	Once/week
Ca	Once/week
Mn	Once/week
Mg	Once/week
Mn	Once/week
B	Once/week
Zn	Once/week
Cu	Once/week
Mb	Once/week
Cr	Once/week
Al	Once/week
Pb	Once/week
Hg	Once/week
Ni	Once/week
Cd	Once/week
SO_4	Once/week
Plant Constituents	As Needed
Harvested Biomass	As Needed
Stocked Biomass	As Needed
Standing Crop Biomass	Once/week
Weevils	Once/week
Sameodes	Once/week
Mosquitoes	Once/week
Encroaching Vegetation	Daly
Root Macroinverterbrates	As Needed
Fungal Isolates	As Needed

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Table 4-13. Aquatic Plant Systems Case Studies Summary

Item	San Diego, CA	Austin, TX	Orlando, FL
Aquatic Plants	Water Hyacinths	Water Hyacinths	Water Hyacinths
Preapplication Treatment	Primary	Ponds	AWT
Special Design Features	Supplemental Aeration	Covered System	Supplemental Nutrient Addition
Design Max. Flow, m^3/d	3.79	7,570	30,300
Pond Surface Area, ha	0.65	1.6	12.1
Influent/Effluent BOD, mg/L	~ 130/~9.5	131/17.6	4.9/31
Influent/Effluent SS, mg/L	~107/~10	142/11.3	3.8/36
Influent/Effluent TN, mg/L	23[a]/9[a]	55/12[a]	13.0/8.2
Hydraulic Surface Loading, ma/ha-d	583	4,730	2,500
Capital Cost, $/ma-d	580[b]	158	66
Yearly O&M Cost, $/m^{3-}d	132[b]		18
Capital Cost, $/ha	340,000	741,000	165,000

[a] NH_4 + NO_3-N.
[b] Demonstration facility.

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APPENDIX A

This Appendix contains lists of municipal and selected industrial facilities that employ, or have employed, constructed wetlands and aquatic plant systems. The lists indicate the state and city where projects have been identified. In some cases, the projects will have been abandoned. These lists are included so that the manual user can identify nearby projects and visit them if so desired.

1. Constructed Wetlands

Alabama
Theodore, Jackson County
Russelville
Stevenson
Sand Mountain

Arizona
Lakeside
Camp Verde
Showlow

California
Arcata
Gustine
Hayward
Laguna Niguel
Las Gallinas
Martinez
Santee

Idaho
Idaho City

Iowa
Granger
Norwalk
Riverside

Kansas
Saint Paul

Kentucky
Benton
Hardin
Pembroke

Louisiana
Benton
Carville
Haughton
Sibley

Maryland
Anne Arundel County
Emmitsburg
Glen Burnie

Massachusetts
Spenser

Michigan
Vermontville
Boscommon

Mississippi
Collins
Vay St. Louis (NASA/NSTL)

New Jersey
Avalon
Bernard
Beverly
Hightstown
Washington Township

Nebraska
Kimball

Nevada
Incline Village

Oregon
Cannon Beach

Pennsylvania
Elverton
Iselin
Lake Winola

South Dakota
Hitchcock
Spenser
Wosley

Tennessee
Gatlinburg
Kingston
Tellico

Virginia
Monterey

In Other Countries
Richmond Australia
Mannersdorf, Austria
Listowel, Canada
Port Perry, Canada
Ringsted, Denmark
Rodekro (Jutland), Denmark
Othfresen, Germany
Windelsbleiche, Germany
Coromandel Township, New Zealand
Whangarei, New Zealand

2. Aquatic Plant Systems

Alabama
Enterprise

Arkansas
Wilton

Florida
Jupiter
Kissimmee
Melbourne
Orlando

Minnesota
Sleepy Eye

Mississippi
Bay St. Louis
North Biloxi

North Dakota
Devil's Lake

Texas
Austin
Baytow
San Benito

Virginia
Craig-NC

Washington
Stewart Park

APPENDIX B
CONVERSION FACTORS

Multiply	by	To Get
m^3/d	264	gpd
g/m^2-d	8.92	lb/ac-d
kg/ha-d	0.892	lb/ac-d
kg/m^2	0.2	lb/sq ft
m^3/ha-d	106.9	gpd/ac
m^3/m^2-d	25	gpd/sq ft
m	3.28	ft
m^2	10.76	sq ft
ha	2.47	ac
m^3	264.2	gal

*U.S. G.P.O. 1988-548-158:87o13