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The Use of Aquatic Plants in Wastewater Treatment:
A Literature Review

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Approved:

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Dedication

This report is dedicated to my wife, Dawn, and my son, Andy, who have both been instrumental in my ability to complete my studies at the University of Texas. Their support and concern have been essential to any work that I have accomplished including this report.

The Use of Aquatic Plants in Wastewater Treatment:
A Literature Review

by

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Chapter 1

Introduction

1.1 Background

During most of this century, the trend has been for more mechanized wastewater treatment systems with almost every aspect of the various processes under the direct control of the operator. In the last twenty years, however, approaches that do not involve the same "concrete and steel" mentality have drawn more attention. Shortly after the enactment of the Clean Water Act (PL92-500) of 1972, alternate methods of wastewater treatment once again became recognized as valid means of achieving the required level of effluent quality. Initially, attention was centered on existing natural systems such as wetlands and coastal marshes, but more recently, constructed systems using aquatic plants have been investigated.

In the early days of sanitary engineering, natural treatment was the only method known. Initially, treatment was not even an objective, nor were the processes understood. Wastewaters were simply disposed of in the nearest river, lake, or swamp if one was available. As the communities grew, the carrying capacity of the receiving water was eventually exceeded and problems began to arise in terms of aesthetics, public health, environmental effects, or, more commonly, a combination of the three. The need for treatment prior to discharge was recognized at this point, and primary treatment was developed to remove most of the larger solids and organic matter. Natural systems were more or less forgotten because they had not performed well under the required loads. As understanding of the environment, disease causing agents, and treatment processes increased, the complexity of the treatment processes also increased to remove higher and higher percentages of the pathogens and contaminants of concern. The cost of treatment unfortunately increased as well, and continues to do so even in the absence of further increases in treatment complexity. The Clean Water Act further aggravated the problem by requiring secondary treatment at many sites that had not previously used that level of treatment.

Natural treatment systems came back into consideration mostly as an attempt to find a more cost effective means of achieving the mandated treatment levels than was available with the existing mechanical or chemical processes. Natural treatment systems are not disposal practices, nor are they random applications of waste and wastewater in various habitats. Natural treatment systems are engineered facilities which utilize the capabilities of plants, soils, and the associated microbial populations to degrade and immobilize wastewater contaminants.

The two main categories of natural treatment systems are land treatment and aquatic treatment systems. Each of these categories can be further subdivided based upon the type of application and the types of plants used.

Land treatment is the application of wastewater or wastewater sludges to the soil, and allowing the plants and soil matrix to remove contaminants. Land treatment is divided into land farming, slow rate irrigation, rapid infiltration, and overland flow treatment systems. These treatment schemes are not within the scope of this report and as such will not be mentioned any further herein.

Aquatic treatment involves passing wastewater through either wetlands or other aquatic plant ecosystems, whether natural or man-made. Removal of contaminants takes place by plant uptake, microbial degradation, filtration, chemical precipitation, and sedimentation. Wetlands systems are designed around emergent aquatic plants (macrophytes) and can be divided into subsurface flow systems and free water surface systems. Observations of the behavior of floating and submerged plants in the latter systems were in part responsible for the investigation of these plant species for use in separate treatment systems. These systems are generally referred to as aquatic plant systems and are differentiated from wetlands by the understanding that the former contains no large emergent species. The two main categories of aquatic plant systems are floating aquatic plant and submerged aquatic plant systems.

Aquatic plant systems take on a variety of forms and use many different species of plants. Several flow schemes have been tried as well as many variations on the varieties of plants used and the amount of plant harvest performed. Conflicting opinions on the contribution of the plants themselves to the treatment have resulted in widely varied design approaches.

1.2 Objectives

The three main goals of this report are as follows:

1) Review the existing aquatic plant treatment technologies and the species used in current and proposed treatment schemes,
2) Review the limitations of aquatic plant systems, and,

3) Review the current design approaches and provide a consolidated approach if possible.

1.3 Scope

This work consists primarily of a literature review of current aquatic plant systems and research. The literature consulted included Environmental Protection Agency design guidance documents, Texas state performance and design regulations, performance reports from existing and past treatment systems, and research papers on the various aspects of proposed and existing aquatic plant systems. Original design examples were developed to contrast previous design views with current concepts, and case studies were included to expand upon the performance and some of the operational requirements of existing systems.

Chapter 2

Characteristics of Aquatic Plant Systems

2.1 Introduction

All aquatic plant systems rely upon the plant species employed to provide or facilitate the treatment desired. Understanding these plants is important to the overall operation of the treatment system. This chapter contains a brief introduction to the types of plants used in aquatic plant systems, their needs, and some of their limitations.

2.2 Vegetation

Algal systems have been around for many years in the form of oxidation ponds, but aquatic plant systems are differentiated from oxidation ponds in that they use aquatic macrophytes for treatment. The macrophytes used are usually floating varieties, but some systems have been investigated with submerged varieties (these are usually proposed in polishing stages). The macrophytes in a system may act in a similar capacity to the algae in an oxidation pond by transferring oxygen to the bacteria performing the degradation, or they may also provide removal of the contaminants of concern by encorporating them into the plant tissues.

Treatment systems which use vegetation are attractive to designers in part because the plants act as a natural nutrient sink. Some plants are also capable of absorbing substantial amounts of metals and some dissolved organics (Lakshman, 1987; Abbasi, 1987; Heaton *et al.*, 1987; O'Keeffe *et al.*, 1987; WPCF, 1990; and others). The organics may be destroyed by the plant's metabolic activities or stored, while metals are not degraded, but are usually stored within the plant tissues. Some of the plants used in these systems can also be sold, either whole or in part, and if a market exists they offer a potential for some revenue to offset operating expenses (DeBusk and Ryther, 1987; Bagnall *et al.*, 1987; Chynoweth, 1987).

Aquatic plants have essentially the same nutritional requirements as terrestrial plants, but they have adapted their metabolisms to the aquatic environment. Most aquatic plants have high water contents compared to terrestrial plants. Aquatic plants not only provide treatment by taking nutrients and dissolved constituents into their systems, but also by modifying the environment around them or by providing a growing surface for the aerobic microorganisms which contribute to the treatment. Emergent and floating varieties also tend to transport oxygen from their leaves to their roots and the surrounding media, which allows them to grow in anaerobic environments (Reddy *et al.*, 1989).

2.2.1 Floating Plants

Floating aquatic macrophytes are vascular plants that grow with their photosynthetic parts at or above the water surface and their roots extending down into the water column. Usually these plants do not root into the soil substrate, but many can grow in moist soil if the water becomes too shallow (Dinges, 1982). Some plants, such as the pennywort or the water lily, are normally rooted into the substrate, but are included in this group because they have either the majority of their photosynthetic mass at or above the water surface or can become free floating under high nutrient conditions. Pennywort and alligator weed are plants which are normally found rooted in shallow water or marshy areas. The stolons and stems of these plants are buoyant, and when the water around them contains sufficient nutrients, the new stolons being extended from the parent plant may remain at the surface and grow hydroponically. Continued growth of the first free-floating "daughter" plant eventually forms a floating mat of intertwined plants which may break free of the plants rooted into the substrate due to wind and wave action in a natural body of water. When these plants are used for water treatment, they are placed in a situation where sufficient nutrients are present, and the only avenue for growth is on the surface of the water.

Free floating aquatic plants draw the carbon dioxide and oxygen that they need from the air, but they depend upon the dissolved constituents of the water for all of their nutrients. Under anaerobic conditions, many of these plants transport oxygen to their roots for metabolic purposes. Excess oxygen is then available to the surrounding media (Reddy *et al.*, 1989). When the roots of the plant are within the water column they act as a living substrate for attached growth of aerobic bacteria which then use the excess oxygen to degrade dissolved organic compounds in the water.

Floating aquatic plants tend to cover the water surface and block out the passage of light to the water below, denying algae the energy needed to grow and reproduce. The mat of plants which usually develops on the surface also causes the water to be isolated from the atmosphere. This results in two main effects: the water tends to be unaffected by wind and remains relatively quiescent, and gas transfer is seriously hindered. When moderate to high organic loadings are applied to floating aquatic plant systems, the water tends to become anoxic or anaerobic in spite of the ability of the plants to translocate oxygen. The quiescent conditions make these systems good at causing sedimentation of algae and suspended solids. Filtration of solids also contributes to removal when floating plants with extensive root systems are used (Dinges, 1982; EPA, 1988; Metcalf & Eddy, 1991). The development of the root system depends upon the plant's growth rate, temperature, nutrient content of the water, and the growth time. Some of these factors can be controlled during design and operation by modifying the recycle ratio as well as the harvest amount and frequency.

2.2.1.1 Water Hyacinth

Water hyacinth (*Eichhornia crassipes* [Mart.] Solms-Laubach) is the largest of the known floating aquatic macrophytes, reaching a height of as much as one hundred twenty centimeters. It is a native of South America that was discovered growing in the Amazon River Basin by Karl Von Martius in 1824. At the time botanists believed the plant's range to be restricted to South America with possible excursions into Central America and the larger islands in the Caribbean (Dinges, 1982). The plant moves readily in the water but is intolerant of high salinity. This is probably the only reason that its range was restricted since the Amazon River empties into the ocean and undoubtedly some of the plants escaped the river. Several theories exist about the water hyacinth's introduction into the United States, but the most widely accepted is that the Japanese delegation to the 1884 Cotton Centennial Exposition in New Orleans, Louisiana, brought some as an exhibit and as presents to visitors. A visitor supposedly took some of these plants to Florida and eventually discarded them in a natural waterway. Since that time, water hyacinths have spread throughout the southern coastal states and to California. In the states where it can grow year-round, water hyacinth has become a very costly pest, clogging waterways, restricting water flow, and increasing water losses because it has an evapotranspiration rate that is three to four times the surface evaporation rate of exposed water (Dinges, 1982; EPA, 1988). Control of these plants is difficult since they are one of the world's most productive plants--they have the eighth fastest growth rate of the top ten weeds (Metcalf & Eddy, 1991). One researcher has estimated that ten plants could produce six hundred thousand and completely cover 0.6 ha (1 acre) on a natural water in an eight month growing season. In nutrient rich waters such as wastewater, the rate can be even higher (Reed *et al.*, 1988). These very characteristics that make the water hyacinth a serious problem on natural waters make it a good candidate for use in wastewater treatment. The range of this plant in the wild has expanded into most of the tropical and subtropical regions of the world. The thirty-second parallels are the approximate limits of the plant's geographic range (EPA, 1978). Water hyacinths can be grown outside this range, but they must be protected from the winter temperatures.

Water hyacinth is a perennial, vascular plant with large, rounded, shiny green leaves and a central stalk of violet flowers. Reproduction is generally vegetative (asexual), but seeds are also produced by the flowers to help ensure survival. When exhibiting vegetative reproduction, the plant extends a stolon (see Figure 2-1), a "daughter" plant forms at the terminal end and then each plant will continue the process. In calm waters, the plants will remain attached by the stolons, forming large, loosely packed mats. In open water, the stolon will extend thirty centimeters, but once boundaries are encountered, the plants begin to fill in the empty spaces and new stolons can become as short as one centimeter. The plants primarily grow horizontally until they reach boundaries, but once crowding begins vertical growth becomes dominant. The petioles of the plant are spongy, filled with many air spaces, and furnish some of the buoyancy of the plant. Under unstressed conditions, the petioles are egg-shaped, but when the plants are crowded, the petioles become elongated as the leaves grow farther away from the plant to compete for light. The roots of the water hyacinth plant are feather-like and are unbranched. They vary in length according to the growth conditions and the frequency of harvest, but they are not affected by crowding. In low nutrient natural waters, the water hyacinth plants tend to be only a few centimeters high, but the roots can extend up to a meter into the water. Under high nutrient conditions the roots will only extend about ten centimeters into the water, but the plant shoots will be over a meter in length since crowding is also likely (Dinges, 1982). The morphology of the plant under crowded, high nutrient conditions is of the most interest to wastewater engineers since these represent the usual operating conditions of a water hyacinth treatment facility. The size and density of the roots on the plant are of interest because they provide the majority of the adsorption sites for dissolved constituents and act as a living substrate for the attached aerobic microbial populations that provide most of the degradation of organics in the treatment scheme (EPA, 1988; Metcalf & Eddy, 1991).

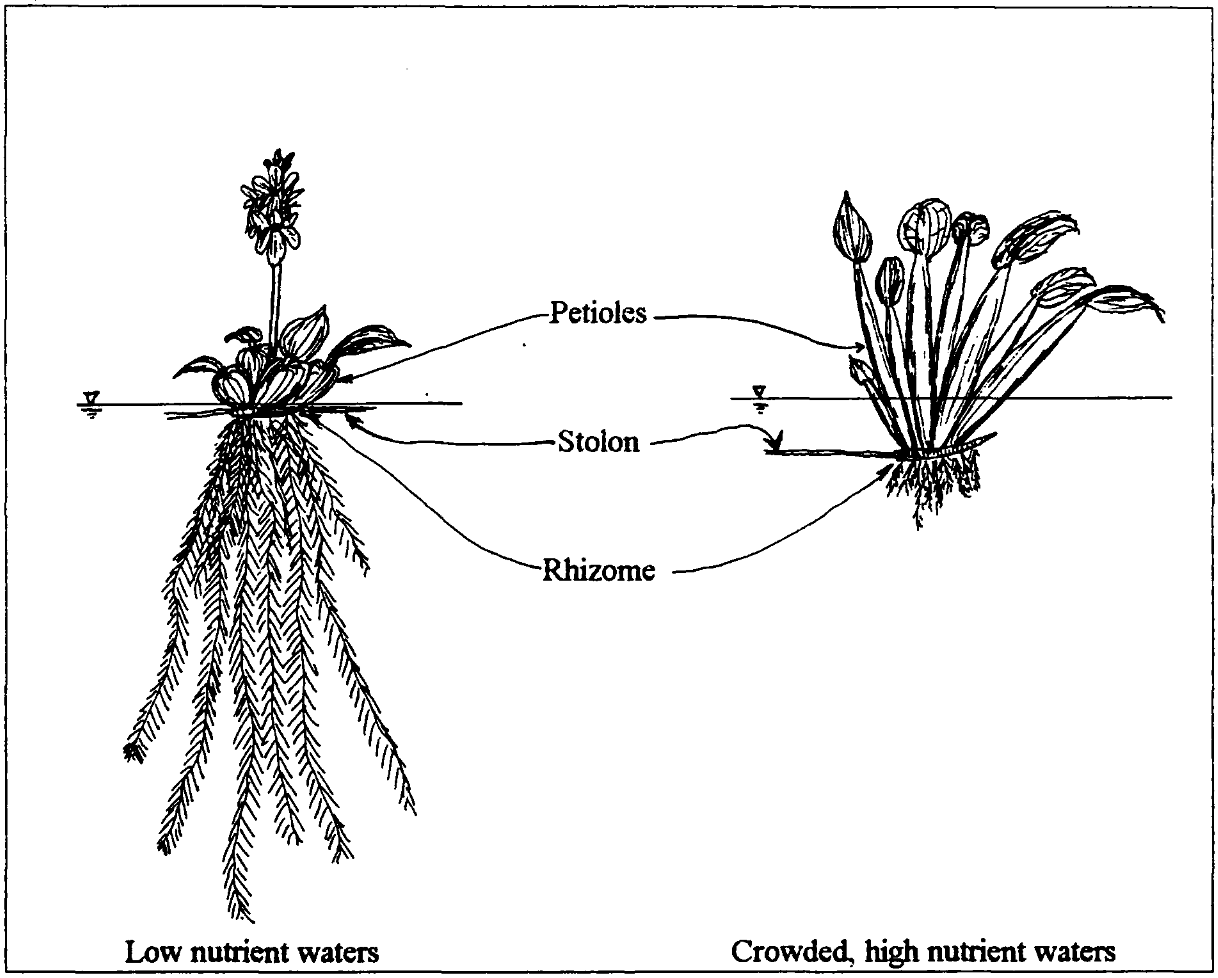


Figure 2-1, Water Hyacinth (*Eichhornia crassipes)*

The roots, stolons, petioles, and flower stalks all originate at the central rhizome which normally floats several centimeters below the water surface. This plant is considered a hardy species and can survive in a large variety of conditions, but if the tip of the rhizome is damaged, the entire plant will die. This is the primary reason that the plant cannot survive freezing conditions. The rhizome is similar in shape to a carrot and grows to lengths of 20 cm. Removal of only 4 cm of the tip results in the death of the entire plant. When the plant encounters freezing conditions, the leaves and stems die and begin to dry out. The decrease in weight above the water surface allows the rhizome to rise towards the surface where it becomes more vulnerable to freezing. If the water temperature at the surface approaches freezing, the tip of the rhizome will freeze and the entire plant will perish and decay. Studies in Japan have shown that for year-round survival in shallow waters, the plant is limited to regions where the mean atmospheric temperature in January does not fall below 1° C (Dinges, 1982). The optimum growth temperatures for the plant are $21\text{-}30^\circ$ C. Growth ceases at temperatures below 10° C, or above $35\text{-}40^\circ$ C. The water hyacinth will grow in waters of pH 4 to pH 10 (Dinges, 1982; EPA, 1991).

2.2.1.2 Water Lettuce

Water lettuce, *Pistia stratiotes* L. is a plant similar in size to the water hyacinth and requires many of the same conditions for survival. As its name indicates, it resembles a loosely packed head of pale green lettuce (Figure 2-2). The leaves grow up to 25 cm long and it has a root system similar to that of the hyacinth (Correl and Johnston, 1970). Water lettuce does not transfer oxygen as well as pennywort or water hyacinth (Reddy *et al.*, 1989), but it is occasionally used in water hyacinth systems because it does grow well and the roots provide a growing surface for bacteria.

Water lettuce reproduces much like the water hyacinth using stolons. Flowers are produced but they are rarely seen since they do not grow taller than the leaves and are not showy like those of the water hyacinth. Very little research has been performed on the ability of water lettuce alone to treat wastewater since it does not appear to have any advantages over the water hyacinth.

2.2.1.3 Pennywort

Pennyworts (*Hydrocotyle umbellata, H. ranunculoides, H. spp.*) are not normally free floating plants. They are normally rooted into the substrate in shallow water, with their leaves and stems growing above the water surface. Pennyworts tend to grow along the water surface and intertwine with other plants, but once they become crowded they will grow vertically. In high nutrient environments, pennyworts will grow in free floating rafts. The leaves on these plants are much smaller than those of the water hyacinth and have long stems compared to the leaf size. *H. umbellata* has crenate circular leaves with diameters of as much as 75 mm and stems as long as 40.5 cm (see Figure 2-3). When crowding occurs, the leaves of the pennywort tend to be self shading and thereby limit production (EPA, 1988; Metcalf & Eddy, 1991). One of the reasons pennyworts are of interest in the field of wastewater treatment is because they are a cold tolerant plant. Most of the approximately 100 species are found in the temperate zones, but *H. ranunculoides* is found as far north as Pennsylvania and

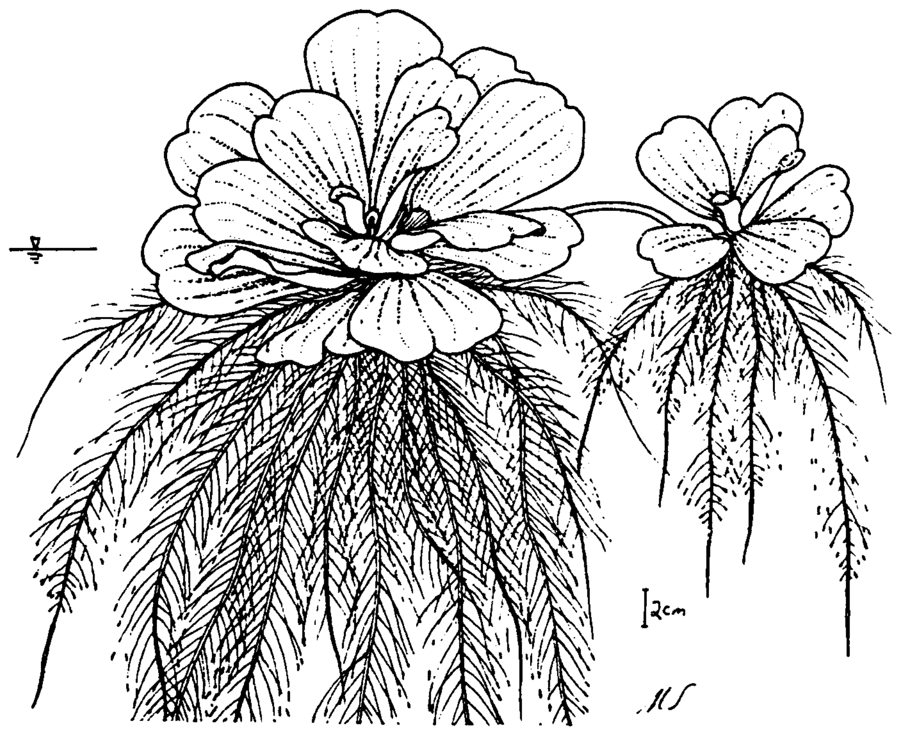


Figure 2-2 Water Lettuce (*Pistia stratiotes*)

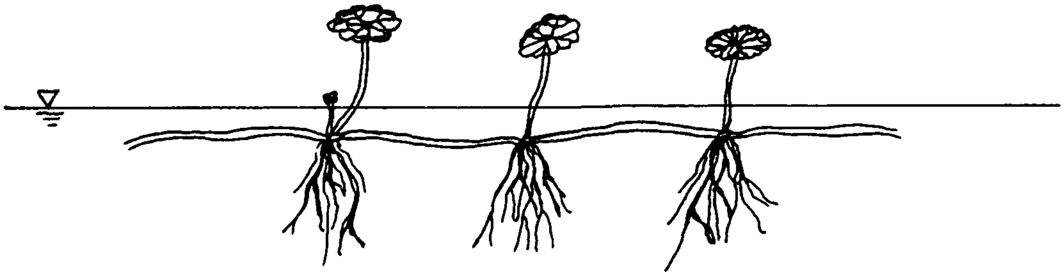


Figure 2-3 Pennywort (*Hydrocotyle spp.*)

Delaware (Correl and Johnston, 1970). They are also of interest because they can transport more oxygen to the water than water hyacinths, and their rate of nutrient uptake is approximately the same throughout the year. In the winter, the nutrient uptake of pennywort plants exceeds that of water hyacinths (Metcalf & Eddy, 1991).

2.2.1.4 Duckweed

Duckweed is the common name for the family of small aquatic plants, *Lemnaceae*. Duckweeds consist of about forty species in four well defined genera: *Spirodela*, *Lemna*, *Wolffia*, and *Wolfiella*. Members of this group can be found in most areas of the globe with the exception of polar and desert regions. Some species are widespread, while others are limited in their range.

Individual duckweed plants consist of a single frond, but the plants may be found in groups connected by stipes. Duckweeds vary widely in size and shape (see Figure 2-4). The smallest, *Wolffia*, has nearly spherical fronds which are about 1 mm in diameter. Others are flat and slender, oval, or circular. *Spirodela polyrhiza* L. is the largest species of the family with flat circular fronds as large as 1.5 cm across. *Lemna* and *Spirodela* have short nonfunctional roots that are usually less than 10 mm in length but can be as long as 3 cm. *Lemna* species have a singe root strand and *Spirodela* species have two to twelve bunched roots. The other two genera do not have roots.

