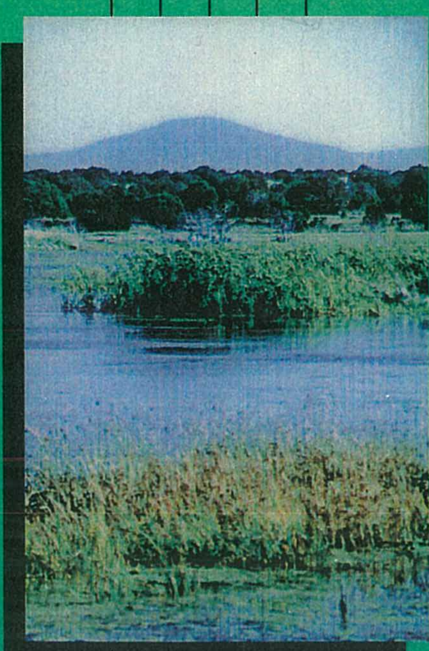
Arizona Guidance Manual for Constructed Wetlands for Water Quality Improvement

Arizona Department of Environmental Quality



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Acronyms

ac	acre
ACOE	U.S. Army Corps of Engineers
ADEQ	Arizona Department of Environmental Quality
AGF	Arizona Game and Fish Commission
APP	Aquifer Protection Permit
AWT	advanced wastewater treatment
BADCT	Best Available Demonstrated Controlled Technology
BOD_5	5-day biochemical oxygen demand
BTU	British Thermal Unit
CEC	cation exchange capacity
CERF	Constructed Ecosystems Research Facility
CFU	colony-forming unit
cm	centimeters
COD	chemical oxygen demand
CWA	Clean Water Act
d	day
DO	dissolved oxygen
EA	environmental assessment
EIS	environmental impact statement
EMWD	Eastern Municipal Water District
EPA	U.S. Environmental Protection Agency
ESA	Endangered Species Act
FAA	Federal Aviation Administration
FAP	floating aquatic plant
FONSI	finding of no significant impact
ft	feet
gpd	gallons per day
ha	hectare
HLR	hydraulic loading rate

Acronyms

(Continued)

HRT	hydraulic residence time
in	inches
kg	kilogram
lb	pound
m	meter
m^3	cubic meters
MCL	maximum contaminant level
mg/L	milligrams per liter
mgd	million gallons per day
mL	milliliter
ML	megaliter
mm	millimeter
NEPA	National Environmental Policy Act
NAGPRA	National American Graves Protection and Repatriation Act
NH_4-N	total ammonia nitrogen
NO_2+NO_3-N	nitrate plus nitrite nitrogen
NPDES	National Pollutant Discharge Elimination System
NTU	nephelometric turbidity unit
ORG-N	organic nitrogen
ORTHO-P	ortho phosphorus
PLSD	Pinetop-Lakeside Sanitary District
PPP	pollution prevention plan
ppt	parts per thousand
SF	surface flow
SSF	subsurface flow
TDS	total dissolved solids
TKN	total Kjeldahl nitrogen
TMDL	Total Maximum Daily Load

Acronyms
(Continued)

TN	total nitrogen
TOC	total organic carbon
TP	total phosphorus
TSS	total suspended solids
UAA	Use Attainability Analysis
USBR	U.S. Bureau of Reclamation
USFS	U.S. Forest Service
USFWS	U.S. Fish and Wildlife Service
wk	week
WRF	Wetlands Research Facility
WWTP	wastewater treatment plant
yr	year

SECTION 1.0

Introduction to Treatment Wetlands

1.1 Overview

Wetlands are ecosystems that occur in areas where water conditions are intermediate between uplands and deep-water aquatic systems. Definitions focus on the dependence of wetland ecosystems on shallow water conditions, which result in saturated soils, low dissolved oxygen (DO) levels in the soils, and colonization by adapted plant and animal communities. Floating aquatic plant (FAP) systems share many properties with wetlands, except most macrophytic plants in FAP systems are floating rather than rooted. Wetland and FAP flora and fauna include microbial species (bacteria and fungi) that biologically transform and inactivate many pollutants. The ability of wetland and FAP systems to improve water quality naturally has been recognized for more than 25 years. During this same period, the use of wetland and FAP systems for water quality treatment has grown from a research concept to an accepted pollution control technology. In addition to improving wastewater quality, constructed wetlands can create additional wetland habitat. This ancillary benefit is especially important where natural wetlands are scarce, or where more greenspace is a public goal.

1.1.1 Constructed Wetland and Floating Aquatic Plant Systems

Wetlands and FAP systems have been engineered to treat wastewaters from municipal, industrial, and agricultural sources. Engineered treatment wetlands include both natural wetlands and wetlands constructed in upland areas. Dozens of pilot and demonstration wetland projects have been built and operated to prove and refine this technology, and dozens of full-scale applications exist throughout much of North America and Europe. Owners have found that engineered wetland and FAP systems often provide cost-effective, low-energy, natural alternatives to energy-intensive, conventional treatment. In addition to providing predictable and consistent water quality improvement, some wetland treatment systems also provide significant secondary benefits, which can be important during permitting and public review. These potential benefits include wildlife habitat creation and public recreation opportunities.

1.1.2 Treatment Wetlands in Arizona

The distribution of natural wetlands is limited in Arizona because of arid conditions and human development. In fact, natural wetlands occupy less than 1 percent of the state's land area (Dahl et al., 1991). Since the late 1970s, wetlands have been constructed in Arizona to accept municipal effluents. These constructed wetlands have provided habitat and advanced treatment of secondary-level effluents. Advanced or tertiary treatment of municipal wastewaters further reduces oxygen-demanding pollutants, suspended solids, and nutrients before ultimate discharge to surface or groundwater. Constructed wetlands for advanced treatment may be more cost-effective than conventional treatment processes in some locations, and the technology conserves energy and fossil fuels.

To date, no full-scale FAP treatment systems exist in Arizona. However, research at Pima County with water hyacinth (*Eichhornia crassipes*) and duckweed (*Lemna* spp.) FAP pilot systems has indicated that, like constructed wetlands, these aquatic systems can achieve advanced treatment goals. Interest in the use of FAP treatment systems in Arizona is expected to increase as smaller communities look for practical methods of improving water quality by retrofitting existing treatment lagoons.

1.2 Purpose and Content of this Manual

The use of engineered wetland and FAP treatment systems for wastewater treatment in Arizona is increasing rapidly. Information from constructed wetlands in Show Low and Pinetop-Lakeside in Arizona and Incline Village, Nevada, and Arcata, California, has generated interest in combining cost-effective wastewater treatment with creation of wildlife habitat and passive recreation areas. In response to this interest, the Arizona Department of Environmental Quality (ADEQ) has commissioned this manual to assist with planning and reviewing new engineered wetland and FAP treatment projects. This manual focuses on implementing engineered or constructed wetlands and FAP treatment systems in upland (non-jurisdictional wetlands[1]) areas.

This manual is intended to serve two purposes. First, it provides guidance to ADEQ to review permit applications for constructed wetland and FAP treatment systems. Second, this manual provides preliminary guidance to engineers and scientists in Arizona who are interested in the potential of constructed wetlands and FAP systems for wastewater management.

Although a large amount of published information on wetland and FAP treatment systems exists, these references are widely scattered and sometimes

[1] Natural wetlands that are defined as "Waters of the United States" are considered to be within the jurisdiction of Section 404 of the Clean Water Act.

difficult to obtain. Also, many of these references provide conflicting guidance on implementing constructed wetland and FAP systems for treatment. This manual consolidates this broad literature into a concise review specific to Arizona. The information is based on the experience of its authors, and it reflects the current consensus for planning, design, and operation of constructed wetland and FAP projects in Arizona. The engineer and permit reviewer should seek additional published information for insight into the historical developments of the technologies upon which this manual is based.

1.2.1 Organizational Preview

This manual is intended to provide a reference for planning and reviewing constructed wetland and FAP treatment system projects in Arizona. Section 2 summarizes the structure and function of wetlands and aquatic ecosystems in Arizona. The section categorizes the state's major wetland and aquatic ecosystem types and summarizes their typical components including landform and soils, hydrology, flora, and fauna. The section ends with a brief review of the water quality functions of wetland and FAP systems.

Section 3 reviews the published information on wetland and FAP systems that have been engineered for water quality treatment. The section provides a brief historical perspective and then presents general knowledge about this technology according to the North American Wetland Treatment System Database and published information about FAP treatment systems.

Section 4 provides case histories for constructed wetland and FAP treatment systems in Arizona and other areas with similar climatic conditions. These case histories are expected to be useful to designers who are new to this technology and who wish to identify sites where they can examine project successes and difficulties.

Section 5 summarizes design considerations for constructed wetlands in Arizona. This section discusses site selection and planning issues and then provides design guidelines for three types of constructed wetlands (surface flow, subsurface flow, and FAP systems).

Section 6 gives guidelines for incorporating ancillary benefits such as wildlife enhancement and public access into constructed wetland projects. The section also discusses available information on controlling nuisance conditions.

Section 7 summarizes information concerning the operation and monitoring of constructed wetlands. This section focuses on the importance of monitoring for successful operation and discusses methods for guiding plant development and optimizing water quality renovation.

Section 8 summarizes the regulatory requirements that pertain to the use of constructed wetland and FAP systems for wastewater management in Arizona. These regulatory issues include federal, state, and local requirements.

Section 9 lists the major published literature sources with detailed information on the use of constructed wetland and FAP systems for water quality treatment. Many of the published papers are consolidated in a relatively small number of symposia proceedings, while others are scattered in individual reports and in scientific journals. One comprehensive book on wetland treatment systems will be published in 1995, and several other textbooks include chapters on design of wetland and FAP systems.

1.2.2 Data Quality

This manual reviews information from a wide variety of sources. Although all of these data describe wetland treatment systems, the depth of expertise and financial resources of different researchers and dischargers varies greatly. As a result, the data summarized in this report reflect a variety of design criteria, operational controls, monitoring efforts, commitment in resources, and quality control. Thus, the reader should use discretion in making interpretations based on specific, limited data. Before making conclusions that will be used to implement a new constructed wetland treatment system, the reader should look for general trends and confirmation among the cited studies.

SECTION 2.0

Structure and Function of Wetland Ecosystems

2.1 Introduction

A basic understanding of wetlands ecology is essential to predict and interpret the performance of constructed wetland treatment systems. This section summarizes the major structural and functional components of natural and constructed wetlands in Arizona. For a more thorough description of wetlands ecology, the reader should refer to the comprehensive book on this subject by Mitsch and Gosselink (1993).

Two aspects are important to understand the interaction between wetlands and wastewater effluents: (1) the effects of the wastewater on the wetland ecosystem and (2) the effects of the wetland ecosystem on the wastewater quality.

Adding wastewater to wetlands causes physical, chemical, and biological changes to a wetland's ecology. These changes result from the presence of more water; from altered temperature or water clarity; from the influence of chemical pollutants that stimulate growth, deplete oxygen, or cause toxicity; from microbes or other biological components in the wastewater; and from disruptive construction or operation processes.

The influence of wetlands on wastewater generally includes reducing pollutant concentrations, changing water properties such as temperature and clarity, and changing microbial or algal components of the wastewater. However, under some conditions, the wetlands also might increase concentrations of some wastewater pollutants.

Although the engineer or scientist may prefer to concentrate on the second set of interactions (the effects of the wetland on the wastewater quality), the wetland designer and manager must consider the equally important effects of the wastewater on the wetland. Without careful attention, drastic ecosystem changes could occur, causing inadequate water quality treatment or failure to meet other project goals as a result of poor plant survival or the development of nuisance conditions.

2.1.1 What are Wetlands?

Natural wetlands are found in a diverse array of land forms, climates, and geographies. The component common to diverse wetland types such as swamps, marshes, fens, and sloughs is the presence of standing water or saturated soils during a portion of the vegetation's growing season. The definition of wetlands used by various agencies of the U.S. government includes these words from Cowardin et al. (1979):

> *Wetlands are lands transitional between terrestrial and aquatic systems where the water table is usually at or near the surface or the land is covered by shallow water.*

and this description from the Clean Water Act (CWA) Amendments of 1977 (33 CFR.323.2(c)):

> *The term "wetlands" means those areas that are inundated or saturated by surface or groundwater at a frequency and duration sufficient to support, and that under normal circumstances do support, a prevalence of vegetation typically adapted for life in saturated soil conditions. Wetlands generally include swamps, marshes, bogs, and similar areas.*

For Arizona wetlands, this definition includes regionally-important wetland categories such as cienegas and tinajas.

According to the U.S. Fish and Wildlife Service (USFWS) Wetlands Classification, wetlands are distinguished by water depth, water salinity, and vegetation type (Table 2-1). This classification system applies to both natural and constructed wetlands. Typically, only palustrine and lacustrine wetland classes (non-tidal, emergent vegetation) are used for effluent treatment.

Wetlands also can be classified by origin. Natural wetlands were created by non-human geophysical factors such as erosion, subsidence, limestone solution, and earthquakes, or by biological factors such as beaver dams. Constructed wetlands are created by human activities. Increasingly, wetlands are constructed for benefits besides water quality treatment. For example, constructed wetlands mitigate impacts to natural wetlands and provide habitat for wildlife, aquaculture, or public use.

2.1.2 General Description of Arizona Wetlands and Riparian Areas

Despite its arid climate, a wide variety of wetland and riparian habitats naturally occur in Arizona. These habitats include freshwater marshes that still remain along the backwaters of the Lower Colorado River; remnant cienega habitats in southeastern Arizona; remaining fragments of the formerly extensive cottonwood-willow riparian forests along the major river systems that traverse the lower portions of the state; xeroriparian habitats dominated by mesquite (*Prosopis* spp.), blue paloverde (*Cercidium floridum*), and ironwood *(Olneya tesota)*; and numerous small isolated wetlands associated with springs and seeps. The species composition and structure of these communities are as diverse as the topography over which they are found..

Table 2-1. USFWS Classification System for Wetlands and Aquatic Habitats.

System	Subsystem	Class
Marine (open oceanfront)	Subtidal (continuously submerged)	Rock bottom; unconsolidated bottom; aquatic bed; reef
	Intertidal (exposed at low tide)	Aquatic bed; reef; rocky shore; unconsolidated shore
Estuarine (tidal embayments; variable salinity)	Subtidal (continuously submerged)	Rock bottom; unconsolidated bottom; aquatic bed; reef
	Intertidal (exposed at low tide)	Aquatic bed; reef; streambed; rocky shore; unconsolidated shore; emergent wetland; scrub-shrub wetland; forested wetland
Riverine (associated with river channels)	Tidal (fluctuating flows)	Rock bottom; unconsolidated bottom; aquatic bed; rocky shore; unconsolidated shore; emergent wetland
	Perennial (continuously inundated)	Rock bottom; unconsolidated bottom; aquatic bed; rocky shore; unconsolidated shore; emergent wetland
	Intermittent (seasonally exposed)	Streambed
Lacustrine (associated with lakes)	Limnetic (deep water)	Rock bottom; unconsolidated bottom; aquatic bed
	Littoral (shoreline, shallow water)	Rock bottom; unconsolidated bottom; aquatic bed; rocky shore; unconsolidated shore; emergent wetland
Palustrine (non-tidal, emergent vegetation)	None	Rock bottom; unconsolidated bottom; aquatic bed; unconsolidated shore; moss-lichen wetland; emergent wetland; scrub-shrub wetland; forested wetland

Source: Modified from Cowardin et al. (1979).

The species composition and structure of Arizona riparian habitats reflects a response to a hydrologic continuum like that indicated by the federal wetlands definition discussed above. Riparian habitats in Arizona can be further subdivided into xeroriparian (the driest), mesoriparian, and hydroriparian (the wettest) habitats. Some of the hydroriparian plant communities found in Arizona would be considered jurisdictional wetlands based on the criteria found in the U.S. Army Corps of Engineers (ACOE) manual for identification and delineation of wetlands (ACOE, 1987).

Appendix A summarizes some of the plant species that naturally occur in wetlands in Arizona. For each species, the growth habit, typical hydrologic ranges, appropriate soil types, elevation range, frequency of occurrence, and geographic distribution are provided.

In simplest terms, Arizona can be divided into three primary geographic regions (Figure 2-1): the warm, dry plains of southern Arizona (the Basin and Range Region); the cooler and wetter mountains that extend diagonally across the state from the northwest to the southeast (the Central Highlands); and the high plains to the north (the Colorado Plateau). Within each region, however, varied topography complicates generalizations. The Colorado River, for example, dissects the Colorado Plateau and creates low elevation communities near the bottom of the Grand Canyon that are similar to those of the Basin and Range Region. Similarly, at higher elevations within the mountains of the Basin and Range Region, habitats may be similar to those within the Central Highlands or the Colorado Plateau. With these examples in mind, the general natural wetland communities within each region can be described more accurately by considering local elevation.

2.1.2.1 Riparian Wetlands

The most common type of natural wetlands in Arizona is the interior southwestern riparian woodland (Brown et al., 1984). Brown et al. (1984) have divided this unit further into the cottonwood-willow series and the mixed broadleaf series. The series are then divided into associations according to the prevalent species. Fremont cottonwood (*Populus fremontii*), sycamore (*Platanus wrightii*), willow (*Salix gooddingii* and other species), and velvet ash (*Fraxanis velutina*) are the most conspicuous species overall, as evidenced by the hundreds of Arizona topographical features named after them. Although fairly pure stands of any of these trees occur, most riparian woodlands of Arizona are composed of various mixtures. Salt cedar (*Tamarix chinensis*) is common and often abundant in disturbed wetlands throughout lower elevations. The willows become more prevalent in the higher elevations and additional tree species, such as alder (*Alnus oblongifolia*) and narrow leaf cottonwood (*Populus angustifolia*), become important. Although numerous shrubs, such as *Acacia greggii*, *Amelanchier utahensis*, *Amorpha frutesens*, *A. californica*, *Celtis reticulata*, *Cercidium floridum*, *Chilopsis linearis*, *Fendlera rupicola*, *Forestiera pubescens*, *Mimosa biuncifera*, *Morus microphylla*, *Prosopis glutinosa*, *P. velutina*, *Ptelea trifoliata*, *Quercus gambelii*, *Rhus glabra*, *R. ovata*, *R. trilobata*, *Rhamnus crocea*, *R. californica*, *Ribes cerneum*, *Robinia neomexicana*, *Rosa woodsii*, *Sambucus mexicana*, *Sapindus saponaria*, and *Ziziphus obtusifolia* are scattered throughout riparian communities, none of these are obligate wetland species and rarely occur as dominant elements. Several vines, such as *Clematis drummondii*, *C. ligusticifolia*, *Humulus lupulus*, *Marah gilensis*, *Parthenocissus inserta*, *Sarcostemma cynanchoides*, and *Vitis arizonicus* are also frequent.

The structure of natural wetland woodlands depends largely on the amount and flow rate of water through the system and the system's ability to retain water. In Arizona, where rains are usually intense and short, plant communities face sporadic, large flows of water. Rain from these storms tends to infiltrate the soil only minimally, because of the watershed's relatively low infiltration potential.

In addition to the stresses imposed by rain and soil conditions, Arizona's riparian areas have evolved with catastrophic flood regimes, resulting in scoured areas ranging from cobble-filled channels to closed-canopy woodlands with an impoverished perennial herb layer. Groundwater loss and damming also have contributed to the loss and degradation of Arizona's natural riparian wetlands.

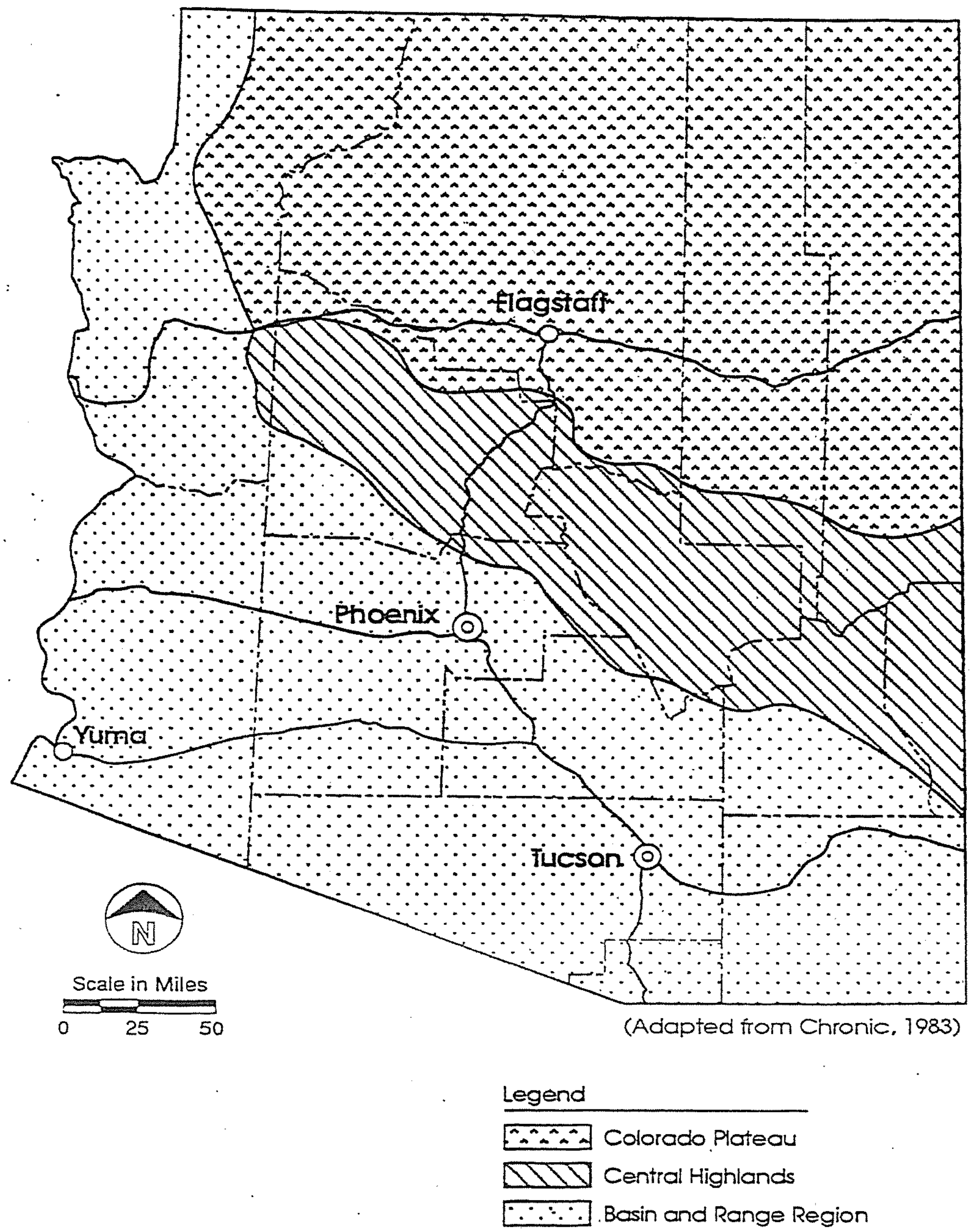


Figure 2-1. Arizon's Primary Geographic Regions. The species composition and structure of wetlands vary according to region and elevation.

In riparian areas where water flow has been stable for several years, a diversity of soil-stabilizing herbaceous perennials, such as cattails (*Typha* spp.), rushes (*Juncus* spp.), spikerushes (*Eleocharis* spp.), sedges (*Carex* spp.), flat-sedges (*Cyperus* spp.), grasses, horsetails (*Equisetum* spp.), and bulrushes (*Scirpus* spp.), are present. When these species remain or reestablish, they add to the stability of the plant community by catching silt and slowing the flow of water. Then, water is more likely to infiltrate the area rather than running off and eroding the soils.

2.1.2.2 Marshlands

Cienegas (natural groundwater-controlled marshlands) historically were never abundant in Arizona and have become increasingly rare because of groundwater depletion. Some have been damaged by pollution. Water flow in Arizona's healthy cienegas is slow and stable. Many of the same perennial herb species that reflect stability in riparian systems occur in cienegas in great abundance. The natural marshlands of Arizona range from the Mohavian, Sonoran, and Chihuahuan Interior Marshlands of the Basin and Range Region to the Rocky Mountain Alpine and Subalpine Marshlands of the higher elevations. Associations based on species dominance are usually localized, because these communities have high species diversity.

2.1.2.3 Lakes and Ponds

Arizona's lakes and ponds are largely artificial, and their water levels often fluctuate greatly. This fluctuation impedes the establishment of stable wetland plant communities. Where water levels have remained stable, the edges of lakes and ponds resemble marsh communities. Tree species, such as those found in riparian communities, generally occur a short distance from the water's edge, especially adjacent to water inflow and outflow channels.

Cattails, followed by bulrushes, are usually the first to invade newly formed or renewed lakes and large ponds (Correll and Correll, 1972). Pondweed

(*Potamogeton* spp.) is also a common early pioneer, especially in small bodies of water, such as cattle tanks. Submersed macrophytes, such as horned-pondweed (*Zannichellia palustris*), hornwort (*Ceratophyllum demersum*), submersed pondweeds (*Potamogeton* spp., in part), naiad (*Najas maritima*), and water-weed (*Elodea* spp.), are often early pioneers in ponds but generally occur later in lakes. These eventually decrease with nutrient loading, increases in phytoplankton densities, and loss of available light (Wetzel, 1983). Rushes and spike-rushes are ubiquitous along the edges (littoral zone) of small bodies of water, at least where cattle have not been concentrated. Although numerous aquatic species occur in Arizona, only a few species typically occur in a single water body.

2.1.3 Constructed Wetlands

A growing inventory of constructed wetlands can be found throughout Arizona. Increasingly, treatment wetlands are creating new habitat or restoring damaged habitat. Riparian wetlands are being created on a limited basis at some sites as mitigation for development impacts. Aquatic habitat has increased throughout the state in the form of treatment lagoons and multipurpose reservoirs.

Wetland and aquatic habitats can be constructed throughout the state where the land is not overly rocky or hilly and when water is available. Constructed wetlands and FAP treatment systems are a potential wastewater management alternative that can be considered nearly anywhere in Arizona. Section 4.0 contains examples from arid and semiarid climates.

2.2 Wetland Structure

Wherever they are located, different wetland types usually share general structural components such as landform, water, soils, plants, microbes, detritus, and fauna (Figure 2-2). This section briefly describes how these components affect a wetland's ability to remove pollutants from wastewater.

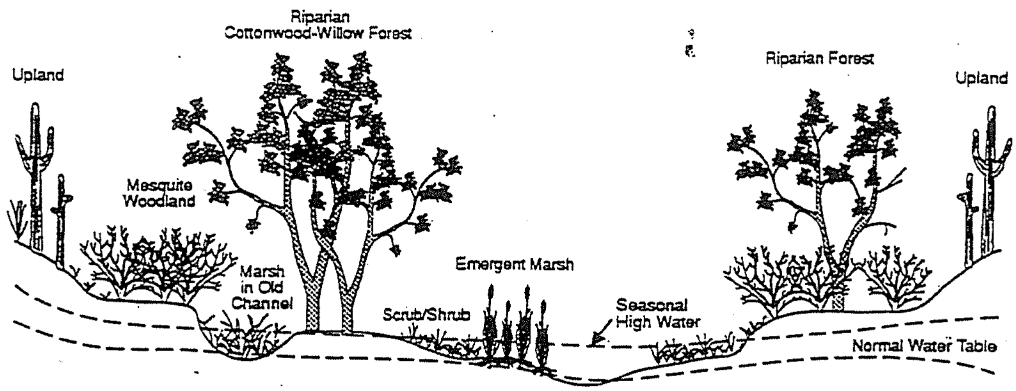


***Figure 2-2. Typical Structural Components.** Although the species vary with location, similar structural components occur in most wetland ecosystems in Arizona.*

2.2.1 Landform

The wetland's landform determines the level and duration of flooding. Natural wetland landforms include the following: closed and open basins in rock or a variety of soils, broad tidal and non-tidal flats, floodplain terraces, and shelves fringing lakes and rivers. These landforms result from natural processes that can occur over very long time periods.

In constructed wetlands, creating the appropriate landform is frequently the most expensive component, and the value of natural energies to create natural wetland landforms becomes apparent. Leveling hilly areas to allow sheetflow of effluent and constructing berms to retain water and allow maintenance can result in significant construction costs.

2.2.2 Hydrology

In most cases, hydrology is the dominant environmental factor dictating the structure and function of wetland ecosystems. A wetland's hydrology depends on its water balance, or the inflows and outflows of water. For treatment wetlands, a water balance can be prepared using local climatic precipitation, evaporation, and infiltration data. A water balance can help estimate the magnitude of surface discharges in response to various hydraulic loadings.

The water balance varies depending on the degree to which the system is open or closed and whether water flows through or over soil layers. Many natural wetlands are open systems whereby water flows in from rainfall and runoff and water flows out to an adjacent system such as a river, lake, or another wetland. Constructed treatment wetlands generally receive only rainfall and pretreated wastewater. Unless specifically planned, stormwater runoff is excluded from constructed treatment wetlands. In general, nearly all wetland treatment systems have some discharge to surface water or groundwater.

Wetlands without surface outlets lose water only by evapotranspiration (the sum of evaporation and plant transpiration) and infiltration to the ground. Closed drainages that lose water only by evapotranspiration may accumulate salts and trace metals over time. Examples of wetlands that do not discharge to surface water include treatment wetlands in arid or semiarid climates where hydraulic loadings are low and evapotranspiration exceeds rainfall, and treatment wetlands that provide feedwater for rapid infiltration beds, land application, or reuse.

Three aspects of wetland hydrology are particularly important: the duration and seasonality of flooding (hydroperiod), and the depth of flooding. Depth/duration curves provide a convenient tool for summarizing these two interrelated hydrological properties (Figure 2-3). The duration of flooded or saturated soil conditions in areas classified as wetlands by the U.S. Environmental Protection Agency (EPA) vary from less than a few weeks per year to continuous flooding. Wetlands used for water quality treatment usually remain flooded continuously or seasonally.