Duckweeds are the smallest and simplest of the flowering plants--*Wolffia* are the smallest seed plants in existence--but flower and seed production is rare among most of the species. Reproduction is usually asexual, with one or two pouches of embryonic tissue at the base of the frond producing a new frond. The fronds may remain connected by long stipes, forming loose colonies of plants (Correl and Johnston, 1970). Each frond produces between ten and twenty new fronds during its life. Duckweeds require very little structural support and as a result have very little vascular tissue. Almost all of the cells of each frond are metabolically active. Because of this, they have one of the fastest reproduction rates among plants. Current estimates show that duckweeds can grow approximately thirty percent faster than water hyacinth (EPA, 1988). Under favorable conditions the standing crop biomass may double in 1-5.3 days. Initially a doubling of the biomass means that twice the surface area is covered, but once the surface is completely covered, growth will continue in some species to form a mat several centimeters thick (Dinges, 1982). Where it exists, *Lemna gibba* L. will probably dominate in mat forming conditions because it has inflated pouches on the underside of its fronds which allow it to grow over the top of species with flat fronds. *L. trisulca* L. floats just beneath the surface except when flowering and may be more protected from the cold as a result. Under warmer conditions, other species will probably dominate since they will grow over the top of *L. trisulca.*

Most of the species cease to grow at temperatures below 7° C. Some species, such as *S. polyrhiza* L. winter by producing a bud which contains large amounts of dense carbohydrates and sinks to the bottom until spring (Correl and Johnston, 1970). Treatment ponds using duckweed may require seasonal operation, or modification of the winter treatment process since the duckweed mat will not be present after freezing temperatures are sustained for any length of time. Fortunately these temperatures, and the lighting conditions that accompany them, also substantially decrease algal growth. In duckweed systems that are primarily used to remove algae from stabilization pond effluent, this may result in few large changes in system operation.

2.2.1.5 Water Fern

Water Ferns consist of two genera which have been used for wastewater treatment, *Azolla* and *Salvinia*. Most of the approximately sixteen species in this family are native to tropical or subtropical regions (Dinges, 1982). Plants from each genus can grow to be substantially larger than duckweeds but they are used in much the same way. *Azolla* species (Figure 2-5) are minute reddish or green normally free-floating plants, but they may also grow on mud. They are usually found densely matted. The stems are pinnately branched and are usually concealed by roots and imbricating leaves. The six species of this genus are widely distributed.

Azolla caroliniana, a native North American species, forms individual plants 3 cm across. The roots of plants in this genus are feathery and approximately 3 cm long. As with other ferns, these plants do produce spores in their reproductive cycle. Vegetative reproduction occurs by division, with the older growth at the center of a cluster of stems dying and decaying to release actively growing branches (Aston, 1973). *Azolla* species may have some promise for use in treating nitrogen poor wastewaters because the submerged lobes of the plants leaves have cavities which are usually inhabited by a blue-green algae, *Anabaena azollae*, that fixes nitrogen from the air if it is lacking in the water (Cook et al., 1974).

Salvinia contains the larger plants in this group, with individual leaflets approaching 3 cm long. This group consists of free-floating ferns with branching horizontal stems. From the surface, the stem appears to support pairs of opposite leaves, but actually each node has a whorl of three leaves (see Figure 2-6). The submerged leaf is greatly modified to resemble a mass of roots. True roots are absent, but the third leaf still provides some attachment surfaces for microorganisms. Under favorable conditions, *Salvinia* exhibits extremely rapid vegetative growth and spread. In some locations *Salvinia auriculata* has been known to cover large areas with blankets of living and dying plants up to 25 cm thick. This species is considered a pest second only to the water hyacinth (Aston, 1973).

Since these plants does not exhibit the same capability as duckweed to survive in thick mats cut off from light, frequent harvesting will probably be required in systems which use them. These plants are larger than duckweed but they are still affected by the wind, and either surface baffles will be required or they will have to be redistributed frequently. *Salvinia* species have been investigated using large scale systems in Australia, and the results were similar to those achieved in duckweed systems (Dinges, 1982).

2.2.1.6 Others

Plants which are considered noxious weeds in natural waterways are usually worth considering as plants for wastewater treatment, especially since they are already acclimatized to the local conditions. Alligator weed, *Alternanthera philoxeroides*, is one of these plants. It is a semiterrestrial herb which is clogging

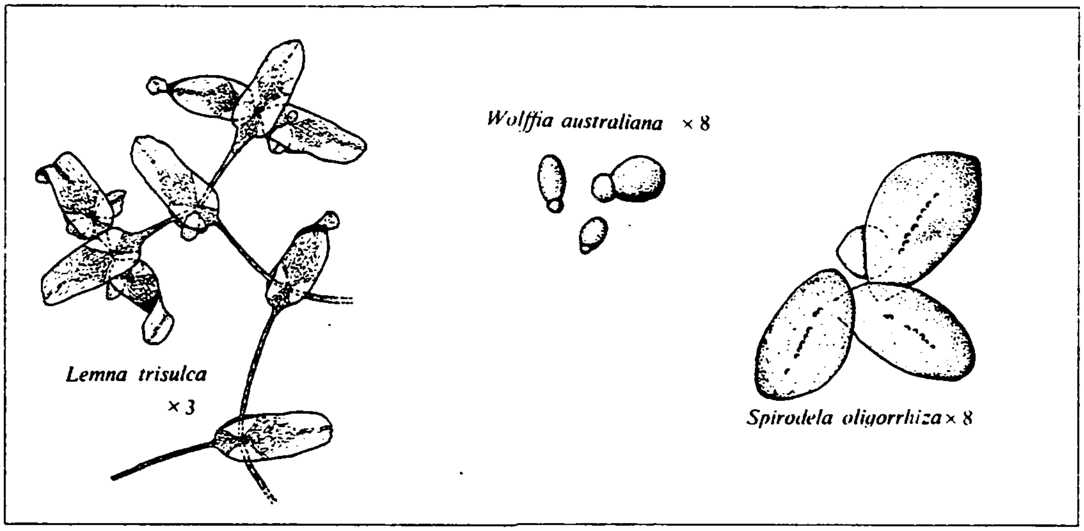


Figure 2-4 Duckweeds (*Lemnaceae*)

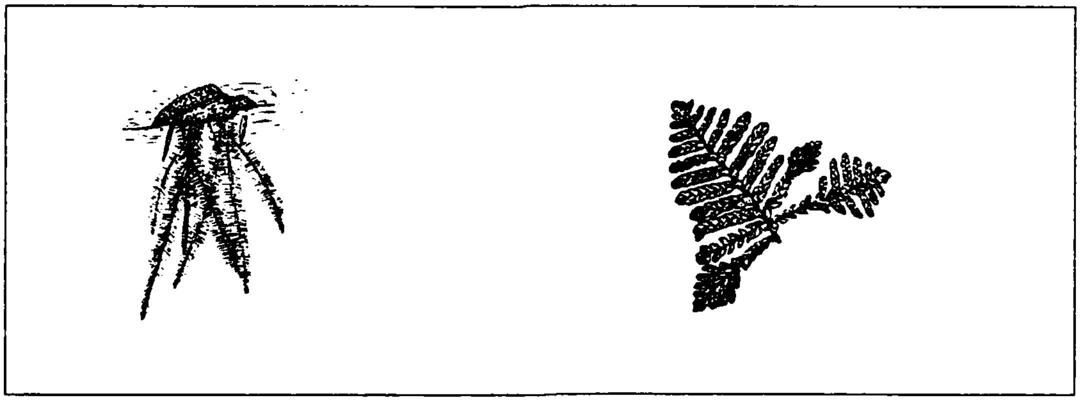


Figure 2-5 *Azolla filiculoides*:
left, x 0.7; right, full size

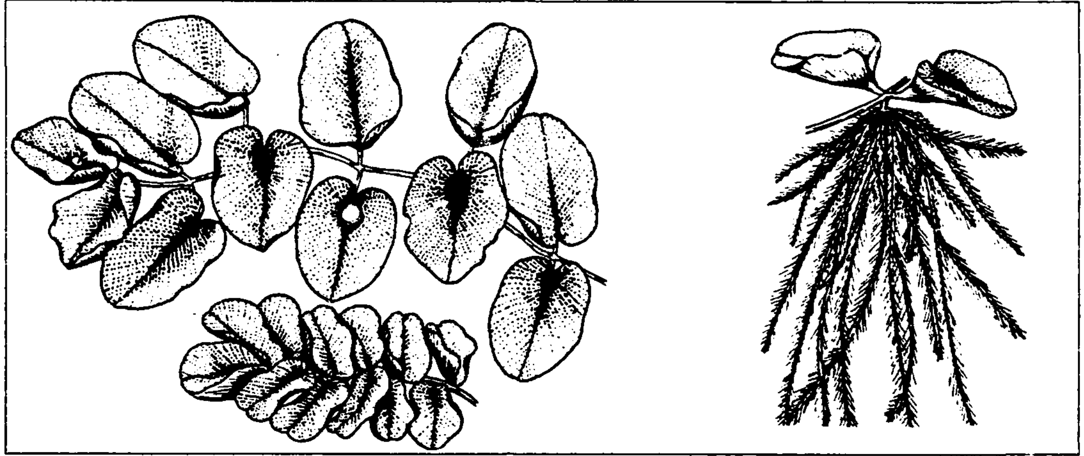


Figure 2-6 ***Salvinia auriculata*:**
left, two surface views x 0.7; right a whorl of leaves x 0.7

waterways in Texas and other parts of the south. Alligator weed has long narrow leaves and a horizontal stem which creates large floating mats under advantageous conditions (Correll and Johnston, 1970; Dinges, 1982). Some rooted plants may be forced to grow in a floating mode. Dinges experimented with *Myriophyllum brasiliense* and *Paspalum fluitans*, and aquatic grass. Both grew well on the surface of the wastewater, with the grass actually forming mats. Since grass has a lower water content than most natural floating aquatic plants, it would be easier to handle and dry, and it would be readily acceptable as hay if the protein content was high enough.

2.2.2 Submerged Plants

Submerged aquatic plants may either be rooted into the substrate or within the water column. Submerged plants procure all of their nutrients from the water or the substrate, and they draw the required oxygen and carbon dioxide strictly from the water. The production of submerged plants is generally limited because their metabolism is adjusted to low light conditions and slow diffusion of gases to and from the plants. Since plants require oxygen during the dark cycle, and produce it during the light cycle, the oxygen content of the water will vary on a daily basis. Since carbon dioxide is produced or consumed on a cyclic basis as well, the pH of the water will also fluctuate from day to night. How much fluctuation occurs will depend upon the buffering capability of the water. Because the plants require oxygen part of the day, they will not survive in anaerobic waters. Wastewaters likely to become anaerobic at night will require aeration at night if submerged plants are to be used in treatment. For submerged plants to be used effectively they must receive sunlight, so the water can not be very turbid but must be relatively clear. The above mentioned limitations tend to make one think that submerged plants are not very useful in water treatment, or that they should only be used in a final polishing step. Submerged plants are capable of absorbing nutrients, metals, and some trace organics, so there is potential for their use in a polishing phase of treatment (Eighmy *et al.*, 1987; Reed *et al.*, 1988). As is the case with floating macrophytes, it is believed that the major removal mechanism of nutrients and trace organics is by bacterial degradation rather than plant uptake.

Of the many species tested, several show relatively aggressive growth rates in wastewater and are capable of withstanding interspecific competition. Some of these are *Elodea canadensis*, *E. nutallii*, *Egeria densa*, *Ceratophyllum demersum*, *Potamogeton foliosus*, and in warmer climates, *Hydrilla verticillata*. Some of these are shown in Figure 2-7. *Elodea* and *Hydrilla* are the most aggressive, but *Hydrilla* is capable of growing at lower light levels and would probably dominate a mixed culture. *Elodea* is found in tropical and temperate regions throughout the world, while *Hydrilla* is present in most "warm regions" (Dinges, 1982). One main problem with these plants is that even the cold-region species experience a severe die back during the winter months when water temperatures approach freezing. In warmer areas, mortality may not occur, but active growth will probably cease (Dinges, 1982).

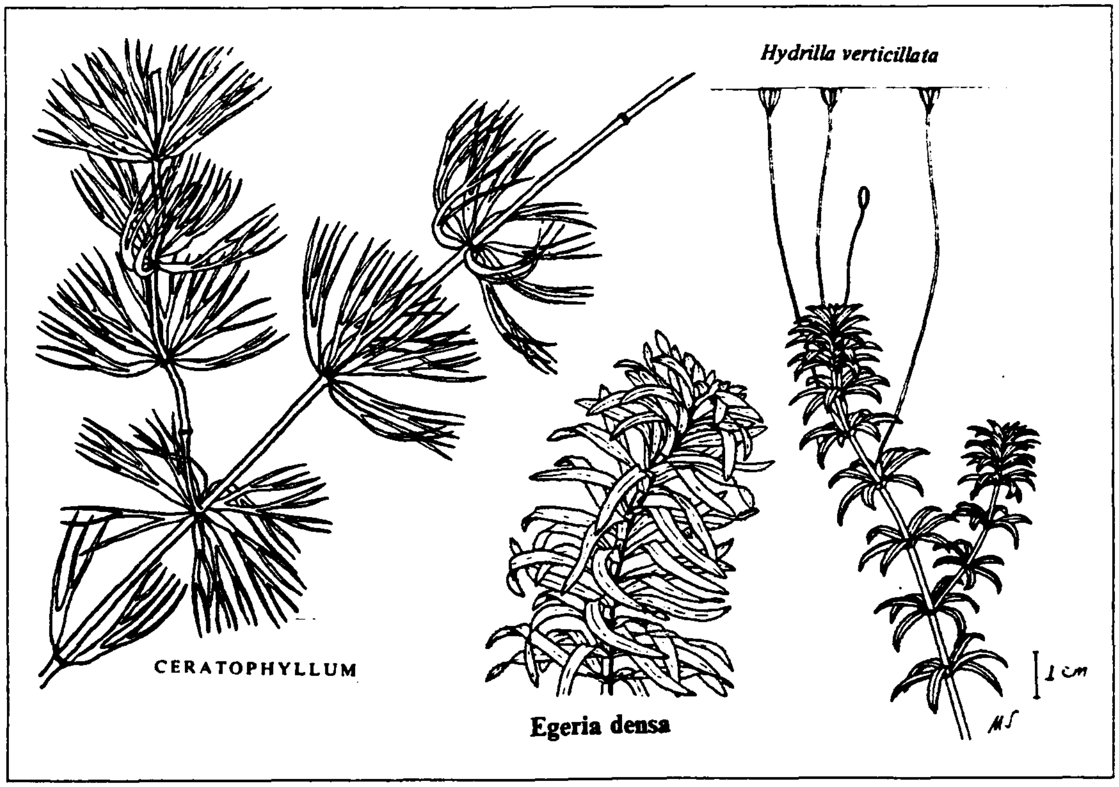


Figure 2-7 Submerged Aquatic Plants

2.3 Removal Processes

The primary removal mechanisms for wastewater constituents in aquatic plant systems are essentially the same as for mechanical systems: sedimentation, filtration, nitrification/denitrification, adsorption, and precipitation (Neuse, 1976; Dinges, 1982). Plant systems also add nutrient and dissolved constituent uptake and subsequent removal by plant harvest. Plants and their associated microbial populations may be used to perform the physical removal, as in the case of a shallow water hyacinth basin where the roots filter out solids and adsorb dissolved constituents. The plants may be alternately used simply to create the proper environment for treatment to occur, such as a deep basin with a duckweed or water fern cover that provides quiescent, dark water ideal for algae removal. Water hyacinths, water lettuce, pennywort, and other large-rooted floating plants may be used in systems managed for nitrification/denitrific-ation by allowing the water to become anaerobic. In this case nitrification occurs in the layer of aerobic bacteria attached to the roots. Any nitrates which are not consumed by the plant quickly diffuse into the bulk of the water where they are subject to denitrification (Reed *et al.*, 1988; Metcalf & Eddy, 1991). Any of the plants systems that have sufficient plant yield may be managed for phosphorus or metals removal. Phosphorus removal in these systems is primarily by plant uptake, microbial immobilization with plant detritus, adsorption to the benthic sediments, and precipitation within the water column. Permanent removal from the system can only be accomplished by harvest and sediment removal (WPCF, 1990).

2.4 Physical Characteristics

The physical characteristics of an aquatic plant treatment system depend entirely upon the objectives of the treatment and the type of plants used. Duckweed or water fern sedimentation systems will probably be relatively deep with no particular surface configuration. Water hyacinth systems tend to be shallow, long and narrow with influent distribution manifolds or weirs. This is to maximize contact with the roots, where the majority of the treatment occur. Nutrient film techniques have been used with pennywort to remove metals, organics, and suspended solids (Dierberg *et al.*, 1987). These systems consist of narrow troughs filled with a mat of plants which rests on the bottom, and a thin layer of wastewater flows through the root and detritus zone. Permanent removal of the adsorbed constituents is then achieved by harvesting the plants. Submerged plant systems generally consist of a large shallow lagoon to maximize gas exchange with the atmosphere, sunlight penetration, and plant contact time. Numerous variations on each possibility exist and will be discussed in more detail in the design section.

2.5 Operational Requirements

Regardless of the system chosen, the items discussed below will be important to the continued success of the treatment. Most aquatic plant systems will only be one component in a larger treatment plant, but they do have some unique requirements which must be considered.

2.5.1 Operator

The operator of an aquatic plant wastewater treatment system needs to be knowledgeable of not only wastewater treatment, but also of the plants used. The operator must understand the methods by which the plants do what is desired of them, any growth requirements of the plants, to what pests and diseases they are susceptible, and how to control those pests. The operator needs to understand the processes well enough that he can adjust the input variables to fine tune the performance of the system.

2.5.2 Nutrients

Most of the aquatic plants used in treatment participate in luxury uptake of nutrients, and many absorb large quantities of metals such as iron. Because of this, the addition of limiting nutrients may be required in lagoons that are the third or fourth in a series of aquatic plant lagoons. One water hyacinth treatment system in Florida found that chlorosis of the plants was occurring in the third unit in series because the iron concentration was well below the 0.3 mg/L needed by the plants for proper chlorophyll production. The operators believed that nitrogen would also become limiting in that unit once the planned harvest schedule was implemented (Dinges, 1982).

2.5.3 Harvest

In systems being managed for phosphorus or metals removal, harvesting must be part of the operation plan since this is the only pathway for permanent removal of these constituents. Less obvious is the need for harvest in systems designed for sedimentation or nitrification/denitrification. The main reasons that harvesting the plants in these systems is desirable are to maintain a healthy vigorous population, and to control pests (Solati, 1987). Systems using water hyacinth or water ferns in a warm climate would eventually become crowded enough that detritus would not be able to get through the mat, and the formation of sudd would probably result. Sudd is a floating mat of partially decayed plant matter. Once this began, all of the nutrients and contaminants in the plants' tissues would quickly return to the water and the effluent goals would most likely be exceeded (Wills and Pierson, 1987). Complete removal of the mat would then become the best way to correct the problem.

2.5.4 Maintenance and Cleaning

Depending upon the design of the system, units will require periodic draining and removal of the benthic sludge. An unharvested water hyacinth system receiving stabilization pond effluent or another high solids content water will probably require cleaning once a year (Dinges, 1976, 1982). Secondary or tertiary cells should be drained and cleaned every two to three years, and deep secondary cells that are harvested regularly should only need to be drained every five years (Reed *et al.*, 1987). Some states require that cleaning be performed more frequently. Texas, for example, requires that each cell be drained and cleaned of sludge and plants annually (TWC, 1991).

2.6 Climatic Constraints

Unprotected aquatic plant systems are limited in their range of year round operation. Even submerged aquatic plants adapted to northern environments experience extreme die-offs during the winter (Dinges, 1982). Sub-tropical plants such as the water hyacinth is even more severely restricted. As stated above, exposure to air temperatures of -3° C for 12 hours will destroy the leaves, and exposure to -5° C for 48 hours will result in the death of the plant (EPA, 1988). Regions with mean January temperatures below 1° C will not support a continuous water hyacinth population (Dinges, 1982). Figure 2-8 shows the ranges in the contiguous United States which will support unprotected water hyacinths on an annual and six-month basis.

Although duckweeds are adapted to cold environments, they survive by going dormant for the winter and cannot be grown effectively at temperatures below 7°C. Figure 2-9 shows the ranges in the contiguous United States where duckweed growth is likely for six, nine, and twelve months of the year.

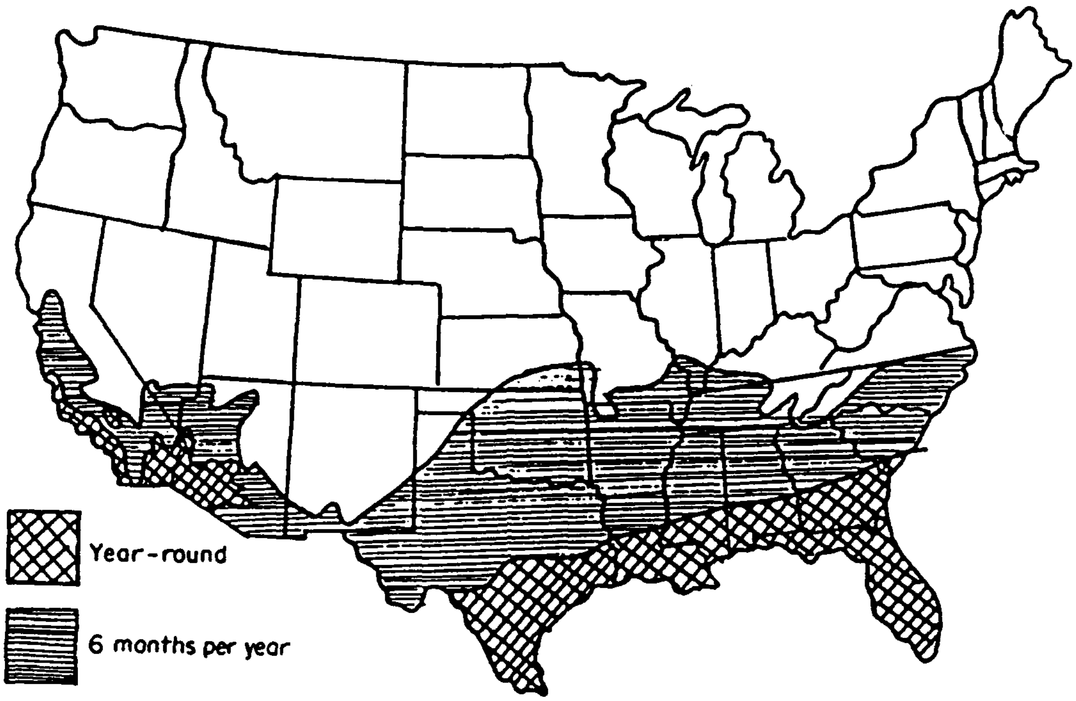


Figure 2-8 Suitable Areas for Hyacinth Systems
after EPA, 1988

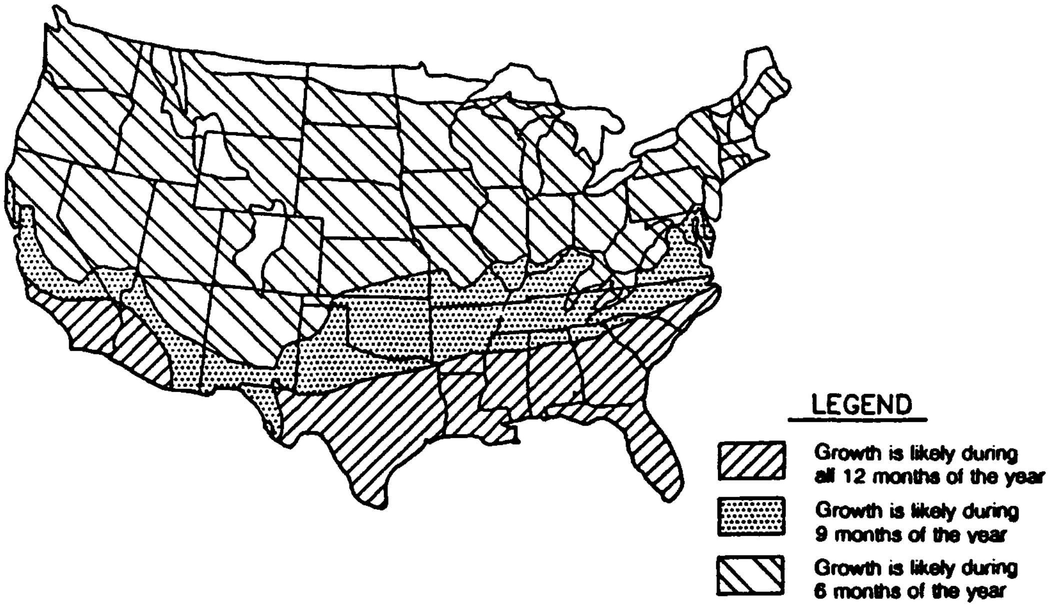


Figure 2-9 Suitable Areas for Duckweed Systems
after EPA, 1988

Chapter 3

Human Health and Environmental Concerns

3.1 Introduction

As with any other treatments system, the primary goal of an aquatic plant treatment system is to protect human health, and the secondary goal is to prevent damage to the environment. The ability of various aquatic plant treatment systems to meet these two goals, together with economic considerations, determines whether they are practical as components in a treatment facility.