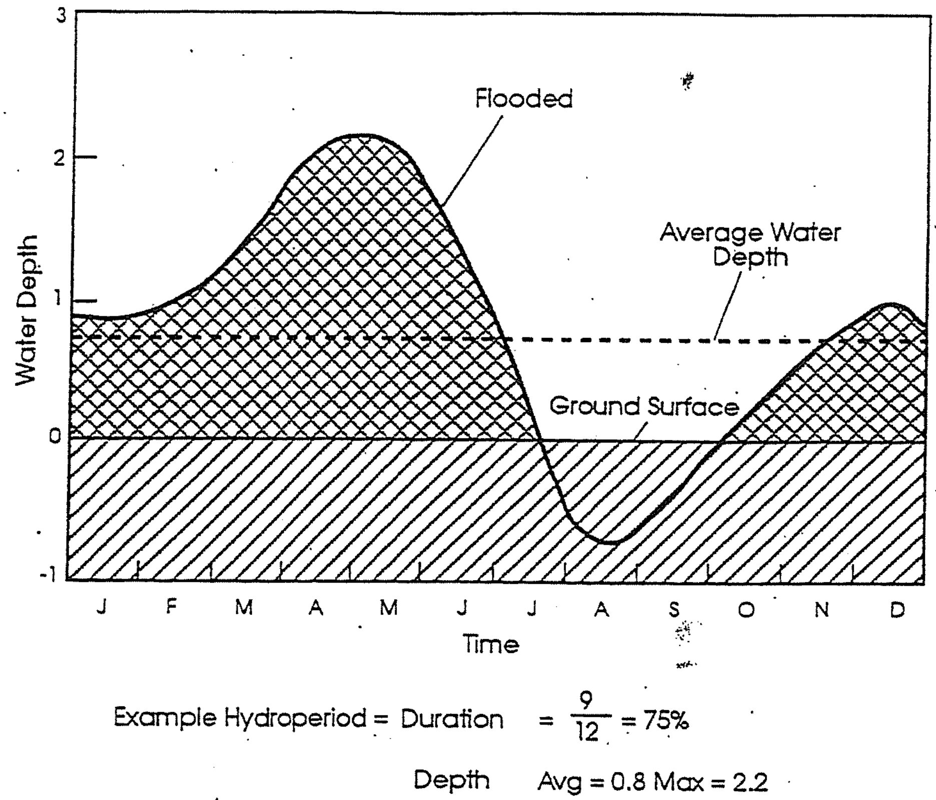


Figure 2-3. Depth/Duration Curve. The hydroperiod and the depth of flooding influence a wetland's structure and function.

In natural wetlands, average water depths vary from below the ground surface to several meters. Treatment wetlands generally have water depths less than 60 centimeters (cm). As discussed below, perennially flooded conditions in most treatment wetlands limit the plant communities that can be established and maintained. Although fluctuating water levels with intermittent drydown periods can be incorporated in constructed wetlands to promote transitional and riparian plant species, this operational mode reduces hydraulic residence time and wetland treatment capacity.

2.2.3 Soils

A wetland's ability to assimilate pollutants depends partly on the physical and chemical characteristics of soils. Wetland soils vary greatly, and their composition reflects parent geological materials or processes occurring in the wetlands. Soils classification is based partially on texture and on the ratio of organic to inorganic matter. Mineral soils are classified according to the content of sand, silt, and clay.

2.2.3.1 Organic Matter

High organic matter content facilitates some physical and chemical sorption processes and encourages growth of specific microbes and plants. Compared to upland soils, wetland soils generally have a higher proportion of organic matter because of the reduced rate of organic matter degradation under flooded soil conditions. Young wetland soils may have low organic matter content, but as the wetland matures, the organic matter content usually increases. The organic matter content increases faster with high nutrient or organic loadings into the wetland.

Some wetland soils with very high organic components are called peats. These soils usually develop under conditions of high rates of plant production or low rates of organic decay. In peat wetlands, plants die, settle to the sediment surface, and become buried before full decomposition. The plants do not fully decompose because inadequate DO or the scarcity of nutrients (usually nitrogen) hinders microbial processes.

2.2.3.2 Chemical Properties

Chemical properties such as a soil's cation exchange capacity (CEC), pH, redox potential, and DO content may be very important to the ability of treatment wetlands to remove pollutants. A soil's cation exchange capacity is a measure of its ability to adsorb and retain metal ions including calcium, magnesium, potassium, and sodium. Because divalent cations are preferentially partitioned to CEC sites, they provide for potential removals of metals such as copper, cadmium, nickel, and zinc. In turn, some cations such as aluminum, iron, and calcium help regulate the quantity of other ions such as phosphate and ammonium that can be retained by the wetland soil. Organic matter may also contribute to the overall adsorption capacity of wetland soils. Typically, clays and clayey loams have higher CECs and overall adsorption capacities than sandy soils.

Hydrogen ion content (pH) affects all chemical reactions in wetland soils. Natural wetlands exhibit a wide range of pH values, from less than 4 in acidic bogs to more than 10 in some arid region evaporite systems. Optimal pH ranges are known for most pollutant transformation or reduction processes occurring in wetland systems. For example, high pH facilitates volatilization of ammonia nitrogen with subsequent loss to the atmosphere. Low pH results in increased metals solubility and poor metals sorption. Moderate pH is important to nitrify ammonia nitrogen to nitrate.

The concentration of DO in wetland soils and in the water also is critical to all aspects of wetland ecology and water quality treatment. Wetland soils have steep redox (oxidation/reduction) gradients because of oxygen-demanding microbial and chemical processes. Microbes need oxygen to decompose organic carbon and transform ammonia nitrogen to nitrate nitrogen. In addition, many chemical reactions consume oxygen. Microbes often catalyze reactions that oxidize reduced forms of iron, manganese, and sulfur. In soils where free oxygen is depleted, oxidized compounds such as nitrate and ferric iron may be reduced, giving up oxygen atoms with free electrons in the process.

2.2.3.3 Physical Properties

The soil's physical properties are also important to water quality. For example, highly-permeable sandy or gravelly soils may allow excessive infiltration and not maintain adequate moisture for wetland plants. Clayey soils are less permeable, but they can cause problems for plant root development. Loamy and sandy soils underlain by clay provide a rooting medium for wetland plants while reducing exchange with groundwater.

2.2.4 Plant Communities

Dozens of plant species occur in natural and constructed wetlands in Arizona. Although most of these species do not occur in treatment wetlands, wetlands can be designed to encourage plant diversity. Plants must be selected to meet project goals.

Each plant species has specific growth requirements related to water depth and the soil's nutrient and oxygen content. Hydrology affects plant growth partially through its influence on DO levels in the soil. Because oxygen diffuses through water more slowly than through air (about 10,000 times slower) and because of the high oxygen demand of decaying organic material, DO is frequently depleted in wetland surface water and soils faster than it can be supplied by diffusion from the atmosphere. Low DO levels in soils limit the ability of many plants to survive in flooded conditions. To survive, wetland plants have developed morphological and physiological adaptations that increase oxygen transport to the plant roots.

Adaptations that allow plants to survive and grow in wetlands include aerenchymous tissues, adventitious roots, and buttresses and knees. Aerenchymous tissues consist of a network of air spaces within plant stems that allow relatively free movement of air from the atmosphere to the roots. Oxygen diffuses to the root zone, which has lower oxygen pressure. Some plants grow adventitious roots, which extrude from the stem above the level of the soils in flooded environments. These roots supply oxygen from the water column, where it may be more available than in the anaerobic soil layer. Wetland tree species may develop extensive buttresses within the zone of fluctuating water levels. These buttresses increase the tree's surface area so that atmospheric gases can enter the tree's root system.

The most commonly used plants in constructed treatment wetlands are cattails, bulrush, and common reed (*Phragmites communis*). Floating aquatic plant systems typically use duckweed or water hyacinth. Appendix A lists other native riparian and wetland plants potentially suitable for constructed wetlands in Arizona.

2.2.5 Animal Communities

Animal diversity is generally a function of the structural and plant diversity within the wetland and its position relative to other habitats. Typical wetland animal groups include invertebrates, fish, amphibians, reptiles, birds, and mammals. Invertebrates include hundreds of species of protozoans, water fleas, crayfish, and aquatic insects, as well as a diverse array of spiders and insects in the above-water portion of the wetland. In most treatment wetlands, mosquito-feeding fish and other topminnows capable of living in low oxygen environments are dominant. Other forage and even some sport or commercial fish may occur in treatment wetlands with adequate water depth and DO conditions. Amphibians usually include a variety of frogs, and wetland reptiles include snakes and lizards. Hundreds of species of birds depend on wetland environments. In fact, birds usually are the most visible faunal component of wetland treatment systems. Small and large mammals also occur in wetlands used for water quality treatment.

Animals are important in wetland treatment systems because they help cycle nutrients and maintain plant and microbial populations. Without microscopic and macroscopic animals to help break down plant litter, treatment wetlands would rapidly fill with undecayed organic litter, and their functional ability would be greatly reduced. A food chain of animals is essential to maintain the proper balance of consumers at each functional level of the wetland ecosystem. The absence of key animal groups in treatment wetlands may indicate stressed conditions that jeopardize the system's performance.

In some wetland treatment systems, wildlife enhancement may be a regulatory or environmental goal. Wetlands can be designed to support the populations and diversity of certain animal groups, such as fish and birds. In those cases, reducing pollutant loadings by either increasing pretreatment or lowering hydraulic loading (greater wetland area for a given wastewater flow) often will increase DO in the wetland water column. As a result, invertebrates and fish populations will prosper and provide forage for wetland-dependent bird species. Deeper, open-water areas will attract waterfowl, and islands and tree snags will provide nesting and roosting habitat. Similarly, seasonally migrant wading birds can be attracted by lowering water depths to create mud flats for foraging. If wildlife habitat enhancement is a goal, the target animal species or groups need to be identified early in the design process.

2.3 Water Quality Improvement Function

As Figure 2-4 shows, wetlands physically filter water and provide conditions that facilitate the chemical and biological processes that cleanse water. Pollutants are taken up and transformed by plants and microbes, buried in sediments, or released in the wetland's discharge.

2.3.1 The Role of Plants

Plants improve water quality by slowing water flow, settling solids, taking up wastewater pollutants, and providing structure for microbes (bacteria and fungi). Of these functions, the most important are physical; dense stands of vegetation create the quiescent conditions that facilitate the physical, chemical, and biological processes that cleanse water. Most herbaceous wetland plants die annually; because this dead plant material requires months to years to decompose, a dense layer of plant litter accumulates. Like the living vegetation, the litter physically filters solids. Microbes decompose the litter and release some of the nutrients that have been taken up by plants, such as nitrogen and phosphorus. The entire uptake and release cycle repeats seasonally and spatially within the wetland, resulting in the gradual "spiralling" of these elements through the system, with some being trapped or transformed and some being discharged downstream.

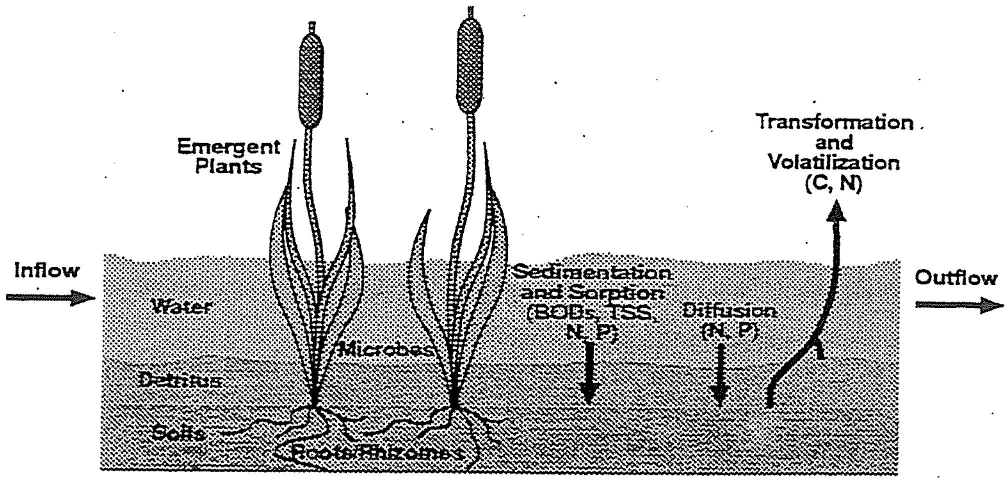


Figure 2-4. Wetland Processes to Improve Water Quality. *Wetland microbes, plants, and soils transform and take up pollutants in the wastewater.*

2.3.2 The Role of Microbes

Live and dead plant material in wetland treatment systems supports a diverse, attached microbial community that mediates the majority of pollutant transformations vital for long-term performance. The most important microbial processes are decomposition of organic matter (including carbonaceous wastewater solids), ammonification (conversion of organic nitrogen to ammonia), nitrification (conversion of ammonia to nitrite and nitrate), and denitrification (loss of nitrogen to the atmosphere).

An array of heterotrophic bacteria and fungi use organic compounds for energy production and growth. Both aerobic and anaerobic decomposition occur in wetlands, and some or all of the original carbon is converted to carbon dioxide, which is lost to the atmosphere. Organic compounds vary in their resistance to microbial decay; some break down in minutes or hours, but others such as humates and tannins strongly resist degradation. Long residence time in wetland treatment systems can increase removal rates for recalcitrant organic compounds.

The processes by which microbes transform and remove nitrogen from wastewaters are complex. Through aerobic and anaerobic processes, microbes transform organic nitrogen to ammonia nitrogen. This ammonia nitrogen is then available to wetland plants as a nutrient. In aerobic environments, microbes transform ammonia nitrogen by nitrification (oxidation) to nitrite and nitrate nitrogen. In turn, during the decomposition of organic matter, nitrate nitrogen is reduced to nitrogen gas, which escapes to the atmosphere. Under some conditions (usually high pH and high temperatures), ammonia also may be lost directly to the atmosphere via volatilization.

2.3.3 The Role of Sediments

Elements that cannot be biologically or chemically transformed still can be removed functionally from the wastewater by sorption in the soils or in the plant litter followed by burial of these materials as new sediments. Sediment accretion rates in wetlands vary depending on inputs of mineral (non-degradable) solids and the wetland's plant productivity and decomposition rates. In some wetland treatment systems, sediments store a significant amount of nutrients and metals.

SECTION 3.0

Wetland Ecosystems for Water Quality Enhancement

3.1 Introduction

This section summarizes the most important developments of the wetland treatment technology in North America with particular emphasis on Arizona and the Southwest. Thousands of scientific articles and reports have been published concerning the potential of wetlands for wastewater treatment. There are hundreds of operational wetland treatment systems in North America and about a dozen operational wetlands in Arizona. A review of information available from some of these systems will provide a useful basis for review of new wetland proposals in Arizona.

3.1.1 Types of Constructed Wetlands

Natural wetlands have received wastewaters for many years. Information on the quality of water exiting these natural wetlands led scientists and engineers to realize the potential benefits of wetlands and to purposely include them in wastewater management systems. Constructed wetlands include systems with surface flow (SF) and with subsurface flow (SSF) through a gravel or soil media. Aquatic systems have deeper water and floating aquatic plants. Figure 3-1 illustrates the three basic types of constructed wetlands (SF, SSF, FAP) that can be used for water quality treatment in Arizona.

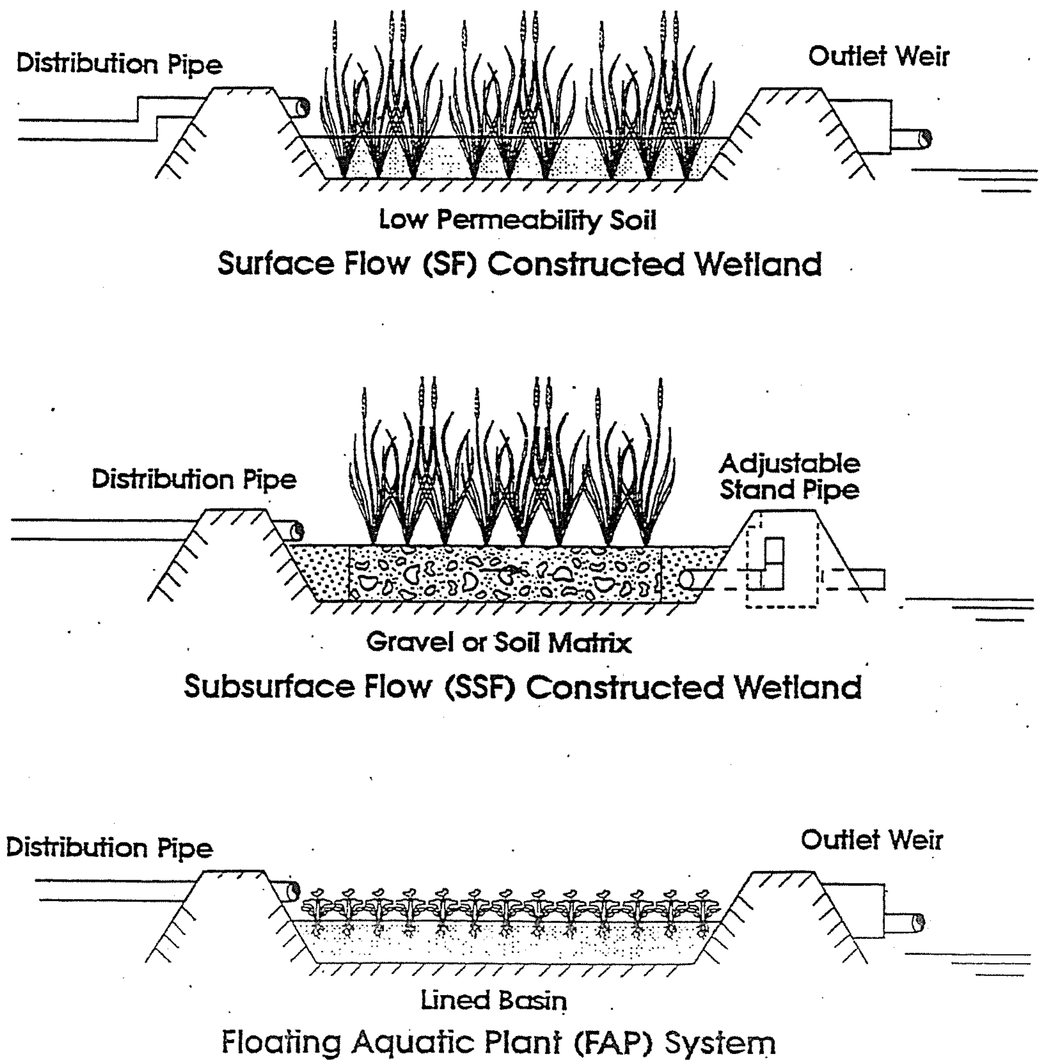


Figure 3-1. Types of Constructed Wetlands. The choice of the most appropriate technology depends on influent quality, effluent goals, and land availability.

Constructed wetlands treat municipal, industrial, and agricultural wastewaters and stormwater. Municipal wastewaters include domestic and commercial wastewaters pretreated in lagoons, septic tanks, or conventional primary, secondary, and tertiary processes (screening, primary settling, trickling filters, and activated sludge). Industrial wastewaters discharged to wetlands for advanced treatment include food processing wastes, textile wastes, chemical facility and refinery wastes, cooling tower blow-down waters, and pulp and paper effluents. Agricultural wastewaters include dairy wastes, feedlot wastewaters, hog farrowing wastewaters, and runoff from many agricultural practices. In addition, wetlands receive point and nonpoint runoff from cities, malls, residential developments, agricultural lands, and watersheds.

3.1.2 Historical Perspective

Increasingly over the past 40 years, natural and constructed wetlands have been engineered for wastewater treatment. The development of the wetlands treatment technology reflects the collective efforts of scientists and engineers who have designed and studied pilot and full-scale wetland treatment systems. Historical studies, full-scale projects, and conferences key to the technology's development are summarized in Table 3-1. The table also lists important published literature and conference proceedings that provide the scientific basis for the wetland treatment technology.

The earliest wetland treatment systems were SSF systems in Europe to treat agricultural and domestic wastewaters. Soil-based SSF wetlands are still the most common application of this technology outside of North America. Research in Michigan, Florida, Mississippi, Wisconsin, and New York in the 1970s led to an expanding number of treatment wetlands in North America. Subsurface flow wetlands using gravel substrates have been promoted in several southern states. Surface flow constructed and natural wetlands for advanced treatment of municipal wastewaters were built throughout North America during the 1980s and 1990s.

Table 3-1. Timeline of Selected Events in Wetland Treatment Technology.

Date	Location	Description
		Selected Research Efforts
1952-late 1970s	Plon, Germany	Removal of phenols and dairy wastewater treatment with bulrush plants by K. Seidel and R. Kickuth
1967-1972	Morehead City, NC	Constructed estuarine ponds and natural salt marsh studies of municipal effluent recycling by H.T. Odum and associates
1971-1975	Woods Hole, MA	Potential of natural salt marshes to remove nutrients, heavy metals, and organics was studied by I. Valiela, J.M. Teal and associates
1972-1977	Porter Ranch, MI	Natural wetland treatment of municipal wastewater by R.H. Kadlec and associates
1973-1974	Dulac, LA	Discharge of fish processing waste to a freshwater marsh by J.W. Day and coworkers
1973-1975	Seymour, WI	Pollutant removal in constructed marshes planted with bulrush by Spangler and coworkers
1973-1976	Brookhaven, NY	Meadow/marsh/pond systems by M.M. Small and associates
1973-1977	Gainesville, Florida	Cypress wetlands for recycling of municipal wastewaters by H.T. Odum, K. Ewel, and associates
1974-1975	Brillion, WI	Phosphorus removal in constructed and natural marsh wetlands by F.L. Spangler and associates
1974-1988	NSTL Station, MS	Gravel-based, subsurface flow wetlands tested for recycling municipal wastewaters and priority pollutants by B.C. Wolverton and coworkers
1975-1977	Trenton, NJ	Small enclosures in the Hamilton Marshes (freshwater tidal) were irrigated with treated sewage by Whigham and coworkers
1976-1979	Eagle Lake, IA	Assimilation of agricultural drainage and municipal wastewater nutrients in a natural marsh wetland by G.B. Davis, A.G. van der Valk, and coworkers
1976-1982	Southeast Florida	Nutrient removal in natural marsh wetlands receiving agricultural drainage waters by F.E. Davis, A.C. Federico, A.L. Goldstein, S.M. Davis, and coworkers

Table 3-1. (Continued)

Date	Location	Description
		Selected Research Efforts (continued)
1979-1982	Arcata, CA	Pilot wetland treatment system for municipal wastewater treatment by Gearheart and coworkers
1979-1982	Humboldt, SK	Batch treatment of raw municipal sewage in lagoons and wetland trenches by Lakshman and coworkers
1980-1984	Listowel, Ontario	Constructed marsh wetlands were tested for treatment of municipal wastewater under a variety of design and operating conditions by Herskowitz and associates
1981-1984	Santee, CA	Subsurface flow wetlands were tested for treatment of municipal wastewaters by R.M. Gersberg and coworkers
		Selected Full-Scale Projects
1972	Bellaire, MI	Natural forested wetland receiving municipal wastewaters
1973	Mt. View, CA	Constructed wetlands for municipal wastewater treatment
1974	Othfresen, West Germany	Full-scale root zone facility treating municipal wastewater based on the design method of Kikuth and coworkers
1975	Mandan, ND	Constructed ponds and marshes to treat runoff and pretreated process wastewater from an oil refinery by Litchfield
1977	Lake Buena Vista, FL	Natural forested wetland was used for year-round advanced treatment and disposal of up to 27,700 m^3/d of municipal wastewater
1978	Houghton Lake, MI	Natural peatland receiving summer flows of municipal wastewater
1979	Drummond, WI	Sphagnum bog receiving summer flows from a facultative lagoon
1979	Show Low, AZ	Constructed wetland ponds for municipal wastewater treatment and wildlife enhancement

Table 3-1. (Continued)

Date	Location	Description
		Selected Full-Scale Projects (continued)
1984	Incline Village, NV	Constructed wetlands for total assimilation (zero discharge) of municipal effluent
1986	Arcata, CA	Constructed marsh wetlands for municipal wastewater treatment
1987	Myrtle Beach, SC	Natural Carolina bay wetlands for municipal wastewater treatment
1991	Columbus, MS	First full-scale constructed wetland for advanced treatment of pulp and paper mill wastewater
1993	Everglades, FL	Treatment of phosphorus in agricultural runoff in a 1,380-ha constructed filtering marsh
		Major Conferences
May 1976	Ann Arbor, MI	Freshwater Wetland and Sewage Effluent Disposal (Tilton et al., 1976)
February 1978	Tallahassee, FL	Environmental Quality Through Wetlands Utilization (Drew, 1978)
November 1978	Lake Buena Vista, FL	Wetland Functions and Values (Greeson et al., 1979)
July 1979	Higgins Lake, MI	Freshwater Wetland and Sanitary Wastewater Disposal (Sutherland and Kadlec, 1979)
September 1979	Davis, CA	Aquaculture Systems for Wastewater Treatment (Bastian and Reed, 1979)
June 1981	St. Paul, MN	Wetland Values and Management (Richardson, 1981)
June 1982	Amherst, MA	Ecological Considerations in Wetlands Treatment of Municipal Wastewaters (Godfrey et al., 1985)
July 1986	Orlando, FL	Aquatic Plants for Water Treatment and Resource Recovery (Reddy and Smith, 1987)
June 1988	Chattanooga, TN	Constructed Wetlands for Wastewater Treatment (Hammer, 1989)
September 1989	Tampa, FL	Wetlands: Concerns and Successes (Fisk, 1989)

Table 3-1. (Continued)

Date	Location	Description
		Major Conferences (continued)
September 1990	Cambridge, UK	Constructed Wetlands in Water Pollution Control (Cooper and Findlater, 1990)
September 1990	Show Low, AZ	Municipal Wetlands (City of Show Low Public Works Department)
June 1991	Arlington, VA	Created and Natural Wetlands in Controlling Non-Point Source Pollution (Olson, 1992)
October 1991	Pensacola, FL	Constructed Wetlands for Water Quality Improvement (Moshiri, 1993)
July 1992	Pinetop-Lakeside, AZ	Effluent Reuse and Constructed Wetlands (Arizona Hydrological Society Summer Seminar)
September 1992	Columbus, OH	INTECOL Wetlands Conference (Mitsch-Chairman)
December 1992	Sydney, Australia	Wetland Systems in Water Pollution Control (Pilgram-Chairman)
November 1994	Guangzhou, China	4th International Conference on Wetland Systems for Water Pollution Control (Hu and Kadlec, Co-Chairmen)

Wetlands that created wildlife habitat and treated water were pioneered in Arizona and Nevada in the late 1970s and early 1980s, and wetland systems larger than 400 hectares (ha) (1,000 acres [ac]) have been built since then in Florida. Currently, wetlands are being planned and built to treat a variety of agricultural and industrial wastewaters in addition to their more traditional use for municipal wastewater treatment.

3.2 Treatment Wetlands

This section characterizes the design and performance of wetland treatment systems to provide a foundation for evaluating the technology. The North American

Wetland Treatment System Database[1] (Database) contains information about more than 200 natural and constructed wetlands that were engineered for pilot study or for full-scale wastewater treatment (Knight et al., 1993; Knight, 1994). The Database, sponsored by EPA, is by no means complete. Over 100 wetland treatment systems in North America probably are not recorded in the Database, including several in Arizona. Funding to complete and periodically update this effort has not been available. However, at this time, this Database provides the most comprehensive and current summary of wetland treatment systems.

The Database includes information on project sites, individual wetland systems at a site, regulatory permits, cell design, operational water quality from wetland cells or systems, published literature citations, and people knowledgeable about each system. The summary in Table 3-2 lists the location, wastewater source, origin of the landform, hydrologic type, system area, vegetation type, design information, and cost, when available. By synthesizing information, the database provides an overview of treatment wetlands, and the following sections discuss patterns in geography, design, permitting, cost, and performance.

3.2.1 Geographical Distribution

Wetlands treat wastewater in all climatic zones. Figure 3-2 shows the distribution of wetland treatment systems as identified in the Database and in a more recent review of Canadian systems (CH2M HILL, 1994). The higher density of wetland treatment systems in some states (Figure 3-2) reflects the following:

- The occurrence of abundant natural wetlands (the southern coastal plain and the northcentral U.S. and parts of Canada)

- The location of pioneering academic research (Florida, Mississippi, and Michigan)

[1] An electronic copy of the Database is available from Don Brown, U.S. Environmental Protection Agency (513) 569-7630.

Table 3-2. Summary of North American Wetland Treatment Systems.