From the public health and environmental viewpoint, natural treatment systems offer a greater potential than conventional systems for exposing the environment to wastewater contaminants due to their larger size (EPA, 1988). Since the sites can be fenced to prevent access by the general public, public exposure to partially treated wastewater is not a problem. The major concerns then become operator exposure, releases of untreated or partially treated wastewater, and final effluent quality. Studies cited by Reed *et al.* (1988) did not find any correlation between normal operator exposure to wastewater or wastewater aerosols and the incidence of operator illness. Aquatic plant systems are designed to prevent the release of insufficiently treated wastewater by either leaks or short-circuiting in the same manner as any other type of treatment systems. Ponds may be lined if the native soil allows too much exfiltration, and all systems are designed and managed to minimize preferential flow paths and maximize treatment.

Effluent quality is judged by measuring the concentrations of the contaminants of concern. The principal contaminants of concern can be broken into the following main categories: biological oxygen demand, suspended solids, nitrogen, phosphorus, pathogenic organisms, heavy metals, and trace organics. Biological oxygen demand (BOD) is not an individual chemical contaminant, but is a measure of the oxygen demand exerted by all of the readily degraded organic contaminants. Pathogenic organisms include bacteria, viruses, protozoa, and helminths. The heavy metals include cadmium, selenium, mercury, zinc, nickel, copper, lead and chromium. Trace organics include highly stable synthetic organics such as chlorinated hydrocarbons.

The primary health concern is from pollution by nitrogen, pathogens, metals, or organics. All of the mentioned pollutants, the major reasons for concern, and the exposure pathways of concern are summarized in Table 3-1.

3.2 Biological Oxygen Demand

Although some of the contaminants which are included in this measurement are unhealthy at the concentrations found in raw wastewater, the primary reason for concern is the oxygen demand they exert on the environment in which they are found. Since oxygen does not dissolve in water sufficiently to match the oxygen demand of the readily degraded organic chemicals involved, microbial metabolism of these chemicals will deplete the water of dissolved oxygen faster than it can diffuse in from the atmosphere. If this occurs in natural waters, most of the animal and plant life will perish and add to the problem.

The primary methods that aquatic plant systems remove BOD from the water are microbial activity, filtration, and sedimentation. Microbial degradation and filtration dominate in floating plant systems, such as water hyacinth systems, where there is an extensive root system. Sedimentation and anaerobic degradation in the benthic zone dominate in systems with small floating plants such as duckweed or water fern. Soluble BOD is less affected in systems without substantial root systems because there is much less aerobic microbial activity in the water column than exists on the roots.

Oxygen is supplied to the bacteria through the roots as discussed above, either directly, or after diffusing into the upper layer of water. Some oxygen also enters the water by diffusion through the water surface, but in floating aquatic plant systems, this is extremely limited due to the mass of plant matter on the surface. Removals of BOD_5 have been reported in the range of 72 to 94 percent in water hyacinth systems (Dinges, 1976; Neuse, 1976; Reed *et al.*, 1988).

3.3 Suspended Solids

Organic suspended solids contribute to the oxygen demand, suspended solids in general cause siltation of receiving waters, and have the potential of harming the habitat and the organisms present. In spite of these possibilities, the main reason that suspended solids are a concern to the public is aesthetic--water that has a high suspended solids concentration does not *look* clean.

Suspended solids are removed primarily by filtration and sedimentation in aquatic plant systems. Systems using floating plants will perform better than sedimentation ponds without plants because of the quiescent conditions under the

Table 3-1 Pollutants, Effects, and Pathways of Concern

Pollutant	Concern	Pathway
BOD		
Health	No direct impact	
Environmental	Oxygen starvation of natural aquatic habitats	Discharge to natural waters
Suspended Solids		
Health	No direct impact	
Environmental	Aesthetics, siltation of natural waters	Discharge to natural waters
Nitrogen (esp. nitrates)		
Health	"Blue baby" syndrome	Drinking water contamination
Environmental	Eutrophication	Discharge to natural waters
Phosphorus		
Health	No direct impact	
Environmental	Eutrophication	Discharge to natural waters
Pathogens		
Health	Disease epidemics	Ingestion via water or food, aerosols
Environmental	Diseased wildlife, soil accumulation	Discharge to natural waters, soils
Metals		
Health	Toxicity, "brittle-bone disease" (Cd), brain damage (Pb)	Ingestion via water or food
Environmental	Toxicity, long-term soil damage	Discharge to natural waters or land
Trace Organics		
Health	Toxicity, Cancer	Ingestion, absorption through the skin
Environmental	Toxicity, other biological problems	Discharge to natural waters and bioaccumulation

plants. Also contributing to the effectiveness of floating plant systems is the fact that suspended algae cannot reproduce and remain active due to the shading of the water by the mat of plants on the surface. Removals of 70 to 95 percent have been reported in water hyacinth systems (Reed *et al.*, 1988).

3.4 Nitrogen

The concentration of nitrate nitrogen is restricted by regulation in potential drinking waters because it has been linked to the occurrence of "blue baby" syndrome, where an infant's blood is hindered from carrying sufficient oxygen. The concentration of all forms of nitrogen is regulated in discharges to surface waters because it can cause eutrophication, and because the unionized form of ammonia is toxic to fish in relatively low concentrations. Nitrogen can be removed from the water by plant uptake, microbially mediated nitrification and denitrification reactions, and volatilization of dissolved ammonia. Because aquatic plants tend to maintain the pH of the water near neutral, very little volatilization of ammonia occurs. Some removal of nitrogen does occur by plant uptake, but the majority is removed by nitrification and denitrification, with the resulting nitrogen gas diffusing into the atmosphere. Managing aquatic plant systems for maximum plant uptake tends to decrease the amount of nitrification and denitrification because it requires frequent harvest, and removes some of the attached microbial growth along with the harvested plants. Removal of nitrogen can range from 26 to 96 percent of the influent total (EPA, 1988).

3.5 Phosphorus

Phosphorus concentration in wastewater effluents is primarily a concern because phosphorus is occasionally a limiting nutrient in natural waters and release of available phosphorus can potentially cause eutrophication. Phosphorus is readily adsorbed onto soil particles, and, in systems where the wastewater is exposed to soils. more removal is likely due to this mechanism than due to plant uptake. Eventually, however, the sorption capacity of the exposed soil will be reached and removal will be almost entirely due to plant uptake. Reddy and Debusk (1987) feel that plant uptake is the only mechanism that can be relied upon for design purposes because it can be managed.

Most of the plants used in aquatic systems undergo luxury consumption of nutrients (see Figure 3-1), which makes them more practical to use for nutrient removal by plant uptake and harvest. Removal rates of 12 to 73 percent of the influent phosphorus are possible depending upon the operating conditions (Wolverton and McDonald, 1979; Reddy and Debusk, 1987; Eighmy et al., 1987).

3.5 Pathogens

Pathogens are of primary health concern because they are by definition disease causing organisms. Removal of these organisms in aquatic plant systems is for the most part identical to the mechanisms in oxidation and facultative treatment ponds--natural attrition due to the adverse growing conditions in the system, adsorption, predation, and sedimentation (EPA, 1988). Some submerged aquatic plants produce chemicals which suppress microbial growth in a similar fashion to the algae found in oxidation ponds, but most of the plants do not (Dinges, 1982).

Floating aquatic plant systems with large root masses also remove pathogens by filtration and subsequent predation by organisms in the root ecosystem (Neuse, 1976). Filtration is most effective for the larger pathogenic organisms, but has very little effect on virus removal (Abasi, 1987). Unless removal curves are developed for the specific systems, curves such as those in Figure 3-2 which were developed for pond systems, should be used in the design process. For these curves, only removal due to the time in the pond environment is taken into account, with no credit given to the filtration in the root zone.

3.6 Heavy Metals

Metals are present in many industrial and municipal wastewaters from a variety of sources. Metals are a concern to the environment as well as to human health because they tend to build up in the food chain and soils and are toxic to the organisms involved once enough has built up in their systems. Two health examples of metals overexposure are given in Table 3-1. More exist, and all are essentially reactions to the toxicity of the metals involved. Most of the metals are micronutrients for both plants and animals, but the concentrations present in wastewater are usually in the nutrient toxicity range (see Figure 3-1). Metals removal is minimal in conventional primary and secondary treatment systems. If significant removal is required, conventional systems usually resort to chemical precipitation and flocculation, reverse osmosis, or ion exchange processes. These processes require significant chemical or power inputs and precipitation also produces large quantities of sludge which must then be placed in a landfill. Removal in aquatic plant systems is largely due to adsorption of the metal cations

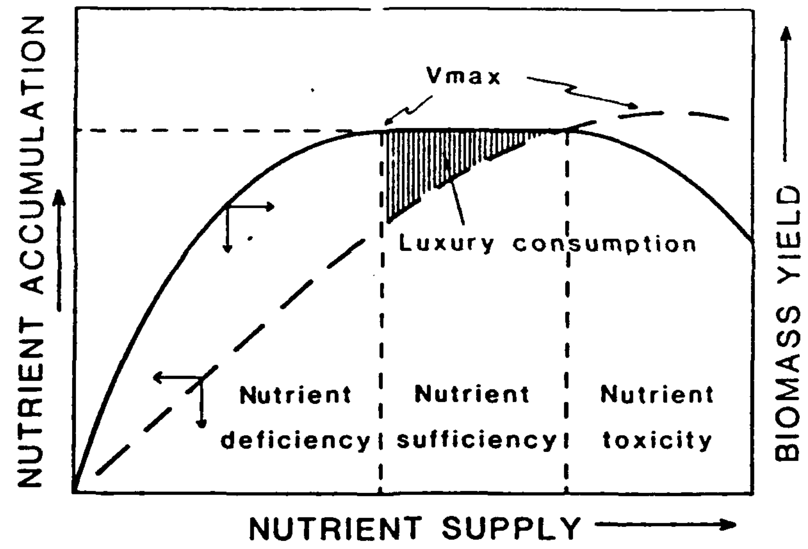


Figure 3-1 Schematic of Nutrient Accumulation and Biomass Yield versus Nutrient Supply (after Reddy and DeBusk, 1987)

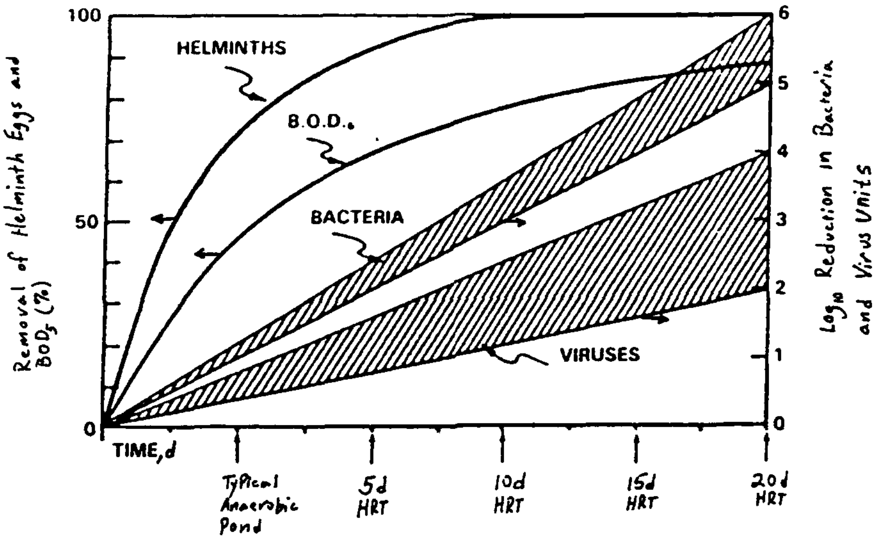


Figure 3-2 Generalized Removal Curves for Helminth Eggs, Enteric Bacteria and Viruses in waste stabilization ponds at temperatures above 20° C (after Krishnam and Smith, 1987)

onto the roots and translocation into the plant tissues. Water hyacinth, water lettuce, and pennywort are capable of substantial adsorption and translocation of metals before the plants begin to suffer from phytotoxic effects (Tokunga *et al.*, 1987; Wolverton and McDonold, 1978; Salati, 1987; Heaton *et al.*, 1987; EPA, 1988; Wills and Pierson, 1987; Jamile *et al.*, 1987). In some cases, water hyacinths are able to concentrate metals on and within the plant to as much as one thousand times the ambient concentration. The majority of the metals taken into the plants are found in the roots, and because mature hyacinths shed roots regularly, the benthic sludge in hyacinth systems will also have high concentrations of metals (Abasi, 1987; Heaton *et al.*, 1987). Removal efficiencies of three parallel water hyacinth channels are given in Table 3-2 for an example of possible removals (Reed *et al.*, 1988).

3.7 Trace Organics

Removal of refractory synthetic organics requires advanced treatment methods in conventional treatment systems such as reverse osmosis or carbon adsorption. In aquatic plant systems, removal is by absorption into the plants themselves. In some cases the organics are degraded by enzymes in the plants. Water hyacinths are capable of absorbing and degrading phenols and biphenols because the roots contain polyphenol oxidase enzymes (Templet and Valez, 1987; O'Keefe *et al.*, 1987). Submerged aquatic plants have shown potential as a final polishing system to remove organics left in the treated wastewater. Table 3-3 contains the results of a pilot scale water hyacinth system used to remove trace organics, and provides some idea of removal potentials (Reed *et al.*, 1988).

3.8 Vectors

In aquatic plant systems, the primary vector of concern is the mosquito. The main goal of mosquito control programs is to maintain the population below the threshold for disease transmission, but if it is at all possible, the programs will maintain the population below nuisance levels. Pesticides are not desired as a primary control mechanism because of the potential for developing a resistant strain, because pesticide residues are not desired in the effluent, and because in some systems (water hyacinth, water lettuce) the larvae are protected from the spray by the leaves of the plants.

Mosquitos are not a problem in duckweed or water fern systems because the larvae cannot penetrate the thick mat of plants to breathe. Water hyacinth and water lettuce systems have the most trouble with mosquitos because the rafts of plants leave pockets of stagnant water that are protected from sprays or natural predators. Many aquatic plant systems use mosquito fish (*Gambusia* spp.) to control the larvae population. Other species may be used as well: goldfish (*Carassius auratus*), frogs (*Hyla* spp.), and grass shrimp (*Palemonetes kadiakensis*). Frogs can survive in anaerobic waters, but the other species require at least an upper layer of water containing more than 1 mg/L of dissolved oxygen (Dinges, 1976; Reed *et al.*, 1988; Metcalf & Eddy, 1992). If mosquito fish are used for larvae control in a water hyacinth system, the plants must be harvested regularly to prevent protected pockets from forming in the mats. Systems with high organic loads will probably require supplemental aeration to keep the fish alive (it also increases treatment, but aeration at the shallow depths involved is not very efficient). Systems with lower organic loads may only require nocturnal aeration

Table 3-2 Metal Removal in Hyacinth Ponds

Metal	Influent Concentration, ug/L	Percent Removal*
Boron	140.0	37
Copper	27.6	20
Iron	457.8	34
Manganese	18.2	37
Lead	12.8	68
Cadmium	0.4	46
Chromium	0.8	22
Arsenic	0.9	18

*Average of three parallel channels, detention time about 5 days

Source: Reed et al., 1988

Table 3-3 Trace Organic Removal in Hyacinth Basins

	Concentration, ug/L	
Chemical	Untreated wastewater	Hyacinth effluent*
Benzene	2.0	ND**
Toluene	6.3	ND
Ethylbenzene	3.3	ND
Chlorobenzene	1.1	ND
Chloroform	4.7	0.3
Chlorodibromomethane	5.7	ND
1,1,1 Trichloroethane	4.4	ND
Tetrachloroethylene	4.7	0.4
Phenol	6.2	1.2
Butylbenzyl phthalate	2.1	0.4
Diethyl phthalate	0.8	0.2
Isophorone	0.3	0.1
Naphthalane	0.7	0.1
1,4 Dichlorobenzene	1.1	ND

* Pilot scale system, 4.5 day detention time, 76 cubic meter/day flow, three sets of two basins each, in parallel, plant density 0-25 kg/sq.meter (wet weight).

**ND = not detected

Source: WPCF, 1990

to provide oxygen when the plants are not undergoing photosynthesis. The water hyacinth system at the Hornsby Bend treatment facility in Austin, Texas used natural aerators consisting of large, shallow open spaces staggered along the outside edges of the ponds which allowed oxygen to diffuse into the water and then flow under the hyacinth mat. Oxygenation was supplemented during the day by attached algal growth on the gravel substrate in the aerators. The mosquito fish were also able to use these open spaces to get to more difficult to reach portions of the hyacinth mat. Also at this facility, which is enclosed in a large greenhouse, mosquito control was greatly assisted by volunteer dragonfly and damselfly populations (Doersam, 1987).

Chapter 4

Performance Expectations

4.1 Introduction

Each treatment facility will perform differently, based upon the design objectives, the macrophyte species employed, and the environmental conditions of the facility. This chapter addresses the performance levels that can be expected from different designs under field conditions.

4.2 Controlling Factors

As with any other biological process, numerous environmental factors affect the rate and efficiency of any reaction taking place. Temperature, nutrient availability, light intensity, oxygen content of the water, toxicity of the contaminants, crowding, growing time between harvests, interspecies competition and many other similar parameters are important to the performance of aquatic plant systems.

Because of the complexity of the interactions of the controlling parameters, lab- and pilot-scale facilities need to be used to evaluate the desired aquatic plant system for proper site specific operational requirements. A good example of the proper use of this process is discussed in the Iron Bridge case study in Appendix A.

4.3 Treatment Objectives

Aquatic plant systems are used to reduce biological oxygen demand, suspended solids, metals, nutrient, and other contaminant concentrations in the water. The level of treatment desired will determine the treatment scheme used. Suspended solids removal using a water hyacinth system will not require as much area or as long of a detention time as nitrogen or phosphorus removal using water hyacinth. Harvesting will be critical in a phosphorus removal process, but would not affect treatment much in a suspended solids removal process, and could even be counterproductive in a nitrogen removal system.

Aquatic plants performed as well as mechanical aerators at reducing BOD_5 in one study, and there was no appreciable difference in the removals after 10 days (Reddy *et al.*, 1989). Pennywort and water hyacinth performed the best in this study, achieving a 70 percent reduction in 5 days. In these systems, both mechanical and natural, the reduction in BOD_5 is due to microbial degradation--the comparison between the systems is primarily that of oxygen delivery to the microbes. In another study, water hyacinths removed the most NH_4^+ from a primary effluent (69.9%), but all of the large plants tested performed about the same in secondary effluent (Reddy *et al.*, 1989).

Treatment by aquatic plant systems is slower and less controlled than by conventional systems, but properly designed aquatic systems are just as reliable as conventional systems for the removal of carbonaceous BOD, suspended solids, and nitrogen compounds (Tchobanoglous, 1987). The performance of several existing or previous water hyacinth and duckweed systems is given for BOD_5 and TSS in Tables 4-1, and 4-2. The behavior of each of the systems listed in these tables depended upon the operating conditions, but they did perform as desired, and as can be seen in the tables, substantial removals of suspended solids and BOD is possible using these systems.

Table 4 - 1. Performance of Existing Water Hyacinth Systems (WPCF, 1990)

		BOD5, mg/l		TSS, mg/l			Detention
Location	Influent type	Influent	Effluent	Influent	Effluent	Depth, m	Time, d
National Space Technology lab	Raw Sewage	110	7	97	10	1.22	54
Lucedale, MS	Raw Sewage	52	23	77	6	1.73	67(b)
Orange Grove, MS(a)	Effluent from 2 Aerated Lagoons	50	14	49	15	1.83	6.8
Cedar Lake, MS	Effluent from 1 Aerated Cell	35	15	155	14	1.5	22
Austin, TX	Facultative Pond Effluent	20.2-41.9	6.6-12.0	34.2-40.0	8.8-9.1	0.7-1.3	6-9

(a) Odors at night

(b) Based on effluent flow rates.

Table 4 - 2. Performance of Existing Duckweed Facilities (EPA, 1988)

		BOD5, mg/l		TSS, mg/l			Detention
Location	Influent type	Influent	Effluent	Influent	Effluent	Depth, m	Time(b), d
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
Sleepy Eye, MN (Del Monte)	Facultative Pond Effluent	420	18	364	34	1.5	70
Wilton, AZ	Facultative Pond Effluent (a)	-	6.5	-	7.4	2.7	0.7
NSTL, MS	Facultative Pond Effluent	35.5	3	47.7	11.5	0.4	8

(a) Partially aerated.

(b) Theoretical hydraulic detention time for duckweed cell only

4.4 Primary Treatment

Primary treatment of domestic wastewater is possible using plants such as water hyacinth, water lettuce, or pennywort, as can be seen by the first two cases shown in Table 4-1, but submerged or small floating plants such as duckweed would probably not provide cost effective, efficient treatment. Filtration, sedimentation, and degradation within the root zone or water column are the major methods that primary treatment is accomplished in aquatic plant systems. Duckweed systems are capable of removing BOD, but they are not as efficient at removing suspended solids as the larger, rooted plants (Wolverton and McCaleb, 1987). Submerged plants are not used in primary treatment because they require relatively clear water for photosynthesis, and the water must have a low enough oxygen demand that it does not become anoxic during dark periods when the plants require oxygen. Primary treatment with aquatic plant systems is not permitted in Texas (Dinges and Doersam, 1986; TWC, 1992) and other states. Most likely this is because of concerns that the root system would quickly clog and cause treatment to suffer. This concern is not entirely valid, because experiments with primary treatment at the Walt Disney World wastewater facilities did not overload the treatment capacity of a water hyacinth system with organic loading rates of 440 $\frac{kg\,BOD_5}{ha \cdot d}$ (Hayes et al., 1987). Some influent limitations do exist however: concentrations of BOD_5 greater than 1000 mg/L cause growth impairment in water hyacinths, and concentrations greater than 1500 mg/L cause growth to cease (Abbasi, 1987). The author in this study was not clear about whether the impairment was due to toxicity effects from the organic chemicals or due to the plants' inability to provide enough oxygen to the roots to support the demand of the roots themselves as well as the attached microbial growth, but one of these two mechanisms is likely to be the cause.

4.5 Secondary Treatment

Secondary treatment and nutrient removal are the two most common uses of aquatic plant facilities for wastewater treatment. All of the floating aquatic plants perform well in various secondary treatment schemes, but the large-leaved varieties (water hyacinth, water lettuce, pennywort etc.) are the best at BOD (Reddy et al., 1989; Dinges and Doersam, 1986; .Tchobanoglous, 1987) and Suspended solids removal in properly designed systems. The small-leaved varieties (duckweed, water fern) are well suited to upgrading oxidation pond effluent by providing removal of suspended algae and some of the remaining BOD (Wolverton, 1987). The large-leaved varieties can also be used to upgrade this type of a system, but usually the area in the existing sedimentation pond is large enough for duckweed treatment, and the small-leaved plants are less troublesome to care for and are easier to harvest if required.

Table 4-3 shows the performance of an water hyacinth pilot facility used for secondary treatment studies by the Texas Department of Health in 1976. For performance to be consistent in any aquatic treatment system, the operating conditions need to be relatively stable in terms of influent quality and quantity (Dinges and Doersam, 1986) so equalization basins are often used if the influent fluctuates. One pair of researchers estimated that under central Florida conditions, at least 3.6 ha of pond area is required to treat 3800 m^3/d of primary effluent to

Table 4 -3. Results of a Texas Department of Health Water Hyacinth Pilot Pond System (after Neuse, 1976).