Site Name	City	State	Wastewater Source[a]	Origin[b]	Hydrologic Type[c]	Wetland Area (ha)	Vegetation Type[d]	Number of Cells	Design Flow (m^3/d)	Construction Cost ($)	Design HLR (cm/d)	Cost/ Area ($/ha)
Andrews	Andrews	SC	MUN	NAT	SF	185.0	FOR	1	7,193		0.39	
Apalachicola	Apalachicola	FL	MUN	NAT	SF	63.7	SHB	1	3,785		0.59	
Arcata	Arcata	CA	MUN	CON	SF	15.2	MAR	6	8,781	514,600	5.79	33,909
Arlington	Arlington	SD	MUN	CON	SF	3.4	MAR	1	643		1.87	
Armour	Armour	SD	MUN	CON	SF	3.4	MAR	1				
Armstrong Slough	South Florida	FL	STO	NAT	SF	12.1	MAR	1	41,880		34.61	
Bellaire	Bellaire	MI	MUN	NAT	SF	66.3	FOR	5	2,445		0.37	
Belle Fourche	Belle Fourche	SD	MUN	CON	SF	29.3	MAR	13	1,893		0.65	
Benton	Benton	KY	MUN	CON	SF	3.0	MAR	2	2,800		9.33	
Bethel	Bethel	MO	MUN	CON	SF	0.3	MAR		57		1.69	
Biwabik	Biwabik	MN	MUN	NAT	SF	40.5	FOR	1	1,060	934,000	0.26	23,062
Brandt	Brandt	SD	MUN	CON	SF	1.0	MAR	1				
Bridgewater	Bridgewater	SD	MUN	CON	SF	2.0	MAR	2				
Brillion	Brillion	WI	MUN	NAT	SF	156.0	MAR	1	5,400		0.35	
Bristol	Bristol	SD	MUN	CON	SF	1.0	MAR	1				
Brookhaven	Brookhaven	NY	MUN	CON	SF	0.5	MAR	7	114		2.34	
Buenaventura Lakes	Buenaventura Lakes	FL	MUN	NAT	SF	68.0	FOR	2	3,029		0.45	
Canistota	Canistota	SD	MUN	CON	SF	4.6	MAR	1				
Cannon Beach	Cannon Beach	OR	MUN	NAT	SF	7.0	FOR	2	1,174	1,274,000	1.68	182,000
Cargill/Frank Lake	High River	ALB,CAN	IND	NAT	SF	1,093.0	MAR	1	5,300	8,150,000	0.05	7,457
Central	Central	SC	MUN	NAT	SF	31.6	FOR	1	4,543		1.44	
Chancellor	Chancellor	SD	MUN	CON	SF	1.0	MAR	1				
Clear Lake	Clear Lake	SD	MUN	CON	SF	2.3	MAR	1				
Clermont	Clermont	FL	MUN	NAT	SF	0.6	MAR	3	42		0.71	
Cobalt	Cobalt	ONT,CAN	MUN	CON	SF	0.0	MAR	1	17		1.83	
Cypress Domes	Gainesville	FL	MUN	NAT	SF	1.6	FOR	2	114		0.73	
Des Plaines	Wadsworth	IL	OTH	CON	SF	10.1	MAR	4	4,635	3,375,000	4.58	333,169
Doland	Doland	SD	MUN	CON	SF	1.1	MAR	1				
Drummond	Drummond	WI	MUN	NAT	SF	6.0	HYB	1	300	25,000	0.50	4,167
Eden	Eden	SD	MUN	CON	SF	0.3	MAR	1				
Ethan	Ethan	SD	MUN	CON	SF	2.8	MAR	2				
Eureka	Eureka	SD	MUN	CON	SF	16.3	HYB	4	1,045	470,000	0.64	28,767
Everglades Nutr. Removal	West Palm Beach	FL	OTH	CON	SF	1,406.0	MAR	4	636,208	14,000,000	4.52	9,957
Fontanges	Fontanges	QUE,CAN	OTH	NAT	SF	0.5	MAR	2	280		5.60	
Fort Deposit	Fort Deposit	AL	MUN	CON	SF	6.0	MAR	2	900	374,000	1.50	62,333
Geddes	Geddes	SD	MUN	CON	SF	0.8	MAR	1				
Great Meadows	Concord	MA	MUN	NAT	SF	22.0	MAR	1	2,000		0.91	
Gustine	Gustine	CA	MUN	CON	SF	9.6	MAR	24	3,785	882,000	3.94	91,875
Gustine	Gustine	CA	MUN	NAT	SF	0.3	MAR	1				
Hamilton Marshes	Hamilton Township	NJ	MUN	NAT	SF	500.0	MAR	3				
Hay River	Hay River	NWT,CAN	MUN	NAT	SF	47.0	MAR	1	1,000		0.21	
Hayward	Hayward	CA	MUN	CON	SF	58.7	MAR	5	75,720		12.90	

Table 3-2. (Continued)

Site Name	City	State	Wastewater Source[a]	Origin[b]	Hydrologic Type[c]	Wetland Area (ha)	Vegetation Type[d]	Number of Cells	Design Flow (m^3/d)	Construction Cost ($)	Design HLR (cm/d)	Cost/Area ($/ha)
Hidden Lake	Orlando	FL	STO	NAT	SF	3.0	FOR	1				
Hillsboro ND	Hillsboro	ND	IND	CON	SF	33.0	MAR	9	5,678	1,600,000	1.72	48,485
Hillsboro OR	Hillsboro	OR	IND	CON	SF	35.7	MAR	17		185,000		5,182
Hilton Head Plantation	Hilton Head Plantation	SC	MUN	NAT	SF	36.5	FOR	1	1,893		0.52	
Houghton Lake	Houghton Lake	MI	MUN	NAT	SF	79.0	MAR	2	6,360	500,000	0.81	6,329
Hoven	Hoven	SD	MUN	CON	SF	11.5	HYB	7	360		0.31	
Huron	Huron	SD	MUN	CON	SF	133.5	MAR	3	9,465		0.71	
Hurtsboro	Hurtsboro	AL	MUN	NAT	SF	0.2	MAR	2	56		3.50	
Incline Village	Incline Village	NV	MUN	CON	SF	173.3	MAR	8	5,000	5,000,000	0.29	28,855
Ironbridge	Orlando	FL	MUN	CON	SF	494.0	HYB	17	75,720	21,020,000	1.53	42,551
Island Lake	Longwood	FL	STO	NAT	SF	42.0	MAR	1				
Jasper	Jasper	FL	MUN	NAT	SF	24.0	FOR	1				
Johnson City	Johnson City	TX	MUN	CON	SF	0.5	MAR	9	114		2.28	
Kadoka	Kadoka	SD	MUN	CON	SF	5.0	MAR	2				
Kimball	Kimball	SD	MUN	CON	SF	6.5	MAR	1				
Kinross (Kincheloe)	Kinross	MI	MUN	NAT	SF	110.0	MAR	1	450		0.04	
Lake Apopka Wetlands Flwy	Apopka	FL	OTH	CON	SF	750.0	MAR	2	733,536		9.78	
Lake Cochrane San	Lake Cochrane San	SD	MUN	CON	SF	0.6	MAR	1				
Lake Jackson	Tallahassee	FL	STO	CON	SF	2.3	MAR	3				
Lake Preston	Lake Preston	SD	MUN	CON	SF	7.8	MAR	1				
Lakeland	Lakeland	FL	MUN	CON	SF	498.0	MAR	7	52,704		1.06	
Lakeside	Lakeside	AZ	MUN	CON	SF	38.0	MAR	7	1,540	286,600	0.41	7,542
Leaf River	New Augusta	MS	IND	CON	SF	0.4	MAR	3	699		17.92	
Listowel Artificial Marsh	Listowel	ONT,CAN	MUN	CON	SF	0.9	MAR	7	154		1.78	
Mandan (Amoco)	Mandan	ND	IND	CON	SF	16.6	MAR	11	2,650	250,000	1.60	15,060
Martin	Martin	SD	MUN	CON	SF	2.8	MAR	1				
Mays Chapel	Cockeysville	MD	STO	CON	SF	0.2	MAR	1	160	27,800	6.68	115,833
Mcintosh	Mcintosh	SD	MUN	CON	SF	3.7	HYB	3	223	530,000	0.60	142,358
Mellette	Mellette	SD	MUN	CON	SF	2.5	HYB	3	124		0.50	
Minot	Minot	ND	MUN	CON	SF	13.6	MAR	4	20,818	475,000	15.33	34,980
Monticello	Monticello	FL	MUN	CON	SF	188.6	HYB	14	3,785		0.20	
Moodna Basin	Harriman	NY	MUN	CON	SF	0.3	MAR	2	114		3.75	
Mt Angel	Mt Angel	OR	MUN	CON	SF	4.0	MAR		7,570	350,000	18.71	86,484
Mt.View Sanitary District	Martinez	CA	MUN	CON	SF	37.0	MAR	3	5,300	90,000	1.43	2,432
Murdo	Murdo	SD	MUN	CON	SF	2.4	MAR	2				
Norwalk	Norwalk	IA	MUN	CON	SF	11.7	MAR	2	1,160		0.99	
Onida	Onida	SD	MUN	CON	SF	2.8	MAR	1				
Orange County	Orlando	FL	MUN	HYB	SF	89.0	HYB	2	13,251	2,900,000	1.49	32,584
Pembroke	Pembroke	KY	MUN	CON	SF	0.9	HYB	1	340		3.66	
Plankinton	Plankinton	SD	MUN	CON	SF	1.9	MAR	1				
Poinciana	Poinciana	FL	MUN	NAT	SF	46.6	FOR	1	1,325		0.28	
Pottsburg	Jacksonville	FL	MUN	NAT	SF	100.0	FOR	1	14,040		1.40	

Table 3-2. (Continued)

Site Name	City	State	Wastewater Source[a]	Origin[b]	Hydrologic Type[c]	Wetland Area (ha)	Vegetation Type[d]	Number of Cells	Design Flow (m^3/d)	Construction Cost ($)	Design HLR (cm/d)	Cost/ Area ($/ha)
Prariewood San	Prariewood San	SD	MUN	CON	SF	0.5	MAR	1				
Presho	Presho	SD	MUN	CON	SF	1.9	MAR	1				
Reedy Creek	Lake Buena Vista	FL	MUN	NAT	SF	82.2	FOR	3	20,066		2.44	
Reliance	Reliance	SD	MUN	CON	SF	0.3	MAR	1				
Richmond	Richmond	CA	IND	CON	SF	36.0	MAR	2	16,000		4.44	
Richton	Richton	MS	MUN	CON	SF		MAR	2	1,325			
Rosholt	Rosholt	SD	MUN	CON	SF	1.6	MAR	1				
Roslyn	Roslyn	SD	MUN	CON	SF	0.6	MAR	1				
Santa Rosa	Santa Rosa	CA	MUN	CON	SF	4.1	HYB	5	7,570		18.69	
Sea Pines	Sea Pines	SC	MUN	NAT	SF	20.0	MAR	1	3,786		1.89	
Seneca Army Depot	Seneca Army Depot	NY	MUN	OTH	SF	2.5	MAR	1	950		3.80	
Show Low	Show Low	AZ	MUN	CON	SF	54.2	MAR	8	5,299	146,750	0.98	2,708
Silver Springs Shores	Silver Springs Shores	FL	MUN	CON	SF	21.0	MAR	2	3,786		1.80	
Sisseton	Sisseton	SD	MUN	CON	SF	102.8	MAR	1	2,033		0.20	
Spencer	Spencer	SD	MUN	CON	SF	1.4	MAR	1	246		1.79	
St. Joseph	St. Joseph	MN	STO	NAT	SF	18.6	MAR	2	900		[illegible]	
Stickney	Stickney	SD	MUN	CON	SF	0.9	MAR	2	257		2.89	
Tabor	Tabor	SD	MUN	CON	SF	0.5	MAR	2				
Tripp	Tripp	SD	MUN	CON	SF	2.7	MAR	2				
University of Florida	Gainesville	FL	MUN	NAT	SF	33.0	MAR	1	7,500		2.27	
USDA-NSCS	Orono	ME	OTH	CON	SF		MAR	1		22,500		
Vereen	Little River	SC	MUN	NAT	SF	229.0	FOR	3	9,466	4,233,000	0.41	18,485
Vermontville	Vermontville	MI	MUN	CON	SF	4.6	MAR	4	380	395,000	0.83	85,870
Volga	Volga	SD	MUN	CON	SF	6.1	MAR	2	825		1.36	
Wakonda	Wakonda	SD	MUN	CON	SF	1.6	MAR	1				
Waldo	Waldo	FL	MUN	NAT	SF	2.6	FOR	1	226		0.87	
Wall Lake San	Wall Lake San	SD	MUN	CON	SF	0.4	MAR	2				
Wessington	Wessington	SD	MUN	CON	SF	0.5	MAR	1				
West Jackson County	Ocean Springs	MS	MUN	CON	SF	22.7	MAR	7	6,057		2.67	
White Lake	White Lake	SD	MUN	CON	SF	1.5	MAR	2				
Wildwood	Wildwood	FL	MUN	NAT	SF	204.0	FOR	3	3,786		0.19	
Willow Lake	Willow Lake	SD	MUN	CON	SF	9.7	MAR	6	246		0.25	
Albany	Albany	LA	MUN	CON	HYB	0.1	MAR	2	132		12.00	
Cottonwood	Cottonwood	AL	MUN	CON	HYB	0.4	MAR	1	587	156,800	14.68	392,000
Crowley	Crowley	LA	MUN	CON	HYB	17.0	MAR	7	13,248	1,660,000	7.79	97,647
Degussa Corp.	Theodore	AL	IND	CON	HYB	0.9	MAR	11	2,040	265,000	22.92	297,753
Iselin	Iselin	PA	MUN	CON	HYB	0.2	MAR	3	45	500,000	2.07	2,272,727
Pelahatchie	Pelahatchie	MS	OTH	CON	HYB	2.6	MAR	5	2,157		8.20	
Shelbyville	Shelbyville	MO	MUN	CON	HYB	0.2	MAR	4	280		17.28	
Terry	Terry	MS	MUN	CON	HYB	0.5	MAR	3	378	190,000	7.27	365,385
Benton	Benton	KY	MUN	CON	SSF	1.5	MAR	1	341		2.34	
Benton	Benton	LA	MUN	CON	SSF	0.5	MAR	1	1,173	262,000	24.44	545,833

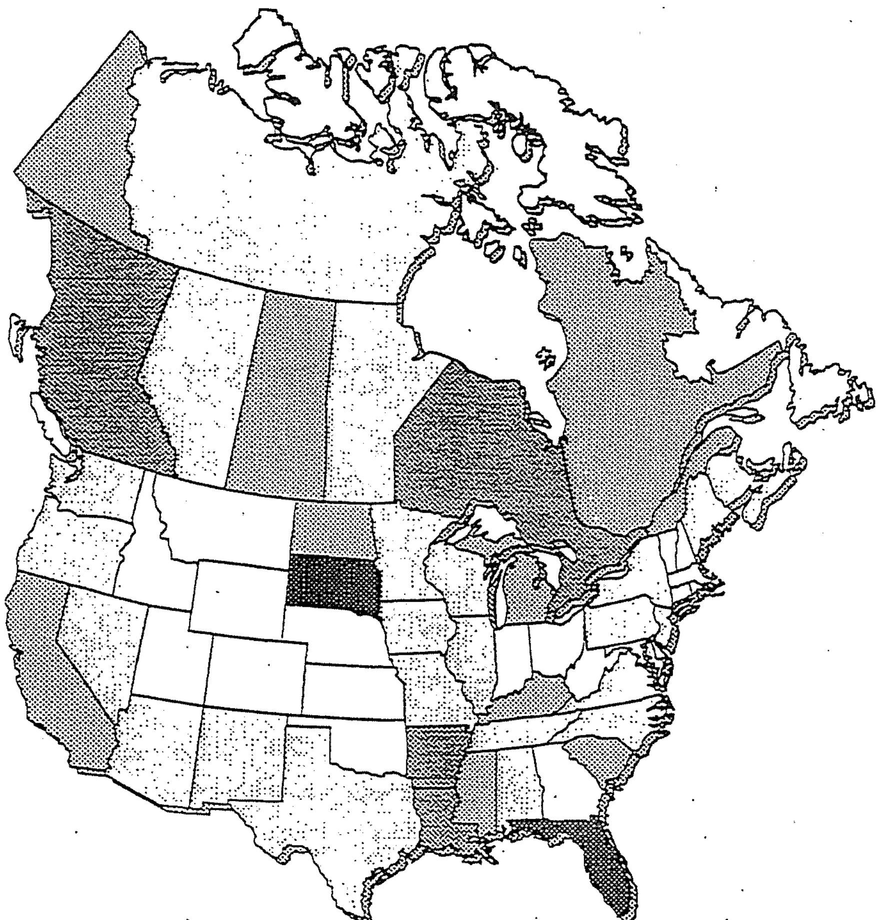
Table 3-2. (Continued)

Site Name	City	State	Wastewater Source[a]	Origin[b]	Hydrologic Type[c]	Wetland Area (ha)	Vegetation Type[d]	Number of Cells	Design Flow (m^3/d)	Construction Cost ($)	Design HLR (cm/d)	Cost/ Area ($/ha)
Bradford	Bradford	AR	MUN	CON	SSF	1.1	MAR	2	757	335,430	6.69	296,316
Bradley	Bradley	AR	MUN	CON	SSF	0.6	MAR	4	1,135	145,000	19.46	248,714
Carlisle	Carlisle	AR	MUN	CON	SSF	4.3	MAR	4	3,255	335,430	7.49	77,199
Carville	Carville	LA	MUN	CON	SSF	0.3	MAR	1	568	100,000	21.85	384,615
Clarendon	Clarendon	AR	MUN	CON	SSF	0.8	MAR	4	2,650	318,600	32.55	391,400
Denham Springs	Denham Springs	LA	MUN	CON	SSF	6.2	MAR	3	11,355	1,500,000	18.46	243,902
Dessau Mobile Home Park	Pflugerville	TX	MUN	CON	SSF	0.2	MAR	2	568		27.04	
Dierks	Dierks	AR	MUN	CON	SSF	0.5	MAR	2	871	164,758	18.56	351,296
Doyline	Doyline	LA	MUN	CON	SSF	0.3	MAR	1	416		14.86	
Eudora	Eudora	AR	MUN	CON	SSF	1.3	MAR	2	2,271	639,619	17.04	479,834
Foothills Village	Loudon Co.	TN	MUN	CON	SSF	0.1	MAR	2	67		6.70	
Foreman	Foreman	AR	MUN	CON	SSF	1.0	MAR	4	908	354,252	8.85	345,275
Gillett	Gillett	AR	MUN	CON	SSF	0.9	MAR	4	454	229,180	4.79	241,751
Greenleaves Subdivision	Mandeville	LA	MUN	CON	SSF	0.4	MAR	1	564	523,553	12.67	1,176,524
Gurdon	Gurdon	AR	MUN	CON	SSF	1.7	MAR	2	3,255	377,411	18.87	218,789
Hammond	Hammond	LA	OTH	CON	SSF	0.1	MAR	1	329	120,000	26.11	952,381
Hardin	Hardin	KY	MUN	CON	SSF	0.6	MAR	2	378		5.91	
Haughton	Haughton	LA	MUN	CON	SSF	0.6	MAR	1	1,324		21.35	
Hornbeck	Hornbeck	LA	MUN	CON	SSF	0.0	MAR	1	231	123,870	25.67	1,376,333
Johnson City	Johnson City	TX	MUN	CON	SSF	0.1	MAR	2	114		10.36	
Kingston Power Plant	Kingston	TN	MUN	CON	SSF	0.3	MAR	4	76	81,000	2.92	311,538
Lewisville	Lewisville	AR	MUN	CON	SSF	0.7	MAR	2	1,514	113,000	21.63	161,429
Lockesburg	Lockesburg	AR	MUN	CON	SSF	0.3	MAR	2	568	112,600	17.97	356,329
Mandeville	Mandeville	LA	MUN	CON	SSF	2.6	MAR	3	5,678	1,000,000	21.75	383,142
Marion	Marion	AR	MUN	CON	SSF	2.5	MAR	8	3,785		15.39	
Mayo Peninsula	Ann Arundel Co.	MD	MUN	CON	SSF	1.5	MAR	4	2,990		19.54	
McNeil	McNeil	AR	MUN	CON	SSF	0.3	MAR	2	57	90,756	1.80	287,203
Mesquite	Mesquite	NV	MUN	CON	SSF	1.9	MAR	3	1,514	515,000	7.97	271,053
Monterey	Monterey	VA	MUN	CON	SSF	0.0	MAR	1	76		33.04	
Ola	Ola	AR	MUN	CON	SSF	0.4	MAR	4	757	4[illegible]5,360	17.81	1,000,847
Paris Landing	Paris Landing State Park	TN	MUN	CON	SSF	0.2	MAR	1	284		18.93	
Pembroke	Pembroke	KY	MUN	CON	SSF	0.5	MAR	1	340		6.30	
Phillips High School	Bear Creek	AL	MUN	CON	SSF	0.2	MAR	1	76	36,266	3.74	178,650
Prescott	Prescott	AR	MUN	CON	SSF	0.8	MAR	2	3,217		37.94	
Provencal	Provencal	LA	MUN	CON	SSF	0.1	MAR	1	344	152,860	24.57	1,091,857
Rector	Rector	AR	MUN	CON	SSF	1.3	MAR	5	1,325		9.92	
Roswell	Roswell Correctional Ctr.	NM	MUN	CON	SSF	0.0	MAR	1	15		37.50	
Shelbyville	Shelbyville	MO	MUN	CON	SSF	0.0	MAR	1	280		68.29	
Sibley	Sibley	LA	MUN	CON	SSF	0.2	MAR	1	492	48,000	23.43	228,571
Smackover	Smackover	AR	MUN	CON	SSF	2.7	MAR	6	1,892	800,000	7.08	299,401
Swifton	Swifton	AR	MUN	CON	SSF	0.4	MAR	2	416	165,200	9.71	385,082
Thornton	Thornton	AR	MUN	CON	SSF	0.3	MAR	1	378		13.36	

Table 3-2. (Continued)

Site Name	City	State	Wastewater Source[a]	Origin[b]	Hydrologic Type[c]	Wetland Area (ha)	Vegetation Type[d]	Number of Cells	Design Flow (m^3/d)	Construction Cost ($)	Design HLR (cm/d)	Cost/Area ($/ha)
Tuckerman	Tuckerman	AR	MUN	CON	SSF	2.1	MAR	4	852	283,500	4.12	137,222
Utica, North	Utica	MS	MUN	CON	SSF	0.7	MAR	2	341		4.67	
Utica, South	Utica	MS	MUN	CON	SSF	0.9	MAR	2	442		4.80	
Waldo	Waldo	AR	MUN	CON	SSF	0.6	MAR	4	1,325	248,267	21.82	409,007
Natural Wetlands		Average				97.7		2	5,422	2,573,714	2.18	35,687
		Maximum				1,093.0		5	41,880	8,150,000	34.61	85,870
		Minimum				0.2		1	42	25,000	0.04	2,708
		Median				40.5		1	2,737	1,274,000	0.65	18,485
		Std. Dev.				198.0		0	8,378	2,861,492	6.24	44,169
		Count				35		35	30	7	30	3
Constructed SF		Average				56.0		4	35,856	2,518,774	3.83	58,494
		Maximum				1406.0		24	733,536	21,020,000	18.71	333,169
		Minimum				0.0		1	17	22,500	0.20	2,432
		Median				3.4		2	1,963	470,000	1.78	32,584
		Std. Dev.				192.9		4	138,131	5,264,840	5.03	76,644
		Count				79		80	48	21	47	23
Constructed SSF		Average				1.2		3	1,444	363,903	16.08	478,147
		Maximum				17.0		11	13,248	1,660,000	68.29	2,272,727
		Minimum				0.0		1	15	36,266	1.80	77,199
		Median				0.5		2	568	255,134	15.12	348,286
		Std. Dev.				2.4		2	2,409	377,130	11.63	447,592
		Count				56		56	56	34	56	34

a = Wastewater Source: MUN - municipal, IND - industrial, OTH - other, STO - stormwater.
b = Origin: NAT - natural, CON - constructed, HYB - hybrid.
c = Hydrologic Type: SF - surface flow, SSF - subsurface flow, HYB - hybrid
d = Vegetation Type FOR - forested, MAR - marsh, SHB - shrub, HYB - hybrid.



USA

STATE		STATE		STATE	
SD	42	AL	5	NV	2
FL	29	NY	5	WI	2
AR	22	IL	4	IA	1
LA	14	OR	4	MA	1
MS	10	MO	3	ME	1
CA	7	TN	3	NC	1
KY	7	TX	3	NJ	1
MI	7	AZ	2	NM	1
SC	7	MD	2	PA	1
ND	6	MN	2	VA	1
				WA	1

CANADA

ALB	3
NWT	2
ONT	11
QUE	9
YUK	7
BC	11
SAS	7
MAN	1
NB	1
PEI	1
NS	1

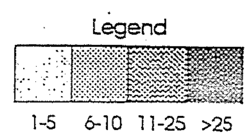


Figure 3-2. Distribution of Treatment Wetlands in the North American and Canadian *Databases. In the U.S., the occurence of treatment wetlands depends somewhat on natural wetlands, academic research, and regulatory support.*

- The strong support provided by state and federal regulatory agencies (South Dakota and Kentucky)

Although climatic factors do not preclude wetlands for wastewater treatment, climate is important in wetland design primarily for two reasons: temperature and hydrology. Minimum winter temperatures limit the ability of wetland systems to treat some, but not all, pollutants. Ice cover is another factor in cold-climate wetlands. Hot summer temperatures also can limit treatment effectiveness for some pollutants.

Excessive net rainfall can hydraulically overload a wetland treatment system, resulting in inadequate residence times for treatment. On the other hand, excessive net evapotranspiration can concentrate pollutants so that dissolved solids and organics reach toxic accumulations. During project design, the water balance should be estimated to anticipate treatment performance.

3.2.2 Design

The design information in Table 3-2 illustrates the broad ranges in wetland design criteria. At the end of the table, each type of wetland treatment system is associated with an average size, cost, and hydraulic loading rate (HLR). However, these numbers vary widely because of site-specific differences in wastewater volume, pretreatment, effluent criteria, and designer preference. Thus, the averages are useful only for general comparison and not for sizing new wetland treatment systems.

Multiple wetland cells arranged in parallel improve system operation and maintenance. For the systems listed in Table 3-2, natural systems typically had one or two alternate discharge locations, constructed SF wetlands had two to four cells, and constructed SSF wetlands had an average of three cells. Because of cost, SSF wetland treatment systems typically are designed with a median area of 0.5 ha (1.2 ac) to receive small flows of 570 cubic meters per day (m^3/d) (0.15 million gallons per day [mgd]).

3.2.3 Permits

The majority of the wetland treatment systems in the Database are designed to discharge to surface water. The few systems designed for zero surface discharge invariably lose some water to groundwater. State and federal permits are required for all wastewater discharges, whether to surface or groundwaters (see Section 8 for a discussion of permit requirements). These permits establish legal limits for pollutant concentrations so that discharges will not impair classified uses of receiving waters. Permit limits are based on the best available technology or on the natural assimilative capacity of the receiving water (called water-quality based). The Database has summarized permit conditions for about 80 natural and constructed wetland treatment systems in North America.

The most commonly permitted parameters for surface discharges from wetland treatment systems are flow, 5-day biochemical oxygen demand (BOD_5), and total suspended solids (TSS). Permit limits typically range between 5 and 45 milligrams per liter (mg/L) for BOD_5 and between 10 and 45 mg/L for TSS. Permit limits for total ammonia nitrogen are included for about 45 percent of the treatment wetlands summarized in the Database and typically range from 1 to 10 mg/L. Effluent limitations for DO, pH, and fecal coliforms also are included frequently in wetland treatment system permits. Limits for total nitrogen and total phosphorus in treatment wetland discharges are relatively uncommon at this time; however, concerns about the potential for eutrophication and elevated groundwater nitrate levels are leading to nutrient standards in some states (for example, Florida and Michigan).

3.2.4 Cost

Natural wetland treatment systems are typically less expensive than constructed wetlands on a per hectare basis: median of \$18,500/ha (\$7,500/ac) for natural wetlands versus \$32,600/ha (\$13,200/ac) for constructed SF wetlands. The median constructed SSF wetlands cost about ten times more at \$350,000/ha

($141,000/ac), but they are typically designed with higher HLRs than constructed SF wetlands: 15.1 cm/d (42 inches per week [in/wk]) versus 1.8 cm/d (4.9 in/wk). Natural wetlands typically are sized more conservatively, with an average HLR of 0.65 cm/d (1.8 in/wk).

3.2.5 Performance

The Database records operational data for several pollutants or other chemical constituents in municipal and industrial wastewaters and in stormwaters. These parameters include the following: BOD_5, TSS, total ammonia nitrogen (NH_4-N), nitrate plus nitrite nitrogen (NO_2+NO_3-N), organic nitrogen (ORG-N), total Kjeldahl nitrogen (TKN), total nitrogen (TN), ortho phosphorus (ORTHO-P), total phosphorus (TP), DO, and fecal coliform bacteria. Table 3-3 summarizes the average performance of Database wetlands in removing these key pollutants for SF wetlands (natural and constructed), SSF wetlands, and all wetland treatment systems combined.

The data in Table 3-3 indicate that, in general, wetland treatment systems effectively assimilate certain wastewater constituents. On the basis of the design loadings in Table 3-2, wetland treatment systems remove from 30 to 70 percent of the BOD_5, TSS, nitrogen, and phosphorus they receive. Comparing site-specific system design and wastewater loadings allows more specificity in predicting performance. Higher than average removal efficiencies occur in wetland systems with minimum short-circuiting, well-developed plant communities, and consistent influent quality.

Long-term data from a few wetland treatment systems indicate that treatment performance for parameters such as BOD_5, TSS, and TN typically does not deteriorate with age. In fact, existing information suggests that, for these parameters, wetland treatment systems have indefinite operational life expectancies as long as loadings are reasonable and wetland cells are designed, built, and maintained with adequate care.

Table 3-3. Summary of North American Wetland Treatment System Operational Performance.

Parameter	Type[a]	Average Concentration (mg/L) In	Out	Eff (%)	Average Mass (kg/ha/d)[b] Loading	Removal	Eff (%)
BOD_5							
	SF	30.3	8.0	74	7.2	5.1	71
	SSF	27.5	8.6	69	29.2	18.4	63
	All	29.8	8.1	73	10.9	7.5	68
TSS							
	SF	45.6	13.5	70	10.4	7.0	68
	SSF	48.2	10.3	79	48.1	35.3	74
	ALL	46.0	13.0	72	16.8	11.9	71
NH_4-N							
	SF	4.88	2.23	54	0.93	0.35	38
	SSF	5.98	4.51	25	7.02	0.62	9
	ALL	4.97	2.41	52	1.46	0.38	26
$NO_2 + NO_3$-N							
	SF	5.56	2.15	61	0.80	0.40	51
	SSF	4.40	1.35	69	3.10	1.89	61
	ALL	5.49	2.10	62	0.99	0.54	55
ORG-N							
	SF	3.45	1.85	46	0.90	0.51	56
	SF	10.11	4.03	60	7.28	4.05	56
	ALL	4.01	2.03	49	1.71	0.95	56
TKN							
	SF	7.60	4.31	43	2.20	1.03	47
	SSF	14.21	7.16	50	9.30	3.25	35
	ALL	8.11	4.53	44	2.99	1.29	43
TN							
	SF	9.03	4.27	53	1.94	1.06	55
	SSF	18.92	8.41	56	13.19	5.85	44
	ALL	9.67	4.53	53	2.98	1.52	51
ORTHO-P							
	SF	1.75	1.11	37	0.29	0.12	41
	SSF	ND	ND	ND	ND	ND	ND
	ALL	1.75	1.11	37	0.29	0.12	41
TP							
	SF	3.78	1.62	57	0.50	0.17	34
	SSF	4.41	2.97	32	5.14	1.14	22
	ALL	3.80	1.68	56	0.73	0.22	31

Notes:

[a]SF - Surface Flow, SSF - Subsurface Flow.
[b]kg/ha/d x 0.892 = lb/ac/d.
ND = No data.
Eff (%) = Efficiency of concentration reduction or mass removal.