	Influent		Effluent	
Characteristic	mean	median	mean	median
BOD5	19	15	3.5	3.2
TSS	46	40	7.1	6
VSS	40	34	5.2	5
NH3	2.1	1.3	0.6	< 0.1
TON	4.3	4	1.2	1.2
PO4	15.4	14.7	10.6	11
BOD20	108	90	20	20
COD	82	70	32	40
Sol. BOD5	8.1	-	2.2	-
Sol. COD	55	-	30	-
FC/100 ml	2536	1700	98	10
Sol. TOC	15.3	-	9.8	-
Chlorophyll a	0.469	-	0.017	-

secondary standards of ≤ 30 mg/L each of BOD_5 and TSS with current technology (T. Debusk and Reddy, 1987).

4.6 Nutrient Removal and Tertiary Treatment

These two have been grouped together because regardless of whether nutrient removal is performed at the advanced secondary or tertiary level, the removal rates and behaviors are about the same. Secondary treatment levels of ≤ 10 mg/L BOD_5 and TSS can be attained without too much trouble, but tertiary treatment to remove these constituents is more difficult and requires more attention. This is because if the plant systems are not managed carefully, the plants themselves will add to the waste stream in the form of detritus, which is released and degrades in the water (Tchobanoglous, 1987).

Nutrient removal in these systems is due to plant uptake and microbial action. Nitrogen removal increases as standing crop density increases (W. DeBusk and Reddy, 1987) which indicates that the removal is microbial as suspected. The largest portion of the nitrogen compounds removed by the system are removed by microbial nitrification and denitrification, although some is also taken up by the plants (T. Debusk and Reddy, 1987; Neuse, 1976; Reed et al., 1988; Metcalf & Eddy, 1991; Dinges, 1982). For other nutrients, such as phosphorus, some precipitation or soil adsorption (if the water is exposed to soil) may occur, but the primary means of removal is by plant uptake and harvest. Phosphorus removal rates are maximum at medium plant densities (W. DeBusk and Reddy, 1987), which indicates that uptake is the primary mechanism since this is when the plants are growing the fastest. Plant uptake of nutrients can range from 16 to 75 percent of the total nitrogen removal and 12 to 73 percent of the total phosphorus removal in the system, depending upon the operational conditions (Reddy and W. Debusk, 1987). Plant uptake accounts for a larger percentage of the nitrogen removal when the system is being operated for something other than nitrification/denitrification and the hydraulic retention time is relatively short.

Plant productivity is the single most important factor in nutrient removal by uptake in high nutrient content waters with relatively constant flows. Both productivity and nutrient concentrations in plant tissues are important in wastewaters with inconsistent flows or compositions (i.e., agricultural drainage) (T. Debusk and Reddy, 1987). The biomass yield for some of the floating and submerged plants used in aquatic treatment systems is given in Table 4-4. The range of nutrient storage with various standing crops, and the resulting uptake and removal by harvesting is shown in Table 4-5.

If plants are allowed to die and remain in the water, the majority of the nitrogen and phosphorus in the tissues will return to the water within a few days. Only about one percent of the nutrients in the tissues is refractory and will remain in the benthic sludge (T. Debusk and Reddy, 1987).

Nitrogen losses in these systems is primarily due to nitrification/denitrification reactions as mentioned above. Rates of denitrification in excess of 1 g/m^2-d have been reported for floating aquatic macrophyte systems (T. Debusk and Reddy, 1987). Nitrogen removal rates range from 2.0 to 20 $\frac{kg\,N}{ha \cdot d}$. No relationship between nitrogen loading and mass removal has been established (T. Debusk and Reddy, 1987). The nitrification/denitrification process is dependent on time and temperature. Temperature controls the rate of each individual reaction, but nitrates formed in the nitrification step must diffuse or disperse out to the anoxic denitrification zones. Because the transport process is usually the rate limiting step in the reaction chain, the best way to improve nitrification/denitrification in a system where all of the other required conditions are right is to increase the contact time that the water has with the root and anaerobic zones. The only way to increase the contact time is to increase the hydraulic retention time by decreasing the hydraulic loading rate. The relationship between hydraulic loading rate and nitrogen removal can be seen in Figure 4-1. There appears to be a first order relationship between the total nitrogen removed and the hydraulic loading rate for loading rates above about 1000 $\frac{m^3}{ha \bullet d}$.

Figures 4-2 and 4-3 show the performance of various plant species during both winter and summer for nitrates and ammonium nitrogen. The plants tend to keep the pH of the water near neutral, so most of the ammonia in the water stays in the non-volatile ammonium form. Because of this, removal of ammonia requires plant uptake or nitrification. During both the summer and the winter, the denitrification process, including the diffusion/dispersion of nitrates into anoxic regions, is the limiting step. This can clearly be seen in Figures 4-2 and 4-3 by comparing the nitrate-nitrogen curves with the ammonia-nitrogen curves. The ammonia-nitrogen concentration falls steadily in each case, but the nitrate-nitrogen concentration either falls more slowly, or rises as time progresses.

Phosphorus removal performance during both summer and winter is shown for most of the same species in Figure 4-4 (Reddy and DeBusk, 1985). The area removal would also occur by microbial action, and this mechanism would probably be more important for degradable chemicals such as phenol.equired for phosphorus

Table 4 -4. Biomass yield of some floating and submersed macrophytes cultivated in central and south Florida

	Yield, g/m2-d		
Species	Medium(a)	Max	Avg. (b)
	Floating: large-leaved		
Eichhornia	N	--	24.2 (12)
crassipes	N	64.4	27.1 (10)
	A	45.9	--
	PS	41.7	--
Pistia	N	29	14.2 (7)
stratiotes	N	40	--
Hydrocotyle	N	29.7	15.9 (4)
umbellata	N	18.3	10.3 (12)
	Floating: small-leaved		
Salvinia	N	13.9	8.8 (12)
rotundifolia	PS	10	8.8 (2)
	SS	9.6	6.4 (2)
Lemna	N	12	3.8 (10)
minor	SS	8.4	4.5 (14)
Spirodela polyrhiza	N	5.9	3.4 (4)
Azolla	N	7.9	2.9 (10)
caroliniana	PS	8.2	--
	SS	6.5	--
	Submersed		
Hydrilla verticillata	N	10.4	4.2 (12)
Elodea densa	N	12.9	2.8 (10)

(a) Media: N = nutrient medium; PS = primary domestic wastewater effluent; SS = secondary effluent; A = agricultural drainage water

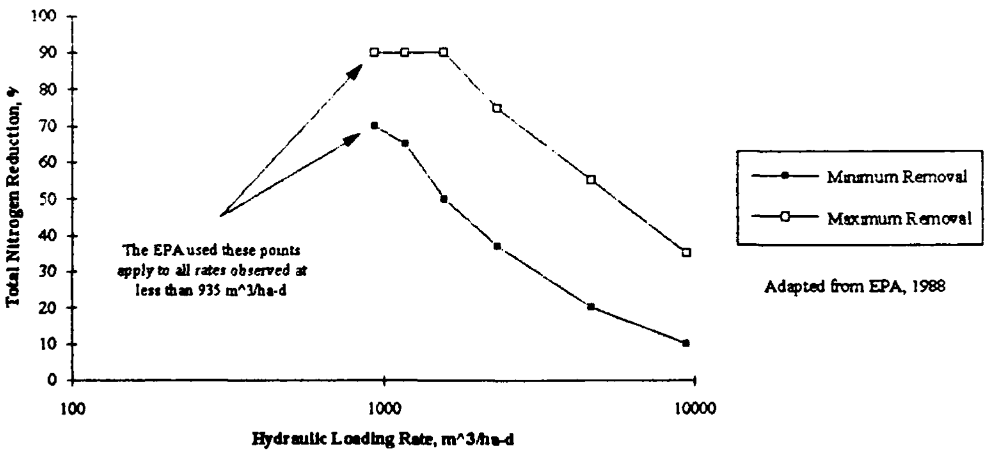
(b) Parentheses show the duration in months.

after DeBusk and Ryther, 1987

Figure 4 - 5. Standing crop storage of N and P, and rate of plant uptake for selected floating macrophytes (after Reddy and DeBusk, 1987)

	N		P	
Species	Storage (kg/ha)	Uptake (kg/ha-yr)	Storage (kg/ha)	Uptake (kg/ha-yr)
Eichhornia crassipes	300-900	1950-5850	60-180	350-1125
Pistia stratiotes	90-250	1350-5110	20-57	300-1125
Hydrocotyle umbellata	90-300	540-3200	23-75	130-770
Alternathera philoxeroides	240-425	1400-4500	30-53	175-570
Lemna minor	4-50	350-1200	1-16	116-400
Salvinia rotundifolia	15-90.	350-1700	4-24	92-450

Figure 4 -1 Nitrogen Removal from Water Hyacinth Tertiary Treatment



The EPA used these points apply to all rates observed at less than 935 m^3/ha-d

Adapted from EPA, 1988

removal is high compared to that required for oxidation or nitrogen removal. DeBusk and Reddy (1987) estimated that it would take 13 ha to treat 3800 m^3/d of wastewater from a concentration of 10 mg/L to 1 mg/L.

Some of the more aggressive submerged species work relatively well in nutrient removal and tertiary treatment systems. *Elodea nuttallii*, *Elodea canadensis*, and *Egeria densa* have shown potential for nutrient removal systems in temperate climates. The total nitrogen content of *E. nuttallii* was measured in one study to be as much as 73 mg/g dry plant, and a total phosphorus content of as much as 23 mg/g dry plant (Eighmy et al., 1987). Plant uptake and harvest in this system removed 40 to 60 percent of the applied nitrogen and 30 to 50 percent of the applied phosphorus.

Tertiary treatment requiring metals removal is also possible with aquatic plant systems. Some of the plants are able to bioconcentrate metals such as cadmium and lead to concentrations as high as 1000 times the ambient concentration (Wills and Pierson, 1987). One researcher estimates that at an optimum growth rate of 60 $\frac{g(dry)}{m^2 \bullet d}$, 1 hectare of water hyacinths could remove 300 g of combined nickel and cadmium per day (Wolverton, 1975).

The rate of metals absorption in the rooted plants appears to be directly related to the root mass (Heaton et al., 1987), and the amount absorption is also proportional to the concentration of metal ions in the wastewater. The majority of the metal ions found in sampled water hyacinths were in the roots (Tokunga et al., 1976). High concentrations of some metal ions such as cadmium, copper, and ferric iron (Fe^{+2}) can be toxic to the plants as the ions build in concentration within the plant tissues over time. Some of these ions may also prevent the plants from

Figure 4-2. Nitrogen Removal by Large-leaved Aquatic Plants
(after Reddy and W. DeBusk, 1985)

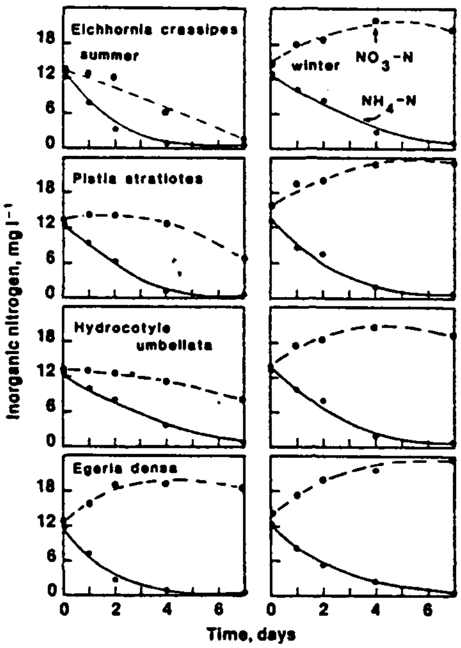


Figure 4-3. Nitrogen Removal by Small-leaved Aquatic Plants
(after Reddy and W. DeBusk, 1985)

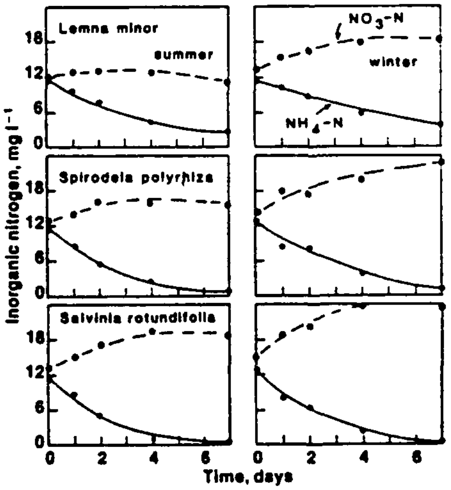
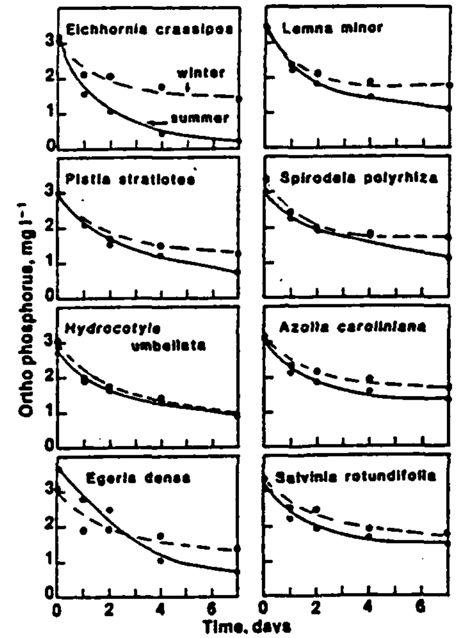


Figure 4-4. Phosphorus Removal by Aquatic Macrophytes
(after Reddy and W. DeBusk, 1985)



neutralizing the water (Wills and Pierson, 1987; Jamil et al., 1987; Dierburg et al., 1987).

There appear to be a limited number of charged adsorption sites on the roots which capture ions quickly and then more slowly translocate them into the plant tissue (Heaton et al., 1987; Wills and Pierson, 1987). This is in part demonstrated by the change in removal rate of metals with time. Initially, the rate is rapid, and appears to be diffusion limited (stirring improves this phase). After the initial rapid removal (about 4 h), a more gradual removal phase begins and lasts much longer (> 24 h). The slower phase appears to be limited by the rate at which the plant assimilates the ions into its tissues (Heaton et al., 1987). Figure 4-5 shows the removal response curves for water hyacinths and lead at various concentrations, and Figure 4-6 shows the effects of stirring on the initial adsorption phase.

Aquatic plants are also capable of removing pesticides, phenols, organic acids and other organic contaminants from the wastewater. Pesticide removal in these systems is no better than in algal systems (Abbasi, 1987). There is no great advantage to using an aquatic plant system to remove these chemicals since the algal system is less complicated.

Water hyacinth has been mentioned above as being capable of degrading phenols in its roots. Duckweed can remove phenols as well; Templet and Valez found that an average of 107 $\frac{\mu g}{h \cdot g(\text{duckweed})}$ of phenol was removed for the first 48 hours, and the removal rate for chlorophenol averaged 33 $\frac{\mu g}{d \cdot g(\text{duckweed})}$ at the sixth day. Although this experiment tested removal by the plants alone in a microbe-free environment, removal would also occur by microbial action in a real system, and this mechanism would probably be more important for degradable chemicals.

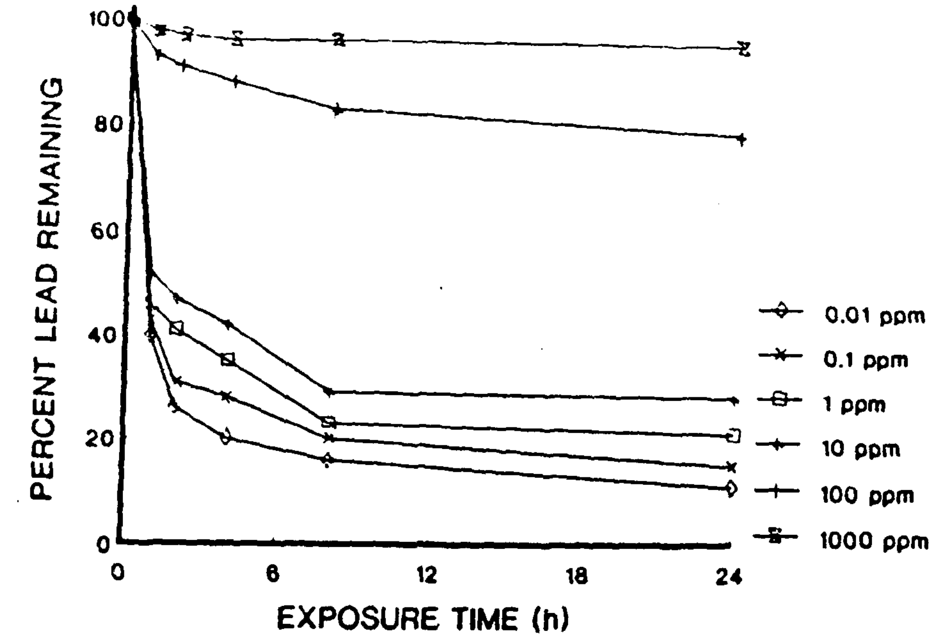


Figure 4-6. Water hyacinth lead uptake at various concentrations (Heaton *et al.*, 1987)

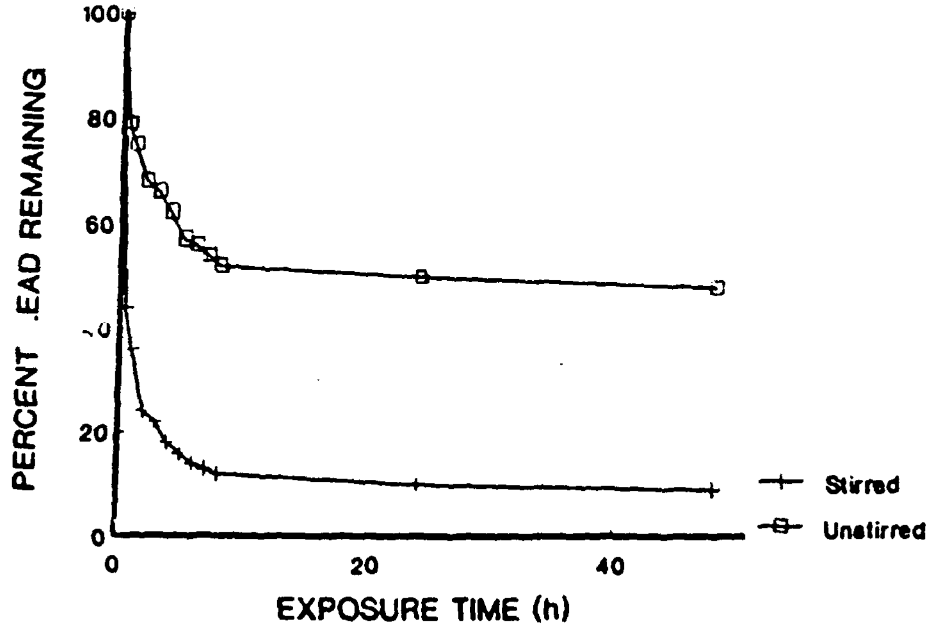


Figure 4-7. Effect of stirring on lead uptake (Heaton *et al.*, 1987)

Chapter 5

Design Criteria

5.1 General

There have been two schools of thought dealing with aquatic plant treatment system design. One stated that the design should be based only upon the plant uptake, and the other insisted that designs be based upon expected removals by sinks other than the plants (Stewart et al., 1987; Tchobanoglous, 1987). Each viewpoint is valid under certain operating conditions, but in most cases a combination of mechanisms is causing the removals. When nitrogen removal is being maximized, the majority of the removal is by processes other than plant uptake, so ignoring uptake yields a conservative approximation that is still near the achievable removal rates. Phosphorus removal in a lined tank is an example of the other extreme--the largest percentage of the removal is due to plant uptake, and ignoring the other mechanisms yields a safety factor of about 2 in the design. The most recent publications from the Water Pollution Control Federation (1990) and the Environmental Protection Agency (1988) use a more balanced approach for design and consider all removal mechanisms to the extent that they can be predicted.

Systems using water hyacinths represent the majority of the aquatic plant treatment facilities that have been built to date. Four variations of water hyacinth treatment facilities are listed in Table 5-1 with some of the advantages and disadvantages of choosing each one. Land usage is a critical factor in aquatic treatment systems. Some of the designs with higher loading rates are more desirable in terms of land use, but these also have shortcomings such as odor problems or extra energy costs which may make them less desirable. Facultative/anaerobic hyacinth ponds are generally not used any longer because satisfactory results can be achieved under aerobic conditions with loadings as high as 100 kg/ha-d (EPA, 1988).

Design for water hyacinth systems has been studied thoroughly enough that recommended ranges of the critical design parameters have been published and used with confidence. Table 5-2 gives the recommended parameter values for three common water hyacinth treatment schemes. Duckweed systems are becoming more popular as upgrades to stabilization pond systems, but this group of plants has not been investigated as completely as the water hyacinth. Table 5-3 lists the recommended design parameter values for an effluent polishing system using duckweed.

Current design practices for duckweed and water fern systems use normal facultative pond design equations to determine area required and the retention time necessary for the desired removal (WPCF, 1990). This approach is conservative because duckweed systems perform consistently better than facultative ponds, but no better approach has been accepted yet.

Water hyacinth systems can be split into three categories based upon the amount of dissolved oxygen in the system and the method of aeration. These three categories are the types listed in Table 5-1 and discussed below.

Aerobic hyacinth systems without supplemental aeration are the most common type of facility among the systems already constructed (EPA, 1988).

These systems are capable of attaining secondary treatment or nitrogen removal depending upon the organic loading rate and the hydraulic detention time. They have the advantage of few mosquitos or odors. Mosquito control measures are still necessary, but the fish used can get to the mosquitos more easily since the entire water column is aerobic.

In cases where no mosquitos or odors are permissible, an aerobic hyacinth system with supplemental aeration will be used. This type of system has the advantage of being capable of accepting a larger organic load because of the aeration. This means that a smaller amount of land is required. The negative side of the system is that additional power is required, and potentially larger quantities of plants will have to be harvested.

The third type of hyacinth treatment facilities is operated under high organic loading rates with little or no supplemental aeration. Facultative/anaerobic systems, as they are called, have a high potential for odor and mosquito problems but they require less land. The surface layer of water in the system will probably remain aerobic during the day because of oxygen transport through the plants' roots, but some aeration may be required at night to control odors. Mosquito fish and other natural mosquito control organisms cannot be used in these systems unless there is a substantial surface layer of aerobic water.

Organic loading rates in water hyacinth systems have been used successfully in the range of 10 to 440 kg BOD_5/ha-d (9 to 400 lb BOD_5/ac-d), although odor problems occurred at the highest loading rates. In systems without aeration, the average BOD_5 loading rate should not exceed 100 kg/ha-d (89 lb/ac-d) to ensure

Table 5-1. Types of Water Hyacinth Systems (after EPA, 1988; WPCF, 1990)

Type	Purpose	Typical BOD5 Loading, kg/ha-d	Advantages	Disadvantages
Aerobic Non-aerated	Secondary Treatment	40-80	Limited mosquitos; limited odors	More land area required; harvesting may be more difficult depending on pond configuration.
Aerobic Non-aerated	Nutrient Removal	10-40	Limited mosquitos; limited odors	More land area required; harvesting may be more difficult depending 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

* Only suitable where odors and mosquitos may not be a problem

Table 5-2. Design Criteria for Water Hyacinth Systems (after EPA, 1988; WPCF, 1990)

	Type of Water Hyacinth System		
Factor	Aerobic Non-aerated	Aerobic Non-aerated	Aerobic Aerated
Influent Wastewater	Screened or Settled	Secondary	Screened or Settled
Influent BOD5, mg/l	130-180	30	130-180
BOD5 Loading, kg/ha-d	40-80	10-40	150-300
Expected Effluent, mg/l			
BOD5	< 30	< 10	< 15
SS	< 30	< 10	< 15
TN	< 15	< 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
Hydraulic Loading, m^3/ha-	> 200	< 800	550-1000
Harvest Schedule	Annually	Twice per Month	Monthly

Table 5-3. Design Criteria for Effluent Polishing with Duckweed Treatment Systems
(after EPA, 1988; WPCF, 1990)

Factor	Secondary Treatment
Wastewater Input	Facultative Pond Effluent
BOD5 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, C	> 7
Harvest Schedule	Monthly

aerobic conditions (EPA, 1988). Typical organic loading rates for several different system configurations are included in Table 5-4.