For other constituents, however, wetland performance may deteriorate with age. Sorption capacity for phosphorus and metals may be overloaded, and net retention of these elements may decline over time. Short-term and startup data from wetland treatment systems may be suspect and should not be used alone to determine long-term performance expectations for these pollutants.

3.3 Floating Aquatic Plant Systems

Because of the hydrologic and vegetation differences between emergent wetlands and FAP systems, the Database does not include FAPs. This section provides an introduction to these treatment units and a summary of the typical treatment performance.

3.3.1 Historical Perspective

FAP systems use floating macrophytic plants in shallow to deep lagoons to treat wastewater pollutants. These systems represent a logical modification of small facultative lagoons that are naturally colonized by volunteer floating plants. Early research with such ponds and in controlled pilot studies indicated that FAP systems have significant potential for reducing concentrations of BOD_5, TSS, nutrients, and metals that typically occur in municipal wastewaters. Because this technology was found to be well-suited for plant harvesting, FAP systems have been used for enhanced nutrient removal.

Research with FAP systems began in the 1970s to compare the effectiveness of these systems to conventional facultative ponds. These initial research efforts were the focus of a workshop sponsored by EPA in 1979 at the University of California, Davis (U.S. EPA, 1980). Major FAP research efforts have been conducted at San Diego, California; Austin, Texas; Walt Disney World, Florida; and NASA/Bay St. Louis, Mississippi. In Arizona, research with FAP systems has been conducted at Pima County.

Although much of the initial work with FAP systems focused on water hyacinths as the principal plant species, a relatively small number of full-scale water hyacinth FAP systems still exist. Beginning in the 1980s, duckweed began to be used in engineered FAP systems. Because of its hardiness, ease of harvesting, and beneficial properties as a soil amendment, the number of full-scale duckweed FAP systems is increasing. Pennywort (*Hydrocotlye* spp.) has also been used in pilot-scale FAP systems. Pennywort is more frost-hardy and less susceptible to insect pests than water hyacinth. However, pennywort does not grow as well as water hyacinth or duckweed in hot climates.

3.3.2 General Features of FAP Systems

Figure 3-3 illustrates the major features of FAP systems. These systems typically consist of shallow to deep (less than 2 meters or 6.6 feet) lined earthen ponds or concrete raceways. In some cases, FAP systems have been enclosed in greenhouses, primarily to protect water hyacinth plants from frost damage. Duckweed systems do not require greenhouse covers, even in cold climates, and generally include floating barriers that are necessary to minimize the effects of wind in large ponds (Figure 3-4).

The complete FAP system generally includes pumping and conveyance piping to the FAP ponds; multiple ponds for parallel or series flow; flow curtains or baffles to optimize plug flow conditions; outlet weirs and a system to drain the ponds for maintenance; a harvesting system to periodically remove plant biomass; and a biomass disposal system for dewatering and ultimate biomass disposal.

3.3.3 Inventory of Existing FAP Systems

A current inventory of operational FAP systems does not exist. The most recently published list (U.S. EPA, 1988) included six ongoing full-scale projects located in Mississippi, Florida, and Texas. Since then, a number of new duckweed systems have been built elsewhere. According to the Lemna Corporation, at least 28 duckweed systems are operating at this time. Table 3-4 provides a partial list of FAP systems operating in North America.

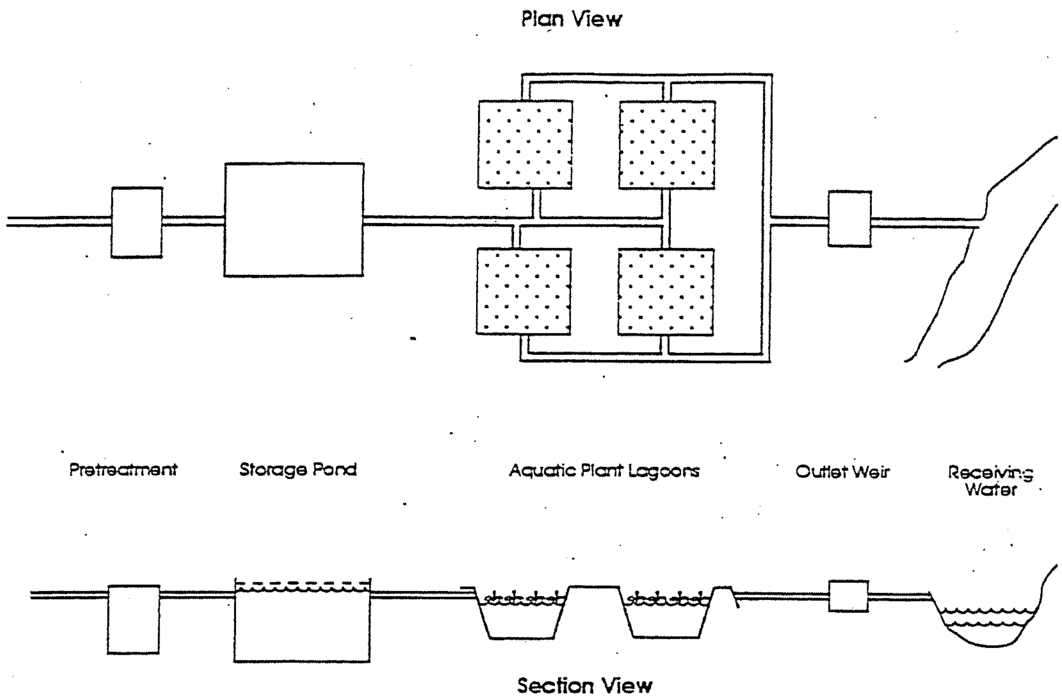
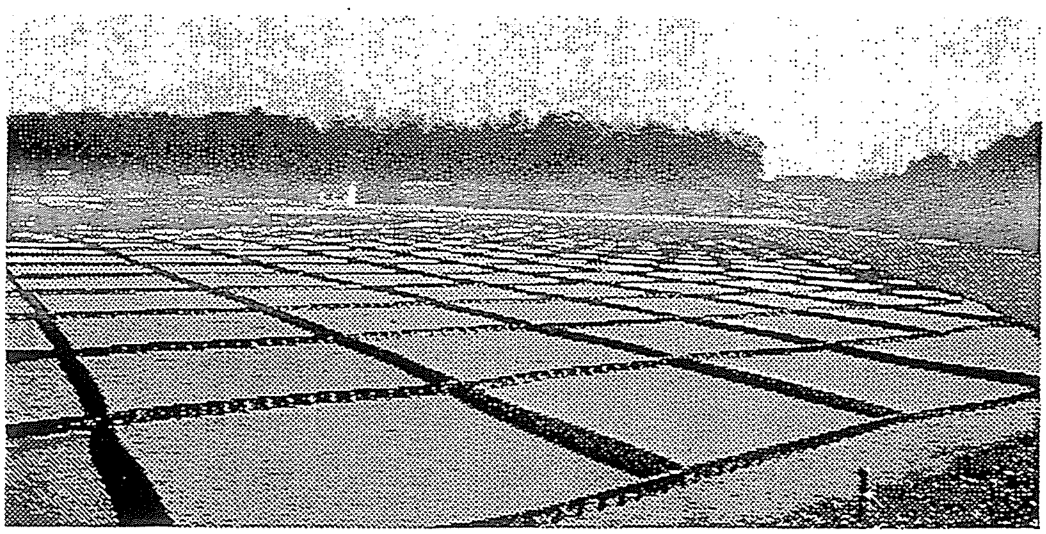


Figure 3-3. Diagram of Floating Aquatic Plant System. Because FAP systems are suited for plant harvesting, they have been used for nutrient removal.



Source: Lemna Corporation

Figure 3-4. Duckweed System at Manakin Farms, Virginia. Floating grids minimize the wind disturbance to floating plants.

Table 3-4. Inventory of Full-Scale FAP Treatment Systems.

Location	State	Treatment Objective	Dominant FAP	Area (ha)	Design Flow (m^3/d)	Design HLR (cm/d)
National Space Tech. Lab	MS	SEC	WH/PW/DW	2	480	2.4
Biloxi	MS	SEC	DW	–	–	–
Austin	TX	SEC	WH/DW	1.6	7,570	47
San Benito	TX	SEC	WH	–	–	–
San Diego	CA	SEC	WH	0.7	3,785	6-28
Alvo	NE	SEC	DW	0.4	45	1.1
Baldwin	LA	TER	DW	–	1,900	–
Boulder City	NV	SEC	DW	–	7,000	–
Broussard	LA	TER	DW	–	2,800	–
Clinton	LA	TER	DW	–	1,060	–
Devils Lake	ND	TER	DW	18.2	19,000	10.4
Ellaville	GA	TER	DW	1.0	760	7.6
Greenleaves	LA	TER	DW	–	1,900	–
Hermitage	AR	TER	DW	–	400	–
Highmore	SD	SEC	DW	–	400	–
Kentwood	LA	TER	DW	–	1,900	–
Manakin Farms	VA	TER	DW	–	400	–
Moorpark	CA	TER	DW	–	11,600	–
Nolsesville	VA	TER	DW	–	200	–
Ogena	WI	SEC	DW	–	135	–
Ponchatoula	LA	TER	DW	–	5,300	–
Tignall	GA	SEC	DW	–	300	–
Campo de Carlos	Mexico	SEC	DW	–	2,600	–
Cleveland	GA	SEC	DW	–	2,650	–
Chaffee	MO	SEC	DW	–	1,930	–
Four Corners	LA	SEC	DW	–	625	–
Joiner	AR	SEC	DW	–	380	–

Table 3-4. (Continued)

Location	State	Treatment Objective	Dominant FAP	Area (ha)	Design Flow (m^3/d)	Design HLR (cm/d)
Kyle	TX	SEC	DW	–	3,800	–
Mamon	LA	TER	DW	–	2,270	–
White House	TN	TER	DW	–	3,000	–
Kinder	LA	TER	DW	–	1,750	–
Laurel	DE	SEC	DW	–	1,892	–
LeCompte	LA	TER	DW	–	1,140	–

Adapted from EPA (1988); Reed et al. (1988); Lemna Corporation (1993).

SEC = Secondary.
TER = Tertiary.
WH = Water hyacinth.
PW = Pennywort.
DW = Duckweed.
ac = ha x 2.47
mgd = m^3/d x 0.000264
in/d = cm/d x 0.394

This review indicates that although the FAP technology is as old as the use of constructed wetlands, it is being used less frequently and in fewer geographical areas. Although the FAP technology began primarily with the use of water hyacinths, there has been a marked shift to duckweed species in new applications of this technology.

Both water hyacinth and duckweed FAP systems have been tested in Tucson, Arizona, at Pima County's Roger Road Sewage Treatment Plant (Karpiscak et al., 1993; 1994). This facility is operated in conjunction with the University of Arizona's Office of Arid Land Studies and is called the Constructed Ecosystems Research Facility (CERF). Initial work at this system focused on water hyacinth and duckweed and recently has expanded to include constructed wetlands research.

3.3.4 Design

There is little information available to summarize the range of criteria for designing FAP systems. On the basis of information in Reed et al. (1988) and Lemna (1988), typical design HLRs for these systems range between 1 and 36 cm/d (0.4 to 14 in/d) for water hyacinth systems and 1 and 10 cm/d (0.4 to 4 in/d) for duckweed systems. Most FAP treatment systems incorporate multiple cells. Water depths available from Reed et al. (1988) for water hyacinth systems ranged from 38 to 183 cm (15 to 72 in). Duckweed systems are typically between 1 to 2 meters (m) (3.3 to 6.6 feet [ft]) deep.

3.3.5 Performance

There are no detailed summaries of the performance of FAP treatment systems. However, performance data have been published for pilot and full-scale FAP treatment systems in U.S. EPA (1988; 1984) and Reed et al. (1988). Table 3-5 summarizes reported FAP treatment system performance for removal of BOD_5, TSS, TN, and TP. Performance was reported over a very broad range of HLRs. Average performance for water hyacinth and duckweed systems in Table 3-5 was similar for BOD_5 and TSS at about 75 to 81 percent removal efficiency. Water hyacinth systems had average nutrient removal efficiencies of 77 percent for TN and 44 percent for TP. The data suggest that performance of FAP systems depends on HLR, influent pollutant concentration, and the absence of hydraulic short-circuiting in the FAP ponds.

Table 3-5. Reported Performance of FAP Treatment Systems.

Location	Design HLR (cm/d)	FAP Type	Average BOD, (mg/L) IN	OUT	Eff (%)	Average TSS (mg/L) IN	OUT	Eff (%)	Average TN (mg/L) IN	OUT	Eff (%)	Average TP (mg/L) IN	OUT	Eff (%)
NSTL, MS	2.4	WH	110	7	94	97	10	90	12	3.4	72	3.7	1.6	57
Lucedale, MS	2.6	WH	161	23	86	125	6	95	--	--	--	--	--	--
Orange Grove, MS	35.7	WH	50	14	72	49	15	69	--	--	--	--	--	--
Williamson Cr., TX	1.1	WH	46	6	87	91	8	91	7.7	3.3	57	7	5.7	19
Coral Springs, FL	3.8	WH	13	3	77	6	3	48	22.4	1.0	96	11	3.6	67
Biloxi, MS	--	DW	30	15	50	155	12	92	--	--	--	--	--	--
Collins, MS	--	DW	33	13	61	36	13	64	--	--	--	--	--	--
Sleepy Eye, MN	--	DW	420	18	96	364	34	91	--	--	--	--	--	--
Wilton, AR	--	DW	--	6.5	--	--	7.4	--	--	--	--	--	--	--
NSTL, MS	--	DW	35.5	3.0	92	47.7	11.5	76	--	--	--	--	--	--
Lakeland, FL	11.4-24	WH	8-32	3-4	50-90	4-36	0-7	80-100	6.7-27.3	1.0-4.2	75-85	3.0-5.0	1.8-3.1	38-40
Walt Disney World, FL	18.9	WH	300	28	91	200	23	89	--	--	--	--	--	--
Austin, TX	28.1	WH	51	29	45	96	44	53	--	--	--	--	--	--
Average Water Hyacinth	14.2		86	13	77	78	13	79	15	2.6	77	5.9	3.2	44
Average Duckweed	--		130	11	75	151	16	81	--	--	--	--	--	--

Adapted from Reed et al. (1988), U.S. EPA (1988), U.S. EPA (1984)

Notes:

in/d = cm/d x 0.394

Eff (%) = Efficiency of concentration reduction.

WH = Water hyacinth.

DW = Duckweed.

HLR = Hydraulic loading rate.

FAP = Floating aquatic plant.

BOD_5 = 5-day biochemical oxygen demand.

TSS = Total suspended solids.

TN = Total nitrogen.

TP = Total phosphorus.

SECTION 4.0

Case Histories of Constructed Wetland Systems in Arid Lands

4.1 Introduction

Constructed wetlands using treated wastewater were first built in Arizona in the late 1970s. Because of the continued value and importance of these constructed wetlands in the communities where they exist, they serve as examples for other communities interested in cost-effective and environmentally sound wastewater management.

Wetland treatment systems in arid climates have characteristics unique to the setting. Because of the high value of water in these regions, the design and operation will be more likely to incorporate all potential beneficial uses, particularly wildlife habitat creation and recreational opportunities. With high evapotranspiration rates, many of the early systems were disposal or evaporite systems. Some recent designs minimize evapotranspiration by using subsurface flow or by using the wetland effluent for irrigation, recharge, or other beneficial reuse. Widely dispersed or remote communities and institutions make small-scale SSF systems a practical option and an attractive design alternative to septic systems. Also, because people associate wetlands with rivers and riparian zones, and because of renewed interest in restoring riparian zones, riparian restoration plans increasingly include wetlands.