The hydraulic loading rates for domestic wastewater applied to water hyacinth systems have varied from 240 to 3,570 m^3/ha-d (25,650 to 381,650 gpd/ac). For secondary treatment, the hydraulic loading rate is usually between 200 and 600 m^3/ha-d (21,600 to 64,600 gpd/ac). Rates as high as 1000 m^3/ha-d (107,000 gpd/ac) have been used successfully when performing advanced secondary treatment with supplemental aeration (EPA, 1988). Organic loading rates will usually control the hydraulic loading rate. Figure 5-1 shows the relationship between organic loading (pretreatment level), temperature, and hydraulic detention time (affected by hydraulic loading).

The depth of an aquatic plant treatment lagoon is not critical if the objective is solids removal, but for most other processes a shallow depth is preferred to allow the bulk of the water to have contact with the plants and the root zone. The majority of investigators recommend a depth of no more than 0.9 m (3 ft) when using water hyacinth. Greater depths can perform well if there is sufficient turbulence to still give the bulk of the water exposure to the plants. Figure 5-2 shows the relationship between turbulence, depth, and total oxygen demand. A larger depth may be recommended for the final cell because hyacinth roots grow longer when there are few nutrients in the water (Dinges, 1982; EPA, 1988).

5.2 Physical Features of Aquatic Plant Systems

Early investigators into aquatic plant treatment of wastewater used long, narrow, rectangular channels to prevent short circuiting and approximate plug flow. Narrow channels are not truly required as long as the influent and effluent are distributed and collected across the width of the channel (Dinges, 1982). Narrow channels with aspect ratios of ten or more are still being used because the distribution and collection systems are easier to fabricate, and harvesting can be performed from the side more easily when the channel is narrow. Figure 5-3 shows some of the configurations that are possible in aquatic plant systems. The horseshoe shaped channel was devised because it requires less piping for recirculation and step feeding the influent (EPA, 1988).

5.3 Design Equations

BOD_5 removal kinetics are generally assumed to be a first order reaction. The steady state mass balance on the first reactor in a series of four is (see Figure 5-4):

accumulation = mass in - mass out - degradation

$$0 = Q_r(C_4) + 0.25Q(C_o) - (Q_r + 0.25Q)C_1 - k_T C_1 V_1$$

Where,

Q_r = recycle flow, m^3/d

C_4 = BOD_5 concentration in the effluent from reactor 4, mg/L

$0.25Q$ = inflow to each individual cell, m^3/d

C_o = BOD_5 concentration in the influent, mg/L

C_1 = BOD_5 concentration in effluent from reactor 1, mg/L

k_T = First order reaction rate constant at temperature, T, d^{-1}

V_1 = Volume of the first reactor, m^3

The value of k_T estimated for 20 °C (68 °F) is 1.95 d^{-1}. A modified Arrhenius relationship applies with a Θ of about 1.06 (EPA, 1988).

Table 5-4. Typical Organic Loading Rates for Secondary Treatment in Aquatic Systems (after Tchobanoglous, 1987)

Treatment System	Figure Reference	Value, kg CBOD5/ha-d	
		Range	Typical*
Semiplug-flow reactor without recycle	5 - 3b	50-200	60**
Plug-flow reactor without recycle	5 - 3c	50-200	60**
Plug-flow reactor with recycle	5 - 3d	50-200	60**
Semiplug-flow reactor with step-feed and 2:1	5 - 3f	100-200	150
As above with supplemental aeration	5 - 3f'	150-300	200
Semiplug-flow variable geometry reactor without recycle	5 - 3g	50-200	80***

* Typical loading values based on an odor free system. Higher loading rates can be used if odors and mosquitos are not an environmental issue

** Limited by influent distribution.

*** With experience, a higher rate may be feasible.

Figure 5-1. Effect of Temperature and Pretreatment on the Required DetentionTime for a Typical Aquatic Treatment System (adapted from Tchobanoglous, 1987)

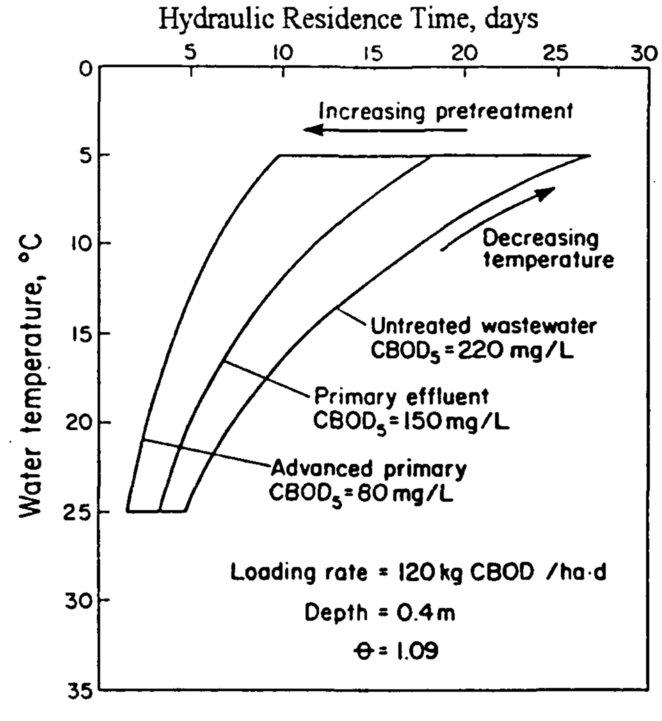


Figure 5-2. Effects of Turbulence and Depth on Total Oxygen Demand Reduction Rates (after Tchobanoglous, 1987)

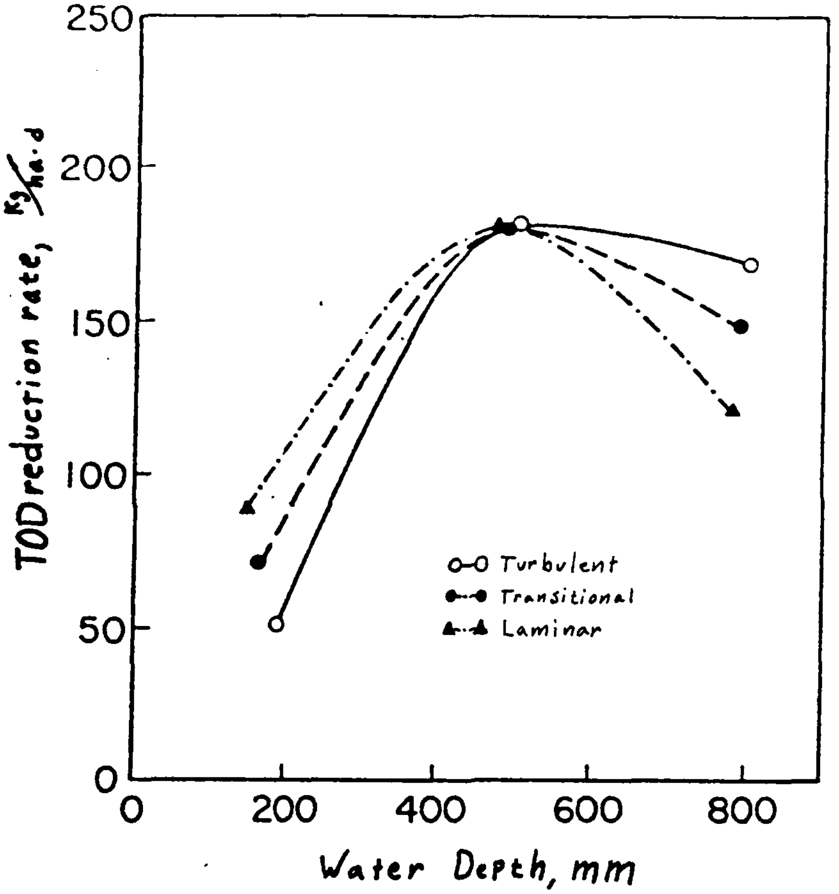
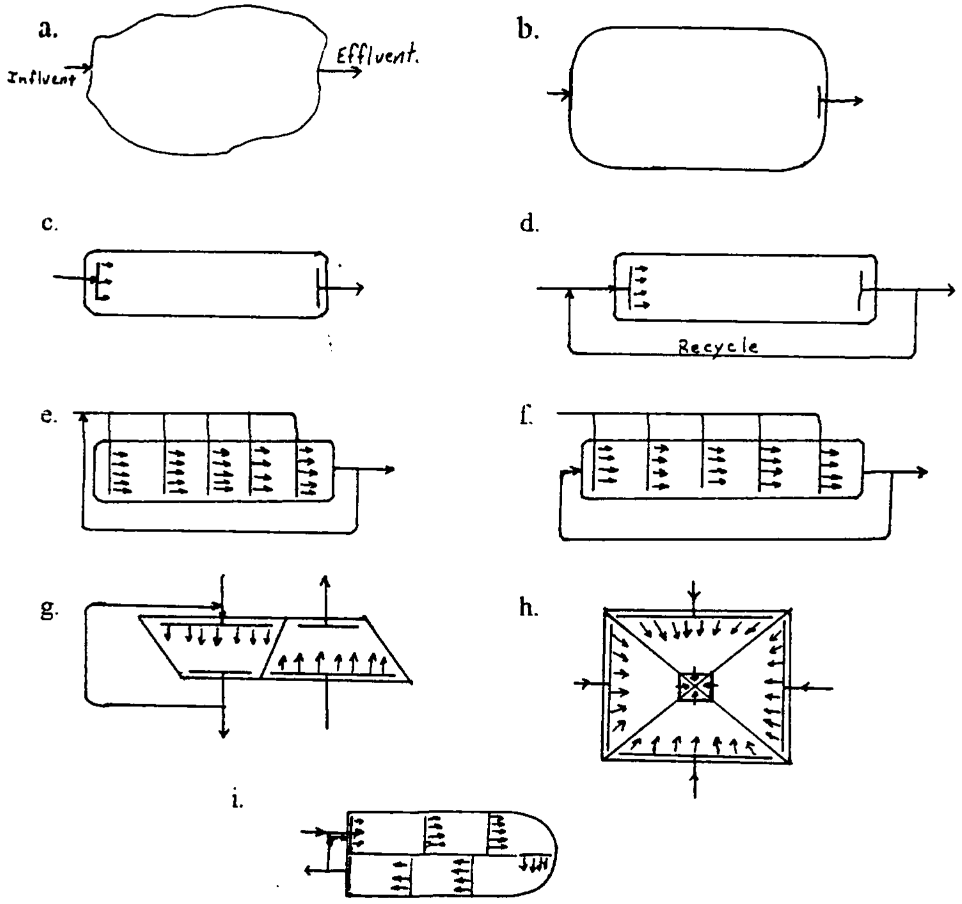


Figure 5-3. Possible System Configurations for Aquatic Treatment Components. (after Tchobanoglous, 1987; EPA, 1988)



a) arbitrary flow, b) semi plug-flow, c) plug-flow, d) plug-flow with recycle, e) semi plug-flow with step feed and recycle type 1, f) semi plug-flow with step feed and recycle type 2, g) variable geometry semi plug-flow with (and without) recycle type 1, h) variable geometry semi plug-flow without recycle, i) folded semi-plug flow with step feed and recycle type 2.

Figure 5-4. Model of a Step-feed Channel with Recycle

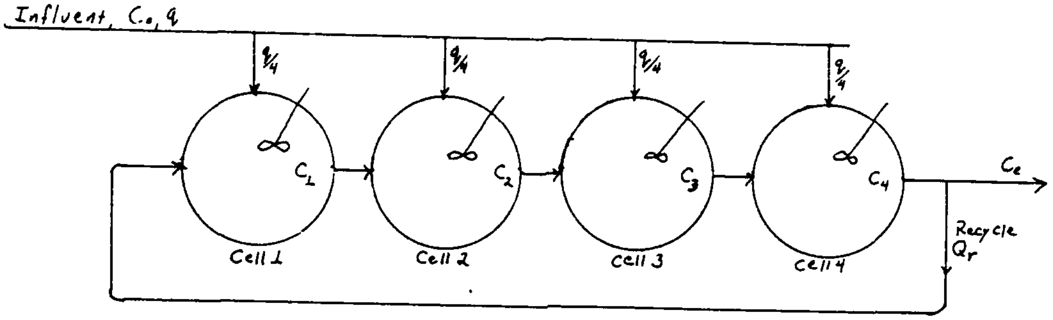


Table 5-5. Nitrogen Removal Rate Constants for Water Hyacinth and Duckweeds

(Reed et al., 1988; WPCF, 1990)

Plant	Season	Plant density kg/ha (dry)	Rate Constant (k) days^{-1}
Water Hyacinth	Summer (27° C)	3,920	0.218
		10,230	0.491
		20,240	0.590
	Winter (14° C)	4,190	0.033
		6,690	0.023
		20,210	0.184
Duckweed	Summer (27° C)	73	0.074
		131	0.011
	Winter (14° C)	40	0.028
		67	0.012

Nitrogen removal rates are a function of plant density and temperature. Until crowding or thermal stress begins, the higher the density and temperature, the larger the nitrogen removal rate. Table 5-5 provides the estimated nitrogen removal rate constants for winter and summer conditions in both duckweed and water hyacinth systems.

5.4 Sample Design Problems

Two sample problems are provided below. The first is not a complete design, but compares the performance of two different influent application methods--single application point plug-flow and step-feed semi plug-flow. The second example problem goes through most of the steps of designing a floating aquatic plant system to meet specific influent and effluent requirements.

5.4.1 Comparison of a Plug-flow and Step-feed Channel

Neuse (1976) recommended a plug-flow water hyacinth channel for TSS and BOD_5 removal, but he observed that biomass formation on the roots supported other investigator's conclusions that the majority of TSS removal was occurring in the first ten to fifteen percent of the channel length (Neuse, 1976; Tchobanoglous, 1987). Tchobanoglous observed that the actual removal in a similar channel was much more rapid than predicted by a first order model, and step feeding the influent had potential of decreasing the overload which often occurred at the inlet and increasing the removal efficiency.

The following is a comparison of the performance of a single channel with and without step feed. The plug-flow channel example is taken from Neuse (1976) and the step feed semi plug-flow channel was created by the author of this report using the same operational parameters for comparison of the two designs. Both channels considered are 4 feet by 50 feet with a total influent flow of 8 gpm and an influent concentration, C_O, of 100 mg/L TSS. From the relationship Neuse derived for flow and removals, this channel would achieve a 50 percent reduction in TSS (see Figure 5-5). The second channel was set up as shown in Figure 5-3f except that there was no recycle. Five step feed stations were used, one at the head of the channel, and one every ten feet downstream, with the influent split evenly among them. Assuming that 90 percent of the total removal occurred in the first five feet, and that the next five feet will remove 90 percent of the remainder, 99 percent of the expected removal for the 50 ft length will occur in the first ten feet.

q_1 = the fraction of influent fed into cell 1 = $\frac{8\text{ gpm}}{5}$ = 1.6 gpm

This flow rate corresponds to a 92% removal in 50 feet.

so, removal in 10 feet = 99% * 92% = 91.1%

$q_2 = 2 * q_1 = 3.2$ gpm. Removal = 99%*75% = 74.3%

$q_3 = 3 * q_1 = 4.8$ gpm. Removal = 99%*62% = 61.4%

$q_4 = 4 * q_1 = 6.4$ gpm. Removal = 99%*57% = 56.4%

$q_5 = 5 * q_1 = 8.0$ gpm. Removal = 99%*50% = 49.5%

C_{1e} = effluent concentration from cell 1 = (1-0.911)100 mg/L = 8.9 mg/L

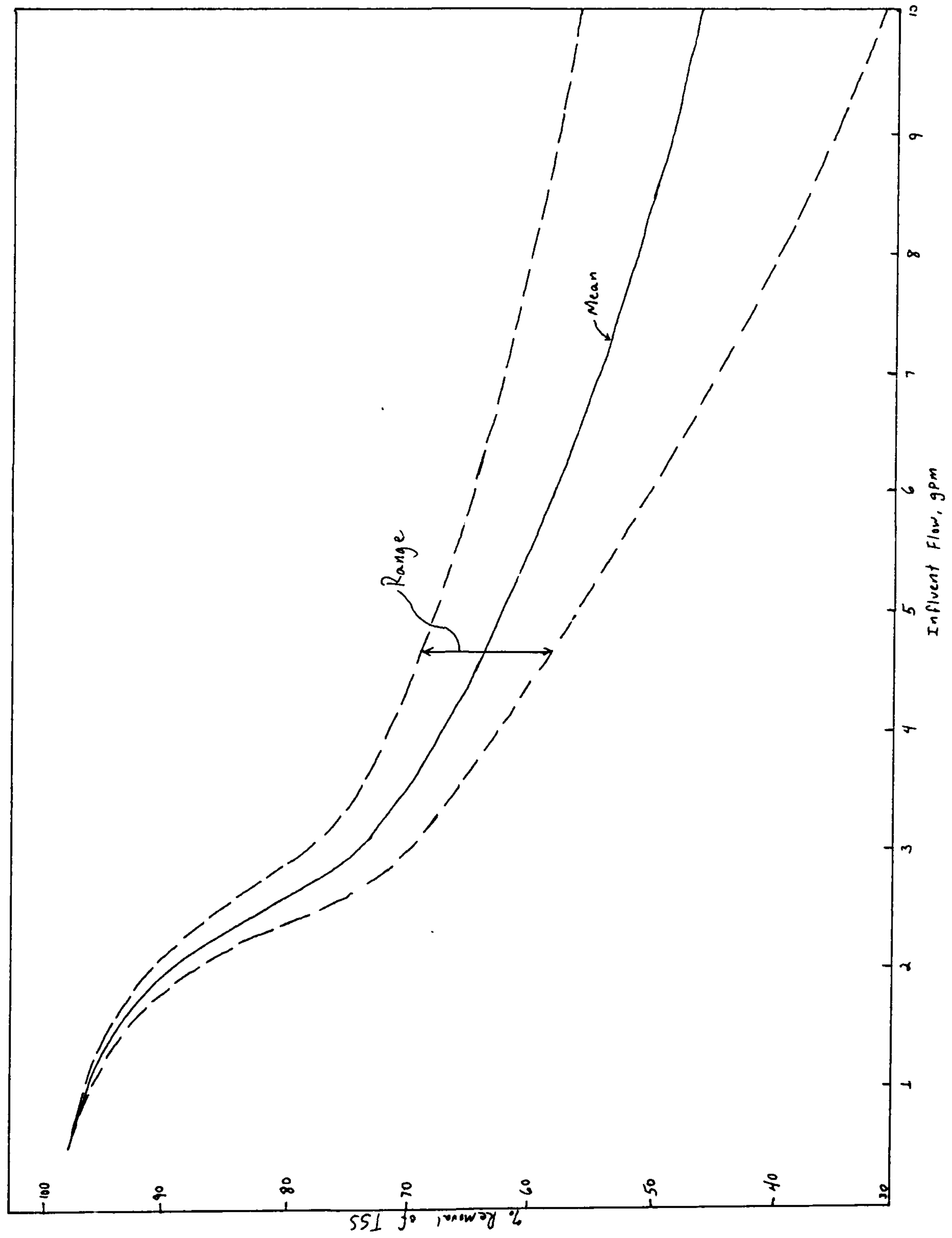
$C_2 = \frac{C_{1e}+C_o}{2}$ = 54.5 mg/L $\qquad C_{2e}$ = (1-0.743)54.5 = 14.0 mg/L

$C_3 = \frac{2C_{2e}+C_o}{3}$ = 42.7 mg/L $\qquad C_{3e}$ = (1-0.614)42.7 = 16.5 mg/L

$C_4 = \frac{3C_{3e}+C_o}{4}$ = 37.4 mg/L $\qquad C_{4e}$ = (1-0.564)37.4 = 16.3 mg/L

$C_5 = \frac{4C_{4e}+C_o}{5}$ = 33.0 mg/L $\qquad C_e$ = (1-0.495)33.0 = 16.7 mg/L

Figure 5-5. Removal of TSS versus Hydraulic Loading Rate (after Neuse, 1976)



The final effluent from the step feed channel would be 16.7 mg/L TSS, while the effluent from the plug flow channel was 50 mg/L TSS. Adding a recycle line to the head of the channel would improve the effluent even more due to the initial dilution. A recycle ratio of 2:1 overall would provide a recycle ratio in the first cell of 10:1, and would increase to 14:1 by the final cell.

5.4.2 System Design Problem (adapted from EPA, 1988)

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

Design flow rate = 700 m^3/d

BOD_5 = 200 mg/L

SS = 300 mg/L

TN = 15 mg/L

TP = 10 mg/L

Critical winter temperature > 20 °C.

Effluent Requirements: BOD_5, SS < 30 mg/L.

Solution:

1. Determine BOD_5 loading:

   $(200\ mg/L)(700\ m^3/d)(10^3\ l/m^3)(1kg/10^6\ mg) = 140\ kg/d$

2. Determine basin surface areas required based upon criteria in Table 5-2:

   50 kg/ha-d BOD_5 for the entire area

   100 kg/ha-d BOD_5 for the first cell

   Total area required = (140 kg/d)/(50 kg/ha-d) = 2.8 ha

   Area of primary cells = (140)/(100) = 1.4 ha

3. Use two primary cells, each 0.7 ha. Use L:W = 4:1, since aspect ratios of 3:1 or greater are desired. Dimensions at the water surface will be:

$0.7 \text{ ha} = L*W = L * L/4 = L^2/4$

$0.7 \text{ ha } (10.000 \text{ m}^2/\text{ha})(4) = L^2 = 28.000 \text{ m}^2$

$L = 167 \text{ m}$

$W = 42 \text{ m}$

4. Divide the remaining area into two sets of two basins, 0.35 ha each.

$0.35 \text{ ha } (10.000\text{m}^2/\text{ha})(4) = L^2 = 14.000 \text{ m}^2$

$L = 118 \text{ m}$

$W = 30 \text{ m}$

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 side slopes, and use the equation below for the approximate volume.

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

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 (for 3:1 slope s = 3)

d = depth of pond, m

Primary cells: $V = [167*42 + (167-7.2)(42-7.2) + 4(167-2.4)(42-2.4)]*1.2/6$

$V = 7,730 \text{ m}^3$

Final cells: $V = [118*30 + (118-7.2)(30-7.2) + 4(118-2.4)(30-2.4)]*1.2/6$

$V = 3,766 \text{ m}^3$

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

Primary cells: $t = 2(7730\ m^3)/700\ m^3/d = 22$ days

Final cells: $t = 2(3766\ m^3)/700\ m^3/d = 11$ days

Total detention time = 33 days (within the acceptable zone)

7. Check hydraulic loading:

$(700\ m^3/d)/(2.8\ ha) = 250\ m^3/ha\text{-}d$ (> 200 so it is ok)

8. Estimate nitrogen removal with Figure 4-1 or Table 5-5 to be sure that enough nitrogen is present to sustain growth in the final cells and to determine harvest frequency.

At a hydraulic loading of less than 935 m^3/ha-d, removal is essentially 90 percent. This will leave about 1.5 mg/L of nitrogen in the final effluent, which is well below the desired 5 mg/L for plant growth. Growth in the final cells will not be at optimum and may even need supplemental nitrogen. An annual harvest would probably be sufficient.

5.5 Costs

Aquatic plant systems can be relatively inexpensive to install as an upgrade to an existing pond, but new facilities require large sections of land (Debusk and Reddy, 1987). This technology is best suited to areas that have warm weather and plenty of open space. It can still be competitive in price if proper planning is done ahead of time (Crites and Mingee, 1987). Table 5-6 gives a cost comparison of various treatment systems with that of a water hyacinth system.

These figures show that construction and operation of an aquatic plant system can be competitive with other designs. This particular set of examples perhaps overinflates the financial benefits of using aquatic plant systems because the Iron Bridge facility is a high volume, short detention time facility for effluent polishing. Construction and operating costs for aquatic plant systems are generally comparable to those of other natural treatment systems such as constructed wetlands or land treatment. Land requirements are the controlling factor in construction costs for these systems, and harvest expenses tend to control operational costs. Phosphorus removal with aquatic plant systems requires a lot of land, and regular harvests, so this treatment scheme tends to be less competitive, and sometimes more expensive, than conventional methods (EPA, 1978). Conventional systems require much less land, but the facilities are more complex and may still cost more than a natural system for a small community (EPA, 1978; Dinges, 1982).

Table 5-6. Comparison of Costs of Various Treatment Systems
(after Crites and Mingee, 1987)

Location	System type	Design flow m^3/d	Area ha	Construction costs $ millions	Unit cost $/m^3-d
Cannon Beach, OR	Existing Wetland	3,440	6.5	0.58	170
Gustine, CA	Created Marsh	3,785	10	0.88	230
Incline Village, NV	Created and Existing Wetland	8,100	49	3.3	410
Iron Bridge Plant, Orlando, FL	Water Hyacinth System	30,280	12	3.3	110
Typical Secondary	Activated Sludge	3,785	--	3-3.8	800-1000

Chapter 6

Operational Requirements

6.1 Introduction

Even if a treatment facility is designed and constructed properly, it will not meet its discharge goals if it is not operated correctly. This chapter will touch on harvesting, crop maintenance, pest control, cleanout requirements, and residual management. As will be seen below, all of these topics overlap and cannot be truly separated, but each will be discussed separately with due mention to the ways that it ties in to the other topics.

6.2 Harvesting

The requirement for harvesting in an aquatic plant treatment facility is one of the largest operating expenses (Doersam, 1987). Even the design of the channels is partially driven by harvesting requirements. As mentioned previously, there is no true requirement that the cells be long and narrow as long as adequate measures are taken to prevent short circuiting. If the channels are narrow, however, harvesting can take place from the shore. There are harvesting methods using boats and barges, but these are more cumbersome and expensive for the most part (Reed *et al.*, 1988). Duckweed and water fern systems are relatively easy to harvest from the water or the land because they are separate small plants and do not tend to intertwine to any great extent. The large-leaved varieties are a different story because each plant tends to be interwoven with other plants.

Harvesting requires the removal of a large bulk of material. Since most aquatic plants are about 95 percent water, when an annual yield of 212 dry mt/ha is reported (Lakshman, 1987), that means that about 4,240 mt of fresh plants were harvested for every hectare of pond surface area. This does represent the maximum observed value, but yields of one third to half the mass were relatively common and would still be formidable to handle. Most of the plants used in aquatic treatment systems must be at least partially dried before anything else can be done with them (Doersam, 1976; Dinges, 1988; Reed *et al.*, 1988). The labor and equipment costs for handling this much mass is what causes harvesting to be the leading operational expense in a system without extensive pumping and aeration.

Not harvesting at all may seem tempting if the treatment method allows it, but even for solids removal, some harvesting is required to maintain the standing crop viability (Stewart *et al.*, 1987). Selective harvesting can be used to help control pest populations or plant diseases. Mosquito control also depends to some extent on harvesting, especially if natural control methods are being used. The open areas left after harvest allow the mosquito fish more easy access into the previously isolated pockets of water where mosquitos could breed without interference.

In systems being operated for nutrient removal (other than nitrogen), harvest is essential to the permanent removal of the nutrients. If plants are allowed to die and decay within the water, almost all of the nutrients in the plant tissues will return to the water (DeBusk and Reddy, 1987). Harvest frequency also has an effect on nutrient removal. Phosphorus removal is better in systems which are harvested frequently to maintain the standing crop in a rapid growth stage. Since nitrogen is removed primarily by microbial action, frequent harvesting impairs the removal since it does not fully allow biomass to form on the roots of the plants. Several studies in Florida showed that unharvested systems had nitrogen removal rates two to three times higher than frequently harvested systems (Reed *et al.*, 1988). The frequency of harvest may also affect metals removal in water hyacinth systems. Approximately 97 percent of the metals found in conjunction with tested water hyacinths was in the roots, which only make up 18 percent of the dry plant mass (Neuse, 1976). Mature hyacinths tend to shed roots as the roots get old (Dinges, 1982). If hyacinths are allowed to go too long between harvests, adsorbed metals will be shed along with the roots. The metals may complex with the organics in the benthic sludge rather than return to solution, but removal would have been more certain if the plants were harvested before the roots began shedding.

The amount and method of harvest also has an impact on the performance of the system. Leaving a clean edge on a water hyacinth mat when harvesting will produce slow regrowth, while a ragged edge or small clumps remaining will regrow much faster (Bagnall *et al.*, 1987). Also, if more than about twenty percent of the standing crop is harvested, the open spaces may allow enough sunlight to penetrate the water to cause significant algal growth and confound the system's attempts to remove solids.

6.3 Crop Maintenance

For the best system performance, the standing crop needs to be kept healthy and at the desired density and growth rate. Harvesting is used to maintain the density and combat small outbreaks of pest infestations, but much more than that is required for the plants to remain healthy and perform as desired. Nutrients must be provided if any are lacking. In several series-flow systems, the plants in the final pond experienced chlorosis because all of the iron was being taken out of the water before it got to the last cell. Ferrous sulfate was added to the pond regularly after this was discovered to maintain the iron concentration above 0.3 mg/L (Reed *et al.*, 1988). The Iron Bridge wastewater facility experienced serious plant growth impairment due to a deficiency in molybdenum, which is only required in trace quantities (EPA, 1988). The Iron Bridge case is discussed in more detail in Appendix A. The pH of the wastewater must also be in the acceptable range for the plants or it will have to be neutralized before application to the aquatic plant facility. Table 6-1 indicates some of the survival requirements for various aquatic plants used for water treatment, as well as where the plants can be found in the United States.

6.4 Pest Control

Duckweed and water fern have very few natural pests, but several pests of water hyacinth have been introduced to this country for the purpose of hyacinth control. Two species of hyacinth weevils (*Neochetina eichhorniae* Warner and *Neochetina bruchi* Hustache) and a leaf mining mite (*Orthogalumna terebrantis* Wallwork) are probably the most serious hyacinth pests (Dinges, 1982). The weevils appear to be most active when the plants are under density stress, and a species of moth (*Sameodes allijuttales*), the caterpillar of which also feeds on hyacinth is most likely to be a problem in hot, dry weather (Reed *et al.*, 1988). Harvesting patches of plants with minor pest infestations may be a successful means of removing them, but when serious infestations occur, pesticide spraying will probably be required. Larger pests, such as turtles, coots, and nutria are more difficult to control, but they do not normally present as much of a threat to the system (Dinges, 1982). The Austin, Texas, Hornsby Bend Hyacinth Facility was able to keep the larger animals out of the greenhouse facility by erecting portable barriers across any open doorways (EPA, 1988). Unenclosed facilities will probably not be able to prevent the entrance of pests, but will have to deal with them as they arrive.

6.4 Cleanout Requirements

The frequency that sludge cleanout is required will depend upon the pretreatment that the wastewater receives before it arrives at the aquatic plant system, and the frequency of harvest. Some states, such as Texas, require annual draining and cleaning of a water hyacinth facility (TWC, 1991), but this is not necessary for many treatment schemes. Cells which are harvested frequently will not require cleaning as often as those that are not, and systems with large influent concentrations of suspended solids will require annual cleaning. Table 6-2 lists the recommended sludge cleanout frequency for water hyacinth ponds under various conditions.

Table 6-1. Floating Aquatic Plants for Wastewater Treatment
(after Reed et al., 1988)

Common name, *Scientific name*	Distribution	Temperature, C		Maximum salinity tolerance, mg/l	Optimum pH
		Desirable	Survival		
Water Hyacinth		20-30	10	800	5-7
Eichhornia crassipes	Southern U.S.				
Water Fern		> 10	5	2500	3.5-7
Azolla caroliniana	Throughout U.S.				
Azolla filiculoides	Throughout U.S.				
Duckweed		20-30	5	3500	5-7
Spirodela polyrhiza	Throughout U.S.				
Lemna trisulca	Northern U.S.				
Lemna obscura	Eastern and Southern U.S.				
Lemna minor	Throughout U.S.				
Lemna gibba	Great Plains and western U.S.				
Wolffia spp.	Throughout U.S.				

Shed roots in the benthic sludge may actually exceed the quantity of solids from the wastewater treated if the hyacinths were not harvested regularly. Once the plant density on the water surface exceeds about 25 kg/m^2 (5 lb/ft^2) wet weight, sloughing of root material begins and within a few months the mass of the accumulated detritus will exceed the mass of settled wastewater solids (Reed *et al.*, 1988).

6.5 Residual Management

Regardless of the type of treatment being performed, there will be residues which must be dealt with, whether they are harvested plants or benthic sludges. Numerous potential uses have been investigated for water hyacinth, and to a lesser extent for duckweeds, but none of them has been clearly the best choice. Dried and composted, both duckweed and water hyacinth can be used as a soil additive. Duckweed can also be used for this purpose without drying or composting because it is manageable as it is (Dinges, 1982). Paper has been made from dried water hyacinth, but it is not practical because the hyacinth fibers do not drain well. Compost made from water hyacinth has the ability to retain water in the soil, and as such it may be an ideal additive to sandy soils that drain too freely for crop use.

Large facilities may have enough crop production to sustain the operation of an anaerobic digester to produce methane gas from the hyacinth and the sludge. If digestion is going to be used, the plants do not have to be dried. They can be chopped up and pumped as a slurry directly into the digester. The methane yield for water hyacinth is about half that of primary sludge (Chynoweth, 1987), so digestion for methane production is not always an economical choice.

Table 6-2. Recommended Sludge Cleanout Frequency for Water Hyacinth Ponds (after EPA, 1988)

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

Table 6-3. Composition of Hyacinth Plants Grown In Wastewater (after Reed et al., 1988)

	Percent of Dry Weight	
Constituent	Average	Range
Crude Protein	18.1	9.7-23.4
Fat	1.9	1.6-2.2
Fiber	18.6	17.1-19.5
Ash	16.6	11.1-20.4
Carbohydrate	44.8	36.9-51.6
Kjeldahl nitrogen (as N)	2.9	1.6-3.7
Phosphorus (as P)	0.6	0.3-0.9

Table 6-4. Composition of Duckweed Grown In Wastewater (after EPA, 1988)

	Percent of Dry Weight	
Constituent	Average	Range
Crude Protein	38.7	32.7-44.7
Fat	4.9	3.0-6.7
Fiber	9.4	7.3-13.5
Ash	15	12.0-20.3
Carbohydrate	35	--
Kjeldahl nitrogen (as N)	5.91	4.59-7.15
Phosphorus (as P)	0.6	0.5-0.7

An innovative reactor design in Florida has been used to produce high quality methane in a cost-effective process. The reactor is a nonmixed design, and since it does not require the additional energy input for mixing, it was able to produce enough methane to make a slightly more income than the reactor cost to run (Dinges, 1982; Hayes *et al.*, 1987). For systems with flows less than 3800 m^3/d (1 MGD), there would probably not be enough biomass produced to keep a digester operating.

Duckweed and water hyacinth have also been used as animal feed. The duckweed can be drained and fed to animals without further drying, but the water hyacinth must be at least partially dried. Duckweed has more potential as a feed because of its lower structural fiber content, and its high protein content. Tables 6-3 and 6-4 list the constituents by weight percent in water hyacinth and duckweed grown on wastewater. If the wastewater contains metals, the dried water hyacinth should be measured for metals content before land applying it or feeding it to livestock. Composting or use as feed are probably the best options for aquatic plant facilities with small flows.

Chapter 7

Summary, Conclusions, and Recommendations

7.1 Summary

This report has introduced the types of aquatic macrophytes used in treatment, the types of treatment systems which can use aquatic macrophytes, and the basic requirements for their design and operation. No consolidated design approach was found because of the diversity of the systems involved.

Most states regulate exotic plants such as water hyacinths, and at least one state (Texas) has regulations which force a particular operational method for water hyacinth systems. Very little regulation or full-scale design experience exists for native north american plants such as duckweed or pennywort, but investigators are beginning to research the characteristics of these plants and systems using them. These plants are better suited to the climate in this country, and may offer more trouble-free operation than is possible with the exotics. Current design practices for duckweed systems do not give any credit to the more efficient removals achieved with duckweed than in normal facultative ponds, but this is changing.

Regardless of the macrophyte system chosen, residual plant material and benthic sludge will result. Composting of the residuals for soil amendments is perhaps the best choice for small aquatic plant facilities, but larger facilities may be able to use devices such as an anaerobic digester to convert the bimass produced into useful endproducts (methane gas in this case).

Aquatic macrophyte systems perform well for suspended solids, biological oxygen demand, and nitrogen removal, but they do not do as well removing phosphorus. Metals and trace organics removal have been investigated, but there are problems with each that must be resolved before aquatic macrophytes can be used for this type of treatment on a large scale.

7.2 Conclusions

Aquatic plant systems are economically competitive and can be designed and built to most treatment levels for domestic wastewater. Primary, secondary, and tertiary effluent standards can be achieved with aquatic plant systems. Nutrient removal is also possible, but phosphorus removal by aquatic plant systems requires enough land that any alternate treatment method should be carefully considered before committing to aquatic system phosphorus removal.

Exotic plant systems, such as water hyacinth systems, are limited in their usefulness within the United States because of temperature constraints. Very few places in the country do not experience freezing weather on occasion, and this would decimate the standing crop in an active hyacinth treatment facility. Native plant systems, such as duckweed or pennywort, are less restricted but they are still less effective during the winter months. Covered facilities can protect the plants from cold, but greenhouses can cause increased problems with pests, and the added capital costs make the system less competitive with conventional systems.

Aquatic plant systems are well suited to areas with an abundance of land and year round warm weather. The lack of mechanical parts, and the probable availability of the plants in the third-world natural waters make aquatic plant systems good candidates for use in underdeveloped countries, and make them relatively simple to get operating. Understanding of the process is of course required to achieve peak performance, but even poorly designed and operated aquatic plant systems tend to perform fairly well (Reed *et al.*, 1988).

The treatment in aquatic plant systems is performed by a complex interaction between aquatic plants and microorganisms. each with its own needs. The operator not only needs to understand standard treatment system reactions and the nutrient requirements of each, but also needs tc understand the requirements of the plants well enough to recognize the signs of a problem while it is still relatively easy to correct. In Appendix A, there is a discussion about a micronutrient deficiency at the Iron Bridge Hyacinth Facility in Orlando, Florida, which caused the facility to be shut down until the problem was found and resolved. The problem occurred during start-up and was relatively easy to solve once the cause was determined, but it took some detailed investigation on the part of the operators to determine that a combination of operational practices were responsible for the deficiency. This deficiency was one of the special operational requirements of this site that had not yet revealed itself during the pilot-scale tests.

Aquatic plant systems are as valid as land treatment systems or conventional systems, but each has its strong and weak points. Aquatic plants are not the answer to every problem, but they should at least be considered during design reviews. Small communities with some open land are prime candidates for an aquatic plant system.

7.3 Recommendations

More attention needs to be devoted to macrophyte species which are native to this country and other temperate climates. Floating plants with large root structures tend to perform the best at active removal of contaminants due to the bacterial population present. For this reason, species of plants which prefer wet conditions and have expansive root systems should be investigated to see if they can be made to grow free-floating in the same manner as the pennywort or alligator weed. A cold tolerant species of grass would probably be ideal for this because it would contain less water than most aquatic plants, which would make it easier to handle, and would possibly be useful as a source of animal fodder, which would provide a means of revenue recovery.

Semi-passive systems using small-leaved macrophytes such as the duckweeds and water ferns should also be investigated further to gather sufficient performance data to design the systems better. Claims have been made that these plants are also useful as active contaminant removal devices, but this needs to be investigated further to establish removal rates.

Special systems for metals or organics removal require more investigation before they will be practical. Metals removal schemes need to develop an application method or schedule that will allow the plants to recover from the toxic effects of the metal. Alternately, these systems need to grow plants in other wastewater to be used in the metals removal process. Plant material resulting from metals removal systems should be checked for the metals concentration to determine what disposal method should be used.

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Appendix A

Case Studies

A.1 Introduction

The following projects are included as being representative of the various uses of aquatic plant treatment systems currently employed. The majority of the full scale or pilot scale operations are water hyacinth/water lettuce or duckweed systems, but one unique pennywort system has been included to show other possibilities for the aquatic plant systems.

A.2 Water Hyacinth Systems

By far the most abundant and detailed information is available on water hyacinth systems. The three systems discussed below represent a wide range of uses for the plant system.

A.2.1 San Diego, California, Hybrid Water Hyacinth System (EPA 1988)

This system was chosen because it represents one attempt to go through an entire investigation of possible alternative treatment schemes using water hyacinth lagoons to achieve secondary treatment of primary effluent. It is important to note that the investigation involved the water hyacinth ponds as one component in a system under real conditions. Aquatic plant systems are rarely used by themselves, but as components of larger systems.

The city of San Diego relies heavily upon imported drinking water to meet its needs and has for many years. Approximately ninety percent of the potable water used by the city is imported. Projections of future needs and supplies have indicated that the city's needs will exceed the available supply by the year 2000. Because of this, San Diego has been searching for alternate water sources and methods of reclaiming the water in the waste stream. Initial attempts at distilling ocean water for potable water and using secondary effluent for irrigation were unsuccessful, so the city investigated other reclamation methods.

In 1981, the San Diego began a demonstration wastewater reuse project that included secondary treatment with water hyacinths among many other potential technologies. The project operated for five years, and during its operation the study was extended and expanded into the study discussed below. The information obtained was used to design a 1 MGD (3,785 m^3/d) facility from the best scheme with a 0.5 MGD (1,892 m^3/d) advanced treatment system to reduce the concentration of salts and to further reduce pollutants. This system also included an anaerobic digester to produce methane from the harvested water hyacinth and the primary sludge. Performance results are not yet available for the demonstration scale facility, so the information provided below is on the pilot scale plant.

The original funding for this project allowed for the investigation of aquatic plant systems in wastewater treatment. The primary goals of the project were to find a natural biosystem for wastewater treatment that required lower energy inputs and potentially provided some energy recovery. The secondary goal was to reclaim some water for useful purposes such as irrigation and use as a source of raw potable water. Seven treatment trains involving water hyacinth ponds were evaluated during the study, but the following review is on the performance of the water hyacinth ponds themselves rather than the complete systems.

During the first stage of this study, plug flow ponds were used either in series or in parallel in each treatment scheme. The ponds were 28 ft wide by 416 feet long by 4 feet deep. Profile studies of the ponds revealed that the majority of the TSS and BOD_5 removal occurred in the first 50 feet of the pond, so the next trial of the ponds included a step feed system where one eighth of the influent was fed every 50 feet, beginning at the head of the pond. Various recycle rates were also investigated, with the recycle flow entering the head of the pond or with the influent. An aeration system was required in the hyacinth ponds to prevent hydrogen sulfide odor problems that resulted when the wastewater, which contained high sulfate concentrations, experienced anaerobic conditions. Odor controls for the entire treatment facility were very thorough: a sedimentation basin and a rotary disk filter were enclosed in their own building, with carbon adsorption of the exhaust air; carbon canisters were used at each of three aeration manholes; and ferric chloride was used to precipitate sulfides in an anaerobic fixed-film reactor and a hybrid rock filter. Aeration manholes were aeration devices installed in flow through manholes placed after each of the secondary treatment processes and before the water hyacinth ponds. The recycle water was partially used in a cascade aeration system to maintain the dissolved oxygen concentration above 1 mg/L.

Local requirements for no odor emissions and no mosquitos drove the aeration and harvesting requirements. The system was harvested frequently to maintain a low plant density and allow the mosquito fish ample access to all of the water surface. A large population of mosquito fish was required to ensure complete control of the mosquito larvae population. Occasional drops in the dissolved oxygen concentration and severe drops in the water temperature caused large portions of the mosquito fish population to die. When this occurred, man-made mosquito control agents were used with success, but they had to be applied frequently.

Since harvesting was only performed in this system to allow the fish to control mosquito populations, no correlation was made between the removal efficiency and yield of the cells. The productivity of the hyacinths, 67 $\frac{\text{dry metric tons}}{\text{ha} \cdot \text{yr}}$ (30 $\frac{\text{dry tons}}{\text{acre} \cdot \text{yr}}$), was in the same range as values reported by other investigators.

Effluent characteristics of the ponds were within secondary treatment standards even without step feed of the influent or recycling the effluent. Using recycle increased the organics loading capacity of the ponds by providing initial dilution, and step feed of the influent provided a fairly uniform distribution of the load along the length of the pond. A recycle ratio of two to one with the recycle flow entering the head of the pond was chosen as providing the best overall performance. Recycle ratios of up to five to one provided effluents that usually still met secondary standards, but the turbidity and chlorine requirements were higher at the higher ratios. Figures A-1 and A-2 show the system response to varying influent concentrations of BOD_5 and TSS, respectively. Since the particular treatment scheme shown in these graphs is a series combination of a hybrid rock filter followed by a hyacinth pond, the overall system influent is included (labelled "influent") as well as the actual concentration entering the pond (labelled "pond influent"). The effluent for a full-scale system with step feed and recycle is expected to have $BOD_5 \leq 20$ mg/L ninety percent of the time, ≤ 10 mg/L fifty percent of the time, TSS ≤ 25 mg/L ninety percent of the time, and ≤ 11 mg/L fifty percent of the time. Figure A-3 shows the characteristics of the influent and effluent of each cell of a step feed pond using 2:1 recycle. With the exception of the combined influent to cell 8, the dissolved oxygen concentration remains above 1 mg/L.

The results of the second phase of this study show that a loading of 200 to 250$\frac{\text{kg BOD}_5}{\text{ha}\bullet\text{d}}$ (180 to 225 $\frac{\text{lb BOD}_5}{\text{acre}\bullet\text{d}}$) is appropriate with step feed and aeration. The recommended depth of the pond is 0.9 to 1.2 m (30 to 42 in). The hydraulic loading rate was held constant at 0.058 $\frac{\text{m}^3}{\text{m}^2\bullet\text{d}}$ (62,000 GPD/acre) for all of the tests, which resulted in a hydraulic residence time of 21 days.

Based upon the observed removal rates, a 1 MGD (3,785 m^3/d) treatment facility using an applied BOD_5 concentration of 175 mg/L and a surface loading rate of 225 $\frac{\text{kg BOD}_5}{\text{ha}\bullet\text{d}}$ (200 $\frac{\text{lb BOD}_5}{\text{acre}\bullet\text{d}}$) would require 2.9 ha (7.3 acres). The capitol cost to construct the pond system would be approximately $2.18 million, and the annual operations and maintenance cost would be approximately $494 thousand (in 1986 currency). Anaerobic digestion of the harvested water hyacinths can potentially yield two billion BTU/yr in methane at the measured production rates. This has the potential of decreasing the net operating costs for the entire plant if it is either used to generate electricity or sold to local utility companies.