Compared to the large number of systems in North America, there are relatively few in arid climates. Figure 4-1 lists the known constructed wetland and FAP projects operating in Arizona. The list includes full-scale and experimental projects. Only constructed systems are included (no known natural wetland treatment systems exist in Arizona). This section summarizes the design features and performance of 13 wetland and FAP systems located in arid climates to provide guidance for implementing new projects in Arizona.

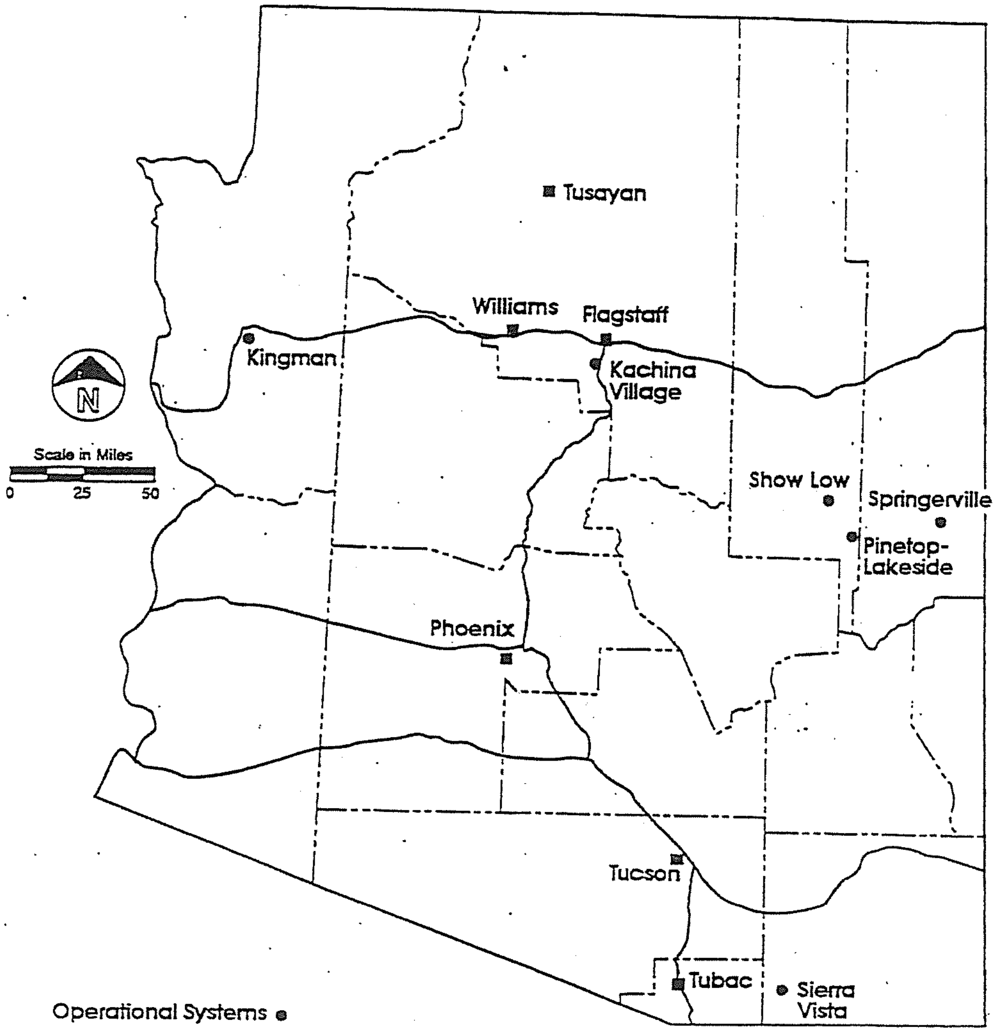
4.2 Surface Flow Constructed Wetlands

Case histories are given for four SF constructed wetlands in Arizona, two projects in California, one in Nevada, and one in Australia. These systems range in size from the 2-ha pilot system at Santa Rosa, California, to the 135-ha total evaporative system at Incline Village, Nevada.

4.2.1 Show Low Constructed Wetlands, Show Low, Arizona

4.2.1.1 Project Description

The Show Low constructed wetlands are widely known examples of the innovative use of constructed wetlands technology. The first wetland in the complex, Pintail Lake, was the first constructed wetland in Arizona to receive municipal wastewater and began receiving effluent in 1979. The complex has grown to include similar wetlands (Redhead Marsh and Telephone Lake in 1986), and as of 1994, the constructed wetland complex included 9 cells totaling 75 ha (186 ac) (Table 4-1).



Operational Systems ●

Pinetop-Lakeside
Show Low
Kingman
Sierra Vista
Kachina Village
Springerville

Proposed Systems ■

Flagstaff
Williams
Tubac
Phoenix
Tucson
Tusayan

Figure 4-1. Locations of Wetland and FAP Treatment Systems in Arizona. These systems are suitable throughout the state.

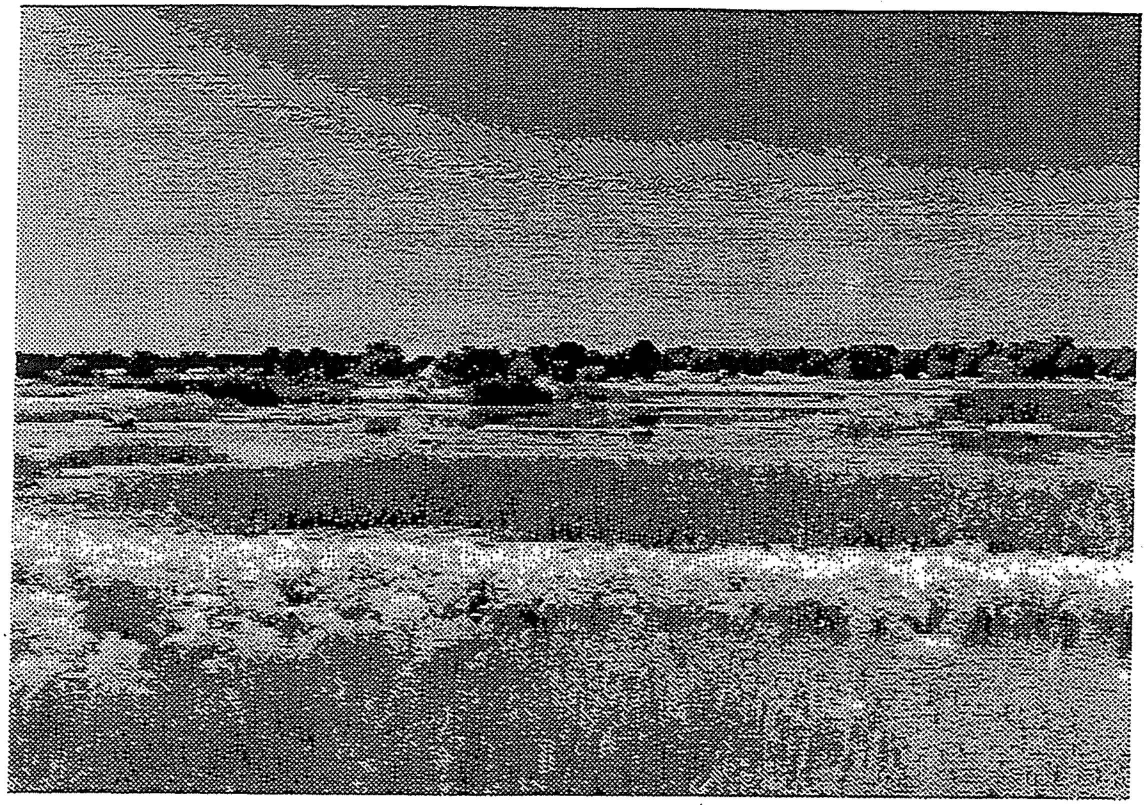
Table 4-1. Show Low, Arizona.

Construction Start Date:	Phase 1 Pintail Lake 1977		
	Phase 2 Redhead Marsh 1986		
Operation Start Date:	1979		
Construction Cost (year):	$146,750 (1977)	$300.000 (1986)	
Operation Cost:	$9,000	USFWS	
	$3,000	AGF	
	$12,000	City of Show Low	
Constructed Wetland Area:	75 ha (186 ac)		
Design Flow:	5,375 m^3/d (1.42 mgd)		
Wastewater Source:	Municipal secondary effluent		
Cell Design:	Pintail Lake	Redhead Marsh	Others
Number of cells	3	3	7
Design depth	0.9 m (3 ft)	0.9 m (3 ft)	0.9-1.8 m (3-6 ft)
Cell areas	23 ha (57 ac)	20 ha (49 ac)	32 ha (80 ac)
Plant types	Emergent	Emergent	Emergent
Discharge Location:	No discharge		
Inflow:	2,135 m^3/d (0.56 mgd)		

USFWS = U.S. Fish and Wildlife Service.
AGF = Arizona Game and Fish.

The Show Low constructed wetlands are located on USFS lands under the terms of a cooperative agreement with the City of Show Low. When a strict discharge limit was imposed on Show Low Creek, the city had to look elsewhere to dispose of its treated effluent. The USFS, Arizona Game and Fish Department (AGF), and the city became partners in this created wetland project as each entity saw opportunities to accomplish its goals in a cooperative venture. This partnership continues today, and other groups have joined, including the local Audubon Chapter.

The wetland was designed to optimize wildlife habitat (Figure 4-2). The ponds were designed with nesting islands and water levels to favor emergent vegetation, and diverse plant species were used. Also, the constructed wetlands were fenced to exclude domestic livestock grazing.



Source: Mel Wilhelm

Figure 4-2. Pintail Lake at Show Low, Arizona. The Show Low wetlands provide wildlife habitat and treat municipal wastewater.

4.2.1.2 Operational Performance

The Show Low wetlands were designed to improve water quality as water moves through successive ponds in series. Water clarity is especially important to allow submergent vegetation to grow in the water column. Wildlife response to the created and improved wetlands is the best indicator of success. Bird surveys conducted during a 16-week period in 1991 found 125 species using the wetlands. To date, 14 bird species are of special interest because of their rarity. Four of these special species nest in the constructed wetlands.

4.2.1.3 Special Features/Issues

The Show Low wetlands were originally designed as zero discharge facilities. Recently, three of the basins have been declared "waters of the U.S.," and efforts are underway to acquire permitting to recognize the ecological benefits of the basins receiving effluent. The construction of wetland treatment systems in former or existing waters of the U.S. is discussed in Section 8.

In addition to wildlife, these constructed wetlands attract human visitors. The Pintail Lake Public Use Facility includes a paved trail for handicapped access and a viewing blind large enough to accommodate 50 students. This facility attracts local, instate, out-of-state, and international visitors and is a popular outdoor classroom for local students to learn about recycling, wetland ecology, and wildlife.

4.2.2 Jacques Marsh, Pinetop-Lakeside, Arizona

4.2.2.1 Project Description

The Jacques Marsh constructed wetland is an important component of the wastewater management system for the Pinetop-Lakeside Sanitary District (PLSD) in north-central Arizona (Figure 4-3). It is the result of a cooperative effort among the USFS, AGF, and PLSD. Jacques Marsh is constructed on National Forest lands with no previous history as a lake or pond. Table 4-2 provides a summary of the Jacques Marsh history, cost, and design.

In the 1970s, surface and groundwaters near the Pinetop-Lakeside community were considered to be contaminated; the PLSD was formed in 1973 to clean up these waters. With the help of an EPA construction grant, a wastewater collection system, treatment plant, and Jacques Marsh were completed in 1980. The marsh receives about 0.7 mgd of secondary treated municipal wastewater.

Figure 4-3. Jacques Marsh at Pinetop-Lakeside, Arizona. The wetland was created to help clean contaminated water.

Table 4-2. Jacques Marsh, Pinetop-Lakeside, Arizona.

Construction Start Date:	1979		
Operation Start Date:	September 1980		
Construction Cost (year):	$286,600 (1979)	$500,000 (1986)	
Operation Cost:	USFWS	AGF	PLSD
Labor	$4,000	$6,000	$5,000
Power	$5,000		
Miscellaneous	$2,000		
Total	$12,000		
Constructed Wetland Area:	51 ha (127 ac)		
Design Flow:	7,570 m^3/d (2 mgd)		
Wastewater Source:	Municipal secondary effluent		
Cell Design:			
Number of cells	8		
Discharge Location:	No discharge		

USFWS = U.S. Fish and Wildlife Service.
AGF = Arizona Game and Fish.
PLSD = Pinetop-Lakeside Sanitary District.

The decision to construct Jacques Marsh rather than to discharge water from the treatment plant into Billy Creek, which runs through the area, has reduced worries about pollution and human contact, and has created a wetland area that provides recreation, outdoor education, and wildlife habitat.

4.2.2.2 Operational Performance

Jacques Marsh has become both a productive wildlife habitat and an effective water treatment facility. The marsh maintains its water clarity better than other northern Arizona wetlands, possibly as a result of the presence of submergent plant growth. There is no surface discharge reported from Jacques Marsh.

Jacques Marsh is next to a subdivision, but no mosquito or odor problems are reported. The area is open to the public and receives moderate use at present. Long-term plans call for developing a trail and viewing blinds to facilitate public use. A variety of waterfowl and elk use the area.

4.2.2.3 Special Features/Issues

At present, the Jacques Marsh is a zero discharge facility. Long-term plans include possible discharge to a riparian zone north of the wetland. The ability of water to flow from pond to pond makes this facility a highly effective water treatment operation. The PLSD treatment facility is sized for 7,570 m^3/d (2 mgd) and present production is 2,650 m^3/d (700,000 gpd).

Because of its location, Jacques Marsh is convenient for use by local schools as an outdoor classroom. The local environmental learning center uses the area to teach students about ecology, wildlife, and recycling. Volunteer projects to work on the marsh have also been successful.

4.2.3 Springerville Marsh, Springerville, Arizona

4.2.3.1 Project Description

The Springerville Marsh resulted from the City of Springerville's need to dispose of treated effluent and the AGF's willingness to allow development of wetland habitat on its lands. The marsh is in the northeastern corner of Springerville next to Nutrioso Creek (Figure 4-4).

The City of Springerville and AGF entered into a lease agreement in 1982 that allowed five wetland basins to be constructed for wastewater treatment on 65 ha (160 ac) belonging to AGF. The system was designed for up to 1,325 m^3/d (350,000 gpd) of secondarily treated effluent. Initially, there was no planned discharge, but the city is pursuing an aquifer protection permit to allow some discharge to the groundwater. Table 4-3 summarizes the system's history.

The wetland habitat consists of five ponds and fifteen nesting islands. Some emergent plants have been planted but vegetation development has been slow because of a shortage of water. Probably less than 20 percent of the potential habitat has developed so far.

4.2.3.2 Operational Performance

An oxidation ditch pretreatment facility easily meets the standard of 30 mg/L for BOD_5 and TSS prior to discharge to the wetland. There have been no indicators of any bioaccumulation problems. Additional habitat development is limited by water availability.

4.2.3.3 Special Features/Issues

The Springerville Marsh