A.2.2 Austin, Texas, Water Hyacinth Facility (Doersam, 1987; EPA, 1988)

The state of Texas has been gathering information on water hyacinth treatment facilities since 1970. Several studies of field-, pilot-, and full-scale systems have been performed at various locations, including Austin. Water

Figure A-1 BOD_5 performance data for San Diego, CA pond #3 with 200 percent recycle (EPA, 1988)

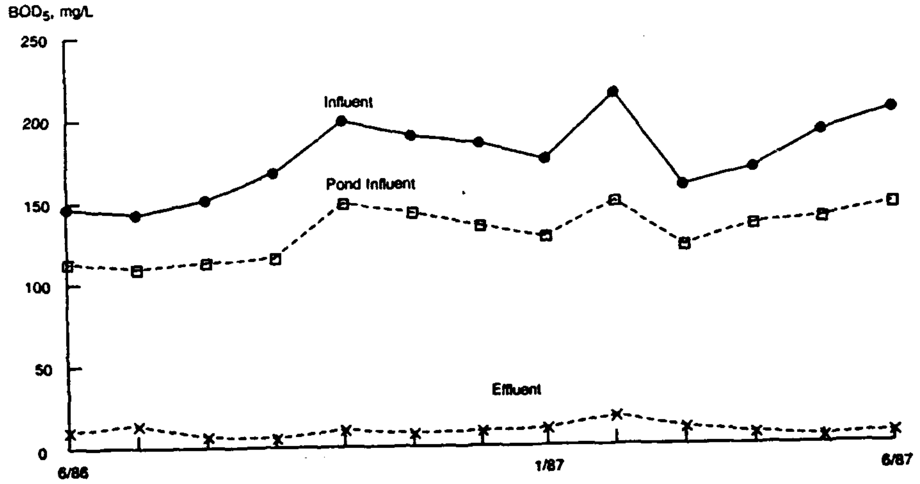


Figure A-2. SS performance data for San Diego, CA pond #3 with 200 percent recycle (EPA, 1988)

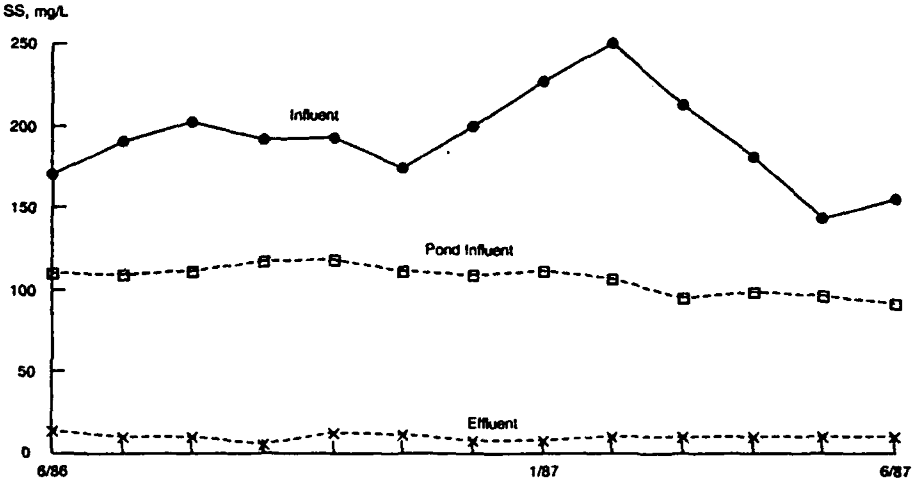
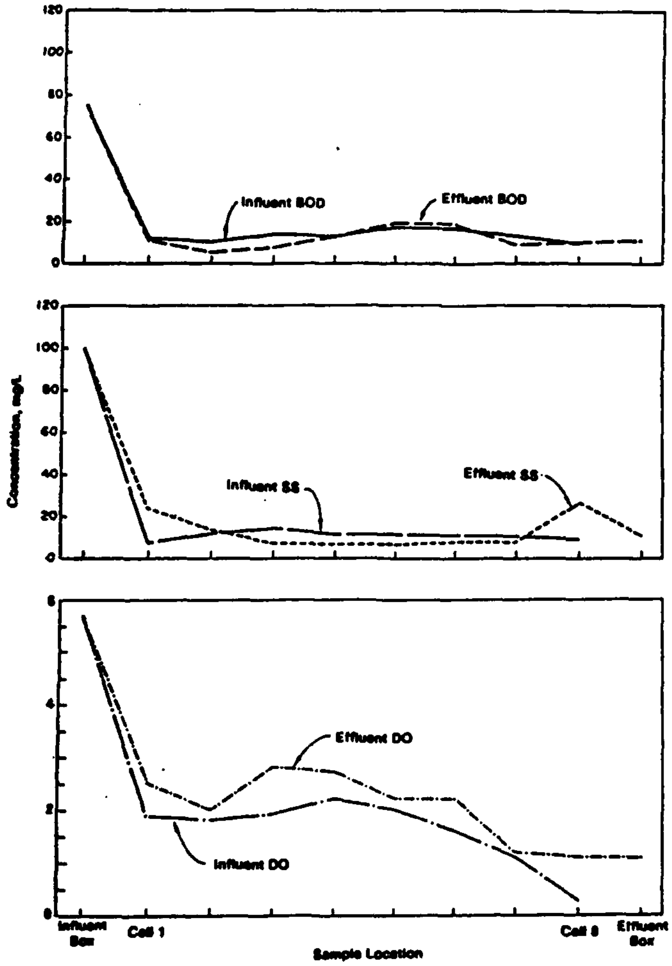


Figure A-3 Influent and effluent BOD, SS, and DO for step-feed hyacinth pond (EPA, 1988)



hyacinth systems have been shown to be feasible, except that winter freezing is a problem in much of the state.

The city's Hornsby Bend Sludge Treatment Facility receives waste activated sludge from several area treatment plants. The facility began operation in the 1950's and recently underwent major renovations, including the construction of a new water hyacinth facility.

The original design called for supernatant from the sludge holding lagoons to be passed through a chlorine contact lagoon and then discharged into the Colorado River. The effluent quality exceeded the imposed discharge limits of 30 mg/L BOD_5 and 90 mg/L TSS. To help correct this problem, water hyacinths were introduced into the 1.2 ha (3 acre) chlorine contact lagoon in 1977. They served as a seasonal upgrade for several years, but the basin configuration was not well suited to water hyacinth treatment, and freeze damage occurred each year. A greenhouse structure was proposed as part of the planned renovations to offer protection for the plants and afford year round treatment.

A new three basin water hyacinth facility was approved and built with a permanent greenhouse structure. The construction was partially funded by the EPA's Construction Grants Program as an innovative wastewater treatment process. This facility was the first permanent greenhouse structure funded by the EPA.

The 2 ha (5 acre) greenhouse structure contains three basins with a total surface area of 1.6 ha (4 acre) when filled to their 17,000 m^3 (4.5 Mgal) capacity. The system is designed to receive a maximum daily flow of 7570 m^3/d (2 MGD), which makes the hydraulic loading 4680 $\frac{m^3}{ha \cdot d}$ (0.5 MGD/acre). The center basin has an area of 0.64 ha (1.6 acre), and each of the outside basins have areas of

0.48 ha (1.2 acre). The length of the basins is 265 m (870 ft), the center basin is 24.2 m (80 ft) wide, and the outer two basins are 18.1 m (60 ft) wide. The depth of each basin varies from 0.9 m (3 ft) at the upstream end to 1.5 m (5 ft) at the downstream end. The middle basin initially received roof run-off during storms, but the resulting temperature change in the water was believed to be responsible for causing stress in some of the species maintained in the pond for mosquito control. Rain water was diverted off of the facility as a result.

The greenhouse structure is completely enclosed with clear fiberglass panels that have a light transmission value of 65 percent. Water hyacinths require high intensity light for growth, so the transmissivity of the panels was monitored with time. The sidewalls of the structure are 3.4 m (11 ft) tall to allow maintenance vehicles and harvest equipment to maneuver easily. Seven overhead doors at each end of the building allow for vehicle access. Separate personnel doors were installed later. Moveable barriers are placed across any open doorways to prevent the entrance of snakes or other predators of the organisms used for mosquito control. The barriers also prevent the return of nutria, a large aquatic rodent, which were a problem in the facility at one time. Doors and ridge vents provide ventilation, and the ridge vents are screened to minimize the immigration of adult mosquitos.

The influent to each pond is distributed across the width of the upstream end using a 30 cm (12 in) perforated pipe. Two secondary distribution pipes are located at 63.9 m (210 ft) and 127.8 m (419 ft) downstream of the upper end of each basin for experimental step application of influent.

Maintenance of the facility includes harvest and annual removal of detritus. The slope of the basin facilitates draining and cleaning. A drain valve is located at the bottom of the outlet structure in each basin. This drain valve is separate from the adjustable telescoping valve used to set the operating water level. The facility is of sufficient size to allow continued operation at the design flow with one basin out of service. The berms separating the basins was topped with a 3 m (10 ft) wide unsurfaced road used during harvesting, but condensation dripping from the roof, and capillary rise from the basins required the installation of a permanent road surface.

Mosquito control was a major consideration in designing the facility. Eight areas in each basin are kept open by chain link fence and galvanized metal strips. These are intended to act as natural aerators by allowing sunlight to penetrate to the gravel substrate where it promotes attached algae growth. During the daytime, the algae releases oxygen into the water, which then flows under the hyacinth mat. Dissolved oxygen concentrations in these areas have been measured as high as 5 mg/L during the day. These areas help ensure the survival of the mosquito fish, and grass shrimp used to control mosquito larvae. Final effluent from the ponds passes over a two step cascade aerator with a total drop of 3 m (10 ft). The dissolved oxygen concentration after the cascade aerator is consistently above 5 mg/L.

The biological stability of water hyacinth basins is the key to successful treatment of wastewater. Maintenance work on one of the sludge lagoons which fed the hyacinth facility caused the influent loading to be erratic and resulted in erratic performance of the system during the first six months of operation. The method used to ensure relatively constant loading after that was to maintain a constant influent flow rate. This was sufficient as long as the influent quality did not vary greatly. Performance of the system for a one year period is shown in figures A-4 and A-5.

Mosquito controls in the system were effective. In addition to the mosquito fish and grass shrimp, leopard, tree, and cricket frogs were stocked for mosquito control. Dragonflies and damselflies also played an important role even though they were not stocked. The adult dragonflies and damselflies ate adult mosquitos, and the larval dragonflies ate larval mosquitos. A noticeable increase in mosquito population was noticed when the weather got cooler, presumably due to immigration of adult mosquitos.

No harvest was necessary during the first five months of operation, but was required constantly in July and August, and less frequently during the winter. A tractor mounted modified backhoe was used to harvest a 1.2 to 1.8 m (4 to 6 ft) strip along the outside edge of each basin. This strip of clear water acted as a temporary aerator and allowed the mosquito predators easier access to any concealed pools of water in the hyacinth mat. The harvested plants were first dried and then encorporated into thickened waste activated sludge to be recycled as a soil additive.

Experience with previous water hyacinth systems at this location indicated that humus accumulation would be rapid and would mostly occur close to in inlet. A partial drawdown of the basin being cleaned was used to avoid having to completely restock the basin.

The total design and construction cost of the system was $1.2 million. As of June. 1989, discharge of pond effluent to the Colorado River was no longer permitted. Effluent was then used to irrigate agricultural land near the facility. Because of the new use for the effluent, discharge standards were not as critical. Problems with hyacinth weevils, mites, and culture maintenance, combined with this decreased effluent requirement resulted in abandonment of water hyacinth treatment. Some hyacinths are still being used, but the majority of the basin surface is now maintained as a duckweed system. Removals are adequate for land application (Doersam, 1992).

A.2.3 Orlando, Florida, Water Hyacinth Tertiary Treatment Facility (EPA, 1988)

The Iron Bridge Wastewater Treatment Facility provides tertiary treatment for a maximum of 90,000 m^3/d (24 MGD) of the city of Orlando's wastewater. The facility was built in 1979. It used primary clarification and RBCs for carbonaceous BOD_5 removal and nitrification, submerged RBCs for denitrification, chemical precipitation and sedimentation for phosphorus removal, and rapid sand filters for effluent polishing. The permitted effluent standards for the plant were 5 mg/L BOD_5, 5 mg/L SS, 3 mg/L TN, and 1 mg/L TP.

Flows to the facility increased with time as would be expected, but by 1982 the city faced an additional requirement of not increasing the waste load discharged to the St. Johns River. In order to meet the increased flows without increasing the waste load, the city had to improve the removal efficiencies of the facility. One proposed method to accomplish this was to use a water hyacinth system to treat 30,000 m^3/d (8 MGD) to an effluent quality of 2.5 mg/L BOD_5, 2.5 mg/L SS,

Figure A-4. BOD$_5$ and TSS Performance of Hornsby Bend Hyacinth Facility, Austin, TX (Doersam, 1987; EPA, 1988).

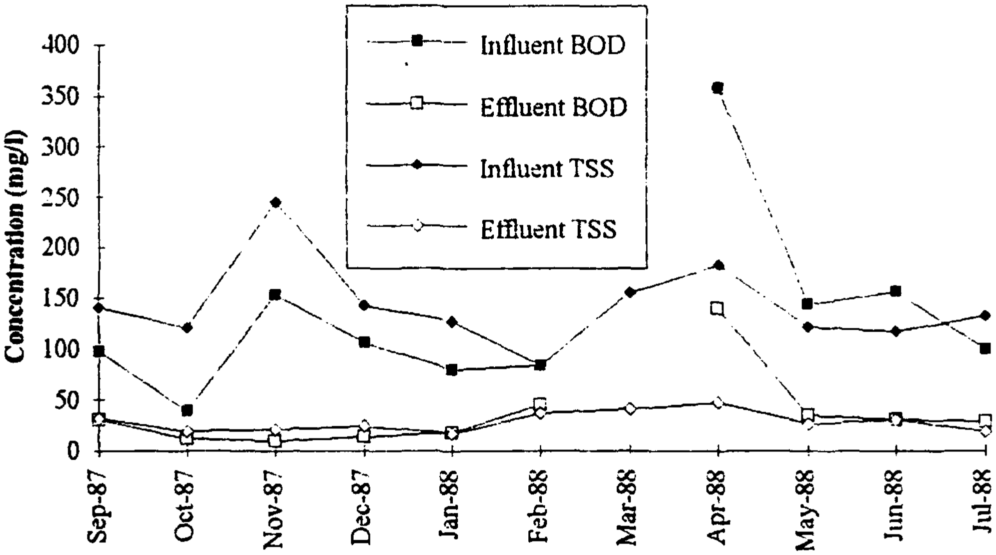
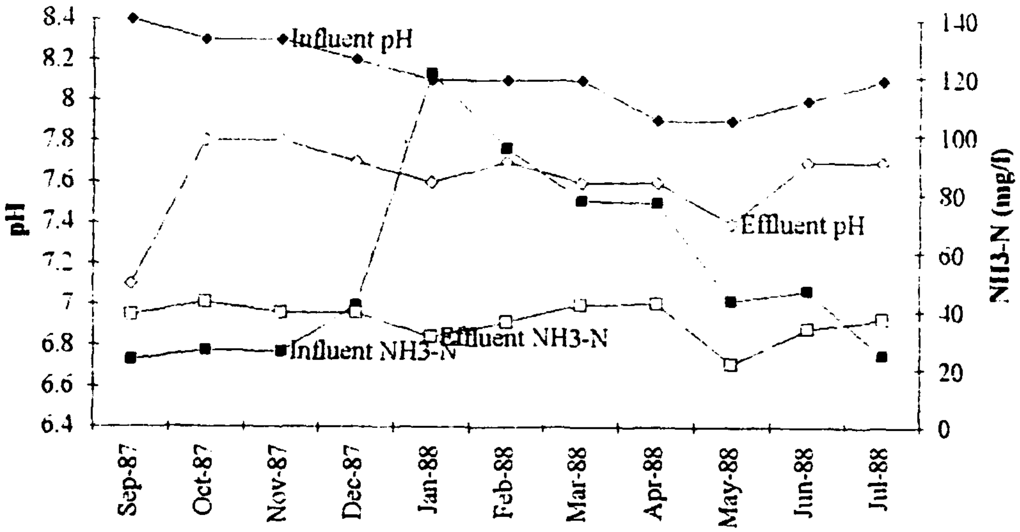


Figure A-5. pH and NH_3-N Performance of Hornsby Bend Hyacinth Facility, Austin, TX (Doersam, 1987; EPA, 1988).



1.5 mg/L TN, and 1.5 mg/L TP. This would allow for a maximum influent flow to the facility of 106,000 m^3/d (28 MGD). In 1983, the city of Orlando decided to test the feasibility of the concept by building and operating a pilot water hyacinth facility. Because the pilot plant was successful, a full-scale system was built and has been operating since 1985.

The pilot facility consisted of five ponds built in series with a total pond area of 253 m^2 (2,720 sq.ft). Each pond is 5.2 m by 9.8 m (17 ft by 32 ft). The required surface area for these ponds was determined using a computer model, HYADEM, developed by Amasek, Incorporated. An assumed wet crop density of 12.2 kg/m^2 (2.5 lb/sq.ft) and influent flow of 54.5 m3/d (14,400 gpd) were used as inputs to the program. The depth of the ponds was set at 0.6 m (2 ft) which resulted in a hydraulic detention time of 2.8 days. Based upon these figures, the surface loading rate was 2,240 $\frac{m^3}{ha \cdot d}$ (0.24 MGD/acre).

The pilot facility was used to determine: the ability of the hyacinth system to achieve the desired effluent concentrations on an average monthly basis; the ability of the hyacinth system to recover following a freezing event; determine the need for micronutrient addition; to determine the applicability and reliability of the computer model used; and to reveal any specific operational requirements. The system was operated under steady state conditions, and measurements of influent, effluent, and crop parameters were taken regularly.

The ponds were first stocked with water hyacinth in September 1983, but problems with the influent quality fluctuating made it difficult to evaluate the system performance for the first three months. Plant productivity was lower than expected during this time, but that has been attributed to possible micronutrient shortages and activity of the hyacinth weevil (*Neochetina eichhorniae*).

By December, the wet standing crop had increased from 455 kg (1000 lb) to 1,650 kg (3,636 lb), an increase of approximately 6.5 kg/m^2 (1.34 lb/sq.ft). On December 25 and 26, a freeze occurred that produced a noticeable effect on the hyacinths but did not kill them. Treatment efficiencies did however decrease in January.

Actual hydraulic loading rates were lower than planned during January 1984 to accomodate a higher than planned nitrogen loading. The flow was reduced to 21 m^3/d (5,600 gpd) at this time. Initially a micronutrient supplement of iron, potassium, and phosphorus was added, but from January on, zinc, copper, manganese, molybdenum, boron, and sulfur were added as well. During January, the last two ponds were also covered with a portable greenhouse to assess their performance during freeze events.

Removal of BOD$_5$, SS, TN, and TP from February 15 to March 15 was stable and averaged 60, 43, 70, and 65 percent, respectively. No major operating problems were encountered during this time. The assessment of the pilot facility's performance concluded that covering the ponds for freeze protection was not cost effective at the Iron Bridge facility because the hyacinths were able to recover from "even severe Florida freeze events," and because of some of "the negative features associated with a covered system."

Design of the full-scale system was performed using the same computer model mentioned above. The basic assumption used by the model is that nutrient removal is directly related to plant growth. Plant growth is modelled in the program with Monod kinetics and the Arrhenius temperature relationship, assuming that growth is occurring in a reactor with constant concentration of the limiting nutrient. Growth rate is related to plant density and surface area coverage and then uses these assumptions to calculate nutrient uptake. The effluent concentration is then calculated from a nutrient mass balance. The main problem with this model is that most researchers have concluded that the majority of nitrogen removal is by nitrification/denitrification, with only a small fraction of the total being consumed by the plants. The results of the pilot-scale system were used to calculate the constants for the growth relationships.

The full-scale system consists of two ponds each with a surface area of 6 ha (15 acre) and hyacinth digestion facilities. Each pond is subdivided into five basins 67 m long and 183 m wide (220 ft by 600 ft) using berms. Six weirs are spaced evenly along the length of each berm to distribute flow and prevent short-circuiting. Advanced waste treatment effluent is fed to both ponds through an inlet manifold. One pond also has an influent line from the secondary facilities. Chemical feed pipes to the influent lines and the weirs in each berm supply the supplemental nutrients which are regulated by a chemical dosing and mixing facility. The ponds are 0.9 m (3 ft) deep and have a hydraulic retention time of approximately 3.5 days.

Water hyacinths were initially stocked in late 1984, and the plant operated in a start-up mode until July 1985. During this time, the system met the nutrient removal goals. Amasek, Inc. took over operation of the system in July 1985. Several problems were encountered during the period of July 1985 to February 1986. These were summarized in a report to the city as follows:

1. When the company took over operation, the crop had developed extensive weevil populations and there was significant encroachment of alligator-weed.
2. The company tried to improve the crop viability by selective harvesting. Growth of the unharvested plants was not as projected and extensive algae growth resulted in violation of SS discharge limits.
3. Insecticide spraying was required to try and bring the weevil population under control. Additional water hyacinth stock was introduced to enhance crop development.
4. Spraying helped improve crop viability, but growth was inconsistent and coverage was not being achieved as designed. This continued the algal growth and violation of discharge standards, but adequate nutrient removal was still being achieved.
5. By January, 1986, the crop was experiencing serious growth problems. Nutrient removal was still occurring, but the rate of removal had declined considerably.
6. Potential causes for the growth problems were identified as follows:
   a. Metal toxicity, with aluminum being the most likely.
   b. Biological interference or competition from the algae and other plants.
   c. *Macronutrient deficiencies, with phosphorus the principal concern.*
   d. Micronutrient deficiencies.
7. In January 1986, the system was shut down in an attempt to restore crop health and solids control. One pond was fertilized to bring levels of

nitrogen, phosphorus, iron and calcium to excess concentrations. Several experiments were established to test the effects of various additives. Thorough testing of the plants and water quality was performed in an attempt to identify toxic or deficient constituent levels.

8. By late January, the plants were experiencing very serious growth problems. and the sanding crop began to decline significantly. The pond that had been fertilized showed no response to the nutrients. This indicated either a toxic influence or a micronutrient deficiency was the cause.
9. In February 1986. flow was reinstated to the unfertilized pond. and crop health improved rapidly. This verified the results of several small scale tests which indicated that there was no phytotoxicity problems. A micronutrient deficiency was therefore the main suspect, and the contractor compared the plants in the Iron Bridge facility to those in other systems.

A thorough investigation revealed that a molybdenum deficiency had 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."

Several modifications to the system operations were enacted to correct the problem: molybdenum and boron were added to the supplemental nutrients, ferric chloride was chosen as a replacement for ferrous sulfate, and lime or soda ash was added to increase the influent alkalinity to 60 mg/L as $CaCO_3$.

From February to May 1986, the system was again operated in start-up mode to establish a healthy crop. In June, one pond was operated as designed except that the influent nitrogen levels were approximately 13 mg/L instead of the 3 mg/L anticipated. In September, the second pond was also placed in service. Influent an effluent concentrations of BOD_5, SS, TN, and TP for the period from June to November are shown in Table A-1. During this period of relatively steady operation, the hyacinth system did not achieve the predicted removal rates. The average BOD_5 and SS concentrations were reduced form 4.87 and 3.84 mg/L in the influent to 3.11 and 3.62 mg/L in the effluent. The system did achieve the predicted removal rate in terms of mass of nitrogen removed. Effluent phosphorus concentrations were always below the design goal of 0.5 mg/L, even though it was necessary to add supplemental phosphorus to the influent to assure that it was not a growth limiting nutrient.

The construction costs of the hyacinth system were $1.2 million for the hyacinth digester, and $2 million for the basins and piping. Operation and maintenance is performed under contract by the Amasec Corporation for a yearly fee of $550,000 which covers all associated costs such as pumping, sludge disposal, and an extensive monitoring program.

Table A-1. Iron Bridge, FL Water Hyacinth System Performance Summary (after EPA, 1988)

Date	Wastewater	BOD5, mg/l		SS, mg/l		TN, mg/l		TP, mg/l (a)	
	Flow, m3/d	Influent	Effluent	Influent	Effluent	Influent	Effluent	Influent	Effluent
Jun-86	16,680(b)	3.24	4.58	3.06	6.31	12.52	8.09	0.37	0.24
Jul-86	17,450(b)	4.12	1.73	3.85	1.86	12.44	8.06	0.33	0.11
Aug-86	16,850(b)	3.33	3.70	3.58	4.28	12.77	7.62	0.55	0.19
Sep-86	32,500(c)	6.16	2.66	5.23	2.91	12.66	7.96	0.75	0.15
Oct-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 hyacinth ponds in operation.

A.3 Duckweed Systems

Although many persons have investigated the use of duckweed in treatment systems and some pond facilities may have been adapted for use with these plants, only one company has been designing and building systems based upon duckweed treatment. The Lemna Corporation of Mendota Heights, Minnesota has designed a patented floating grid and baffle system to provide wind protection to the plants and distribute the water flow evenly beneath them. The floating harvester that was designed for these systems rides over the flexible grid and skims duckweed off the surface of the individual grid cell surfaces. The porous baffles may also act as attached growth surfaces for denitrifying microorganisms. The following case studies were taken from documentation from the company (Lemna Corp., 1991) and an article in Water Environment & Technology (Buddhavarapu and Hancock, 1991). Costs and details such as those provided for the above water hyacinth facilities are not available.

A.3.1 Devils Lake, North Dakota (Lemna Corp., 1991)

The city of Devils Lake had a three cell, series flow stabilization pond system which was not meeting the discharge requirements of 30 mg/L or less of BOD_5, 30 mg/L or less of total suspended solids (TSS), and 1 mg/L or less of total phosphorus (TP) set by the North Dakota Department of Health. The first cell in series was 120 acres and the remaining two cells were 60 acres each. The average depth of each cell was 6 feet. The average flow to the ponds was 3.5 MGD.

The system was upgraded by raising the berms on the lagoons two feet, adding rip-rap to the sides, and installing a three cell, fifty acre duckweed advanced treatment facility after the third lagoon. The cells in this facility have a large aspect ratio, but are folded to minimize land requirements (see Figure A-6). The facility is unusual for a wastewater treatment facility in that it is set up like a park ("Lemna Water Park") with a visitor's center and extensive landscaping. The hydraulic residence time of the new facility is 22 days, and the active storage volume is 77 MG. The pilot scale demonstration project at this site achieved effluent concentrations of BOD_5 and TSS consistently below 25 and 30 mg/L respectively, and stabilized at less than 0.5 mg/L·TP within the first month. Figures A-7, A-8, and A-9 show the response of the system to the varying influent concentrations of TP, TSS, and BOD_5 respectively. Full scale operation has achieved similar results, and has consistently met its discharge requirements.

A.3.2 **Pontotoc, Mississippi** (Lemna Corp., 1991)

The city of Pontotoc operated five oxidation lagoons to treat a total flow of 1.1 MGD. Lagoon number five was not meeting the discharge standards of 15/30/2/6 mg/L for BOD_5/TSS/ammonia/dissolved oxygen (DO), especially the ammonia limitations. This pond had a surface area of 1 acre and was 6 feet deep including a 1 foot storage zone. The design flow for the pond was 13,000 GPD. No structural modifications were required to upgrade to a duckweed system other than the installation of the surface grid/submerged baffle system and a supplemental nitrification (shallow) zone. The maximum design flow for the new system is three times the average daily flow, or 39,000 GPD. The Active storage volume is 1.5 MGD, and the hydraulic residence time is 115 days. The effluent of the system

Figure A-6. Plan view of Devils Lake, ND, Duckweed Treatment Facility (Lemna Corp., 1991)

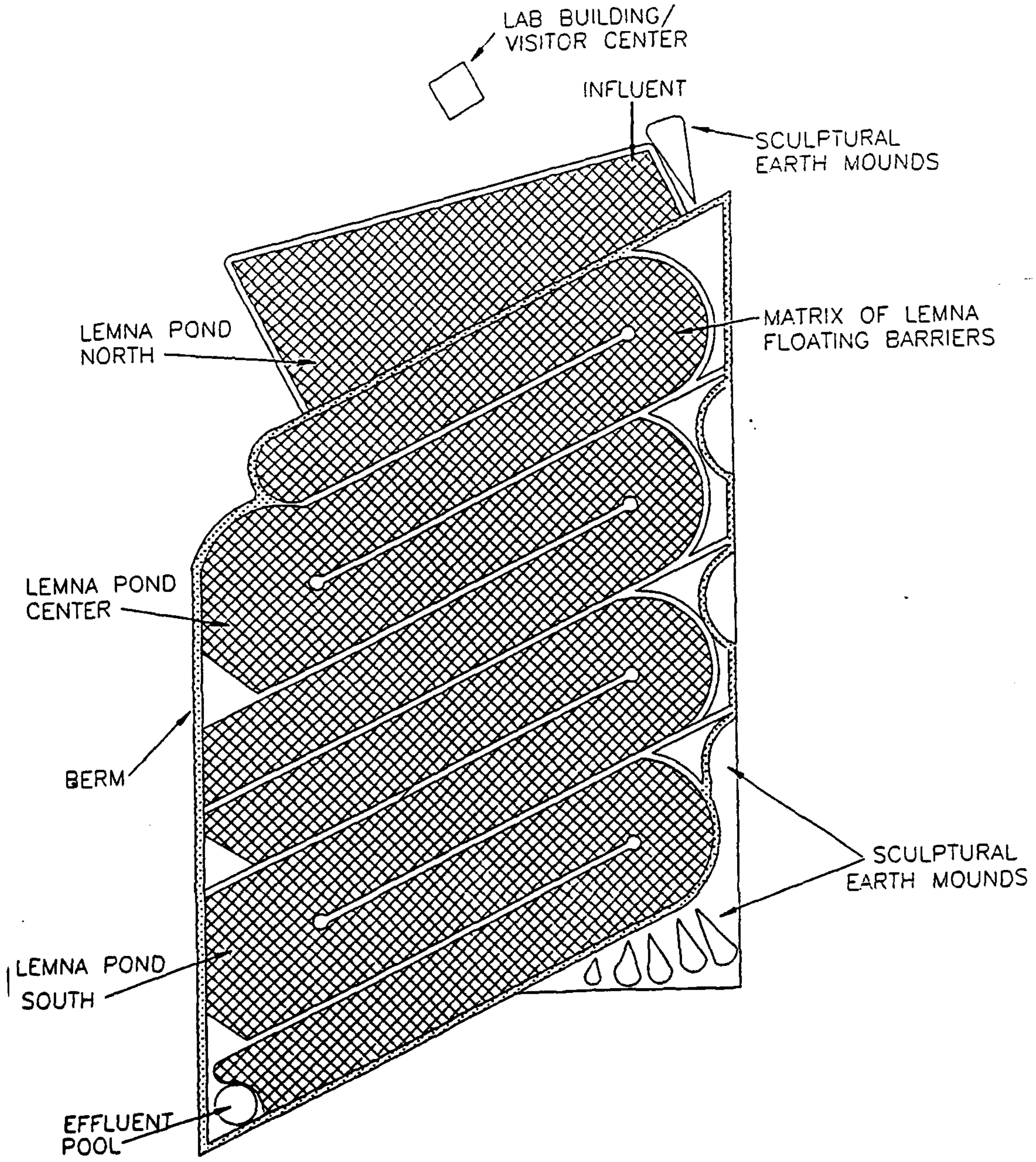


Figure A-7. **Phosphorus Removal for the Devils Lake Duckweed Facility** (Lemna Corp., 1991)

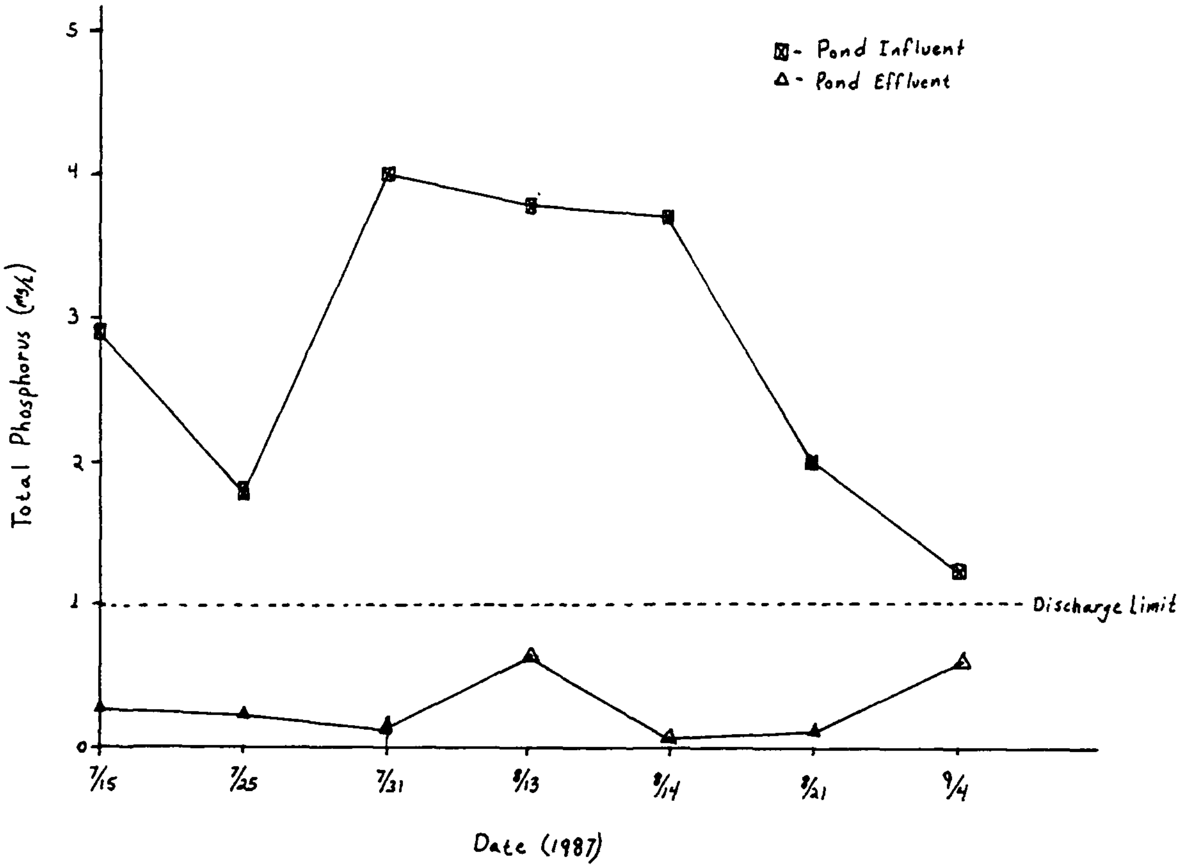


Figure A-8. Suspended Solids Removal for Devils Lake Duckweed Facility (Lemna Corp., 1991)

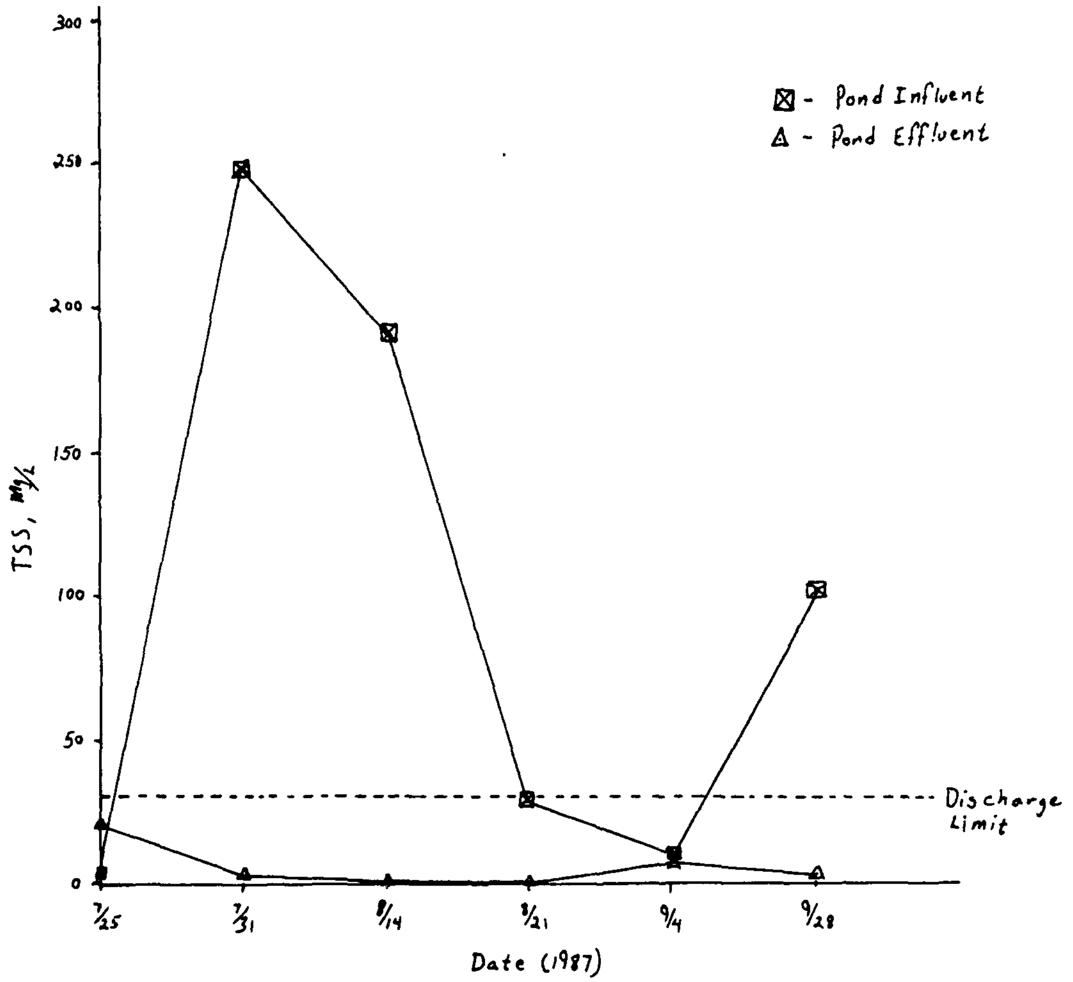
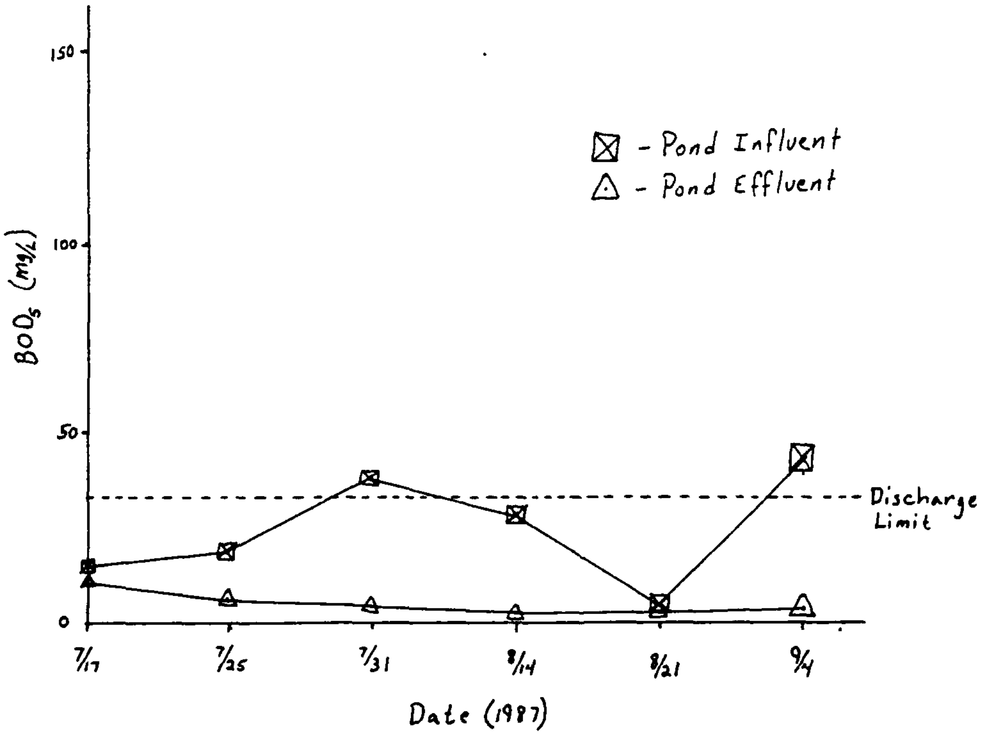


Figure A-9. BOD$_5$ Removal for Devils Lake Duckweed Facility (Lemna Corp., 1991)



stabilized within the first month. Table A-2 shows that the discharge standards were met except for three months when a sludge reduction program was underway.

A.3.3 **Ogema, Wisconsin** (Lemna Corp., 1991)

Ogema had an existing two cell series flow stabilization pond system which was not meeting the BOD and TSS effluent standards of no more than 20 mg/L of each. The system was designed for 75,000 GPD but the average daily flow was 35,000 GPD. The active storage volume of the primary cell was 5.12 MG and that of the second was 1.33 MG, making the hydraulic residence times 145 and 38 days, respectively. The second cell consisted of a 1 acre pond, 6 feet deep, including 1 foot of storage. This cell was used for the duckweed upgrade.

The only modifications required for installation were the repair of the outlet and the installation of the baffle and grid system. Table A-3 shows that the system has consistently performed well as modified. Wisconsin currently requires 150 days of storage for pond systems, but the manufacturer is trying to show that the increased effluent quality of duckweed systems require less storage. In this system, the effluent has been within secondary effluent standards even during the winter.

Table A-2. Pontotoc, MS, Duckweed System Performance (Lemna Corp., 1991)

Date	BOD5, mg/l		TSS, mg/l		NH3, mg/l	
	Influent	Effluent	Influent	Effluent	Influent	Effluent
May-90	117.5	2.5	126.0	8.0	5.8	2.0
Jun-90	60.0	2.0	43.0	15.0	7.0	2.0
Jul-90	84.0	12.0	119.0	32.0	30.0	9.0
Aug-90	57.5	11.0	99.0	18.5	32.8	15.6
Sep-90	93.0	10.0	176.0	6.0	16.5	3.3
Oct-90	N/A	2.0	63.0	14.5	15.3	0.6
Nov-90	N/A	7.0	N/A	4.0	N/A	N/A
Dec-90	N/A	13.8	N/A	17.3	N/A	< 0.5
Mar-91	116.0	13.2	164.0	15.0	N/A	0.9
Jul-91	32.4	5.7	167.0	17.0	12.5	0.9

Table A-3. Ogema, WI, Duckweed System Performance Before and After Installation (Lemna Corp., 1991)

Status	Date	BOD5, mg/l		TSS, mg/l	
		Influent	Effluent	Influent	Effluent
Existing	Jan-90	199	16	300	84
	Feb-90	207	14	373	37
	Mar-90	145	21	209	30
	Apr-90	172	22	287	40
	May-90	68	15	127	39
	Jun-90	127	17	112	27
	Jul-90	122	16	217	51
Lemna Installed	Aug-90	121	5	157	16
	Sep-90	94	6	155	7
	Oct-90	83	5	108	6
	Nov-90	114	8	92	19
	Dec-90	98	19	92	22
	Jan-91	142	21	165	5
	Apr-91	58	11	88	11

A.3.4 Ellaville, Georgia (Lemna Corp., 1991)

Ellaville used a two cell series flow lagoon system with the first cell mechanically aerated. The system was fairly old and the second pond contained significant sludge deposits. The existing effluent standards of $BOD_5 \leq 30$ mg/L and TSS $\leq$ 90 mg/L were being met by the system, but as of May, 1992, the standards were being made more stringent and the plant had not been capable of attaining the new prescribed limits previously. The new limits were $BOD_5 \leq 15$ mg/L, TSS $\leq$ 30 mg/L, DO $\geq$ 6 mg/L, and $NH_3 \leq 2$ mg/L.

A duckweed system was chosen as an upgrade for the second cell. This cell had an active storage volume of 4.0 MG, with a hydraulic residence time of 20 days. The design flow was 200,000 GPD. Minimal modifications were required for installation. The primary cell was managed for initial BOD/TSS reduction with the second cell operated as a polishing pond. Table A-4 shows the effluent characteristics before and after the modification.

A.4 Others

Systems have been investigated for use with pennywort (*Hydrocotyle umbellata*) and various submerged plant systems, but very little information has been published on any existing pilot or full scale operations. Combining pennywort and water hyacinth in the same system has been reported as being a viable method of operating year round in areas where water hyacinths do not perform well in the winter, but no specifics have been reported. One pilot scale system which uses pennywort is a nutrient film technique, where the plants are grown in lined

Table A-4. Ellaville, GA, Duckweed System Performance (Lemna Corp., 1991)

		BOD5, mg/l		TSS, mg/l		NH3, mg/l	
Status	Date	Influent	Effluent	Influent	Effluent	Influent	Effluent
Existing	Jan-90	214	19	173	59	N/A	N/A
	Feb-90	88	12	71	28	N/A	N/A
	Mar-90	109	22	128	53	N/A	N/A
	Apr-90	176	29	209	83	N/A	N/A
	May-90	162	23	131	43	N/A	N/A
	Jun-90	110	30	104	77	N/A	N/A
Lemna Installed	Jul-90	92	7	79	14	N/A	N/A
	Aug-90	182	5	193	10	N/A	N/A
	Sep-90	100	6	127	12	N/A	4.80
	Oct-90	178	13	168	11	N/A	1.12
	Nov-90	104	7	115	22	N/A	0.50
	Dec-90	168	12	196	31*	N/A	1.60
	Jan-91	183	15	60	14	N/A	7.00

* An extensive sludge reduction program temporarily suspended sediments.

raceways with a film of wastewater running through the bare roots. This system removes solids by filtration and sorbs dissolved contaminants as discussed earlier.

Dierburg, DeBusk, and Goulet (1987), investigated a thin film system for removing copper and lead from a wastewater effluent treated to secondary standards. *Two control and two test raceways were built 7.32 m long by 1.22 m* wide and 0.15 m deep and lined with 10 mil PVC sheeting. The plants were stocked and allowed to adapt to the secondary effluent without the metals for two weeks. Secondary effluent was used that had not been chlorinated, and was fed through each bed at about 900 l/d. The effluent film ranged from 3.3 to 4.2 cm thick and had a hydraulic residence time of 8 to 10 h. Once the plants were well established, the influent streams of two of the raceways were inoculated with metals and the other two were left alone. The unamended influent averaged 6.0 mg/L BOD_5, 6.9 mg/L NO_3-N, 0.9 mg/L NH_4-N, and 3.1 mg/L TP. The two raceways with metals also had 2.5 mg/L Cu and 1.0 mg/L Pb in the influent.

The performance of this system appeared to be very good for the first *month, with the effluent metals* concentrations averaging 839 μg/l Cu and 149 μg/l Pb. This equates to an average removal of 69 percent of the copper and 85 percent of the lead. Problems began to arise after this time since the plants began to experience phytotoxicity due to the accumulated copper in the plants. The concentration of the metals in the plant/detritus complex was 1000 times greater than the ambient concentrations, with the highest concentrations being at the head of the channels. Figure A-10 shows the progression of the high metals concentration through the channels during the experiment. The authors pointed out that it is very important to use realistic conditions and time scales when investigating treatment systems to avoid making faulty decisions. This system could have been viewed as very satisfactory if the experiment had been stopped at two or three weeks, but because of the phytotoxicity experienced from about 30 days on, this system could not be viewed as satisfactory without modifications. Perhaps some other application scheme would work, where the metals contaminated stream was applied alternately with a nutrient stream that was not toxic. Another possibility would be to raise the plants in another tank and continue to remove the plants that were experiencing phytotoxicity with new plants.

Most of the specialized applications for aquatic plants being investigated require further research before they can be practical. The investigators of the above thin-film system found that alligator weed and water hyacinth could also be used in a similar system to remove metals, but the same toxicity problems resulted. In this case, the authors recommended further investigation into loading and other application methods to make the system effective for longer periods of time, but the end result may be that this particular method cannot be used for other than batch treatments with plant replacement occurring between batches if this is economically feasible.

Figure A-10. Concentration Response of Pennywort Plants at Three Locations in a Nutrient Film System. (Dierburg *et al.*, 1987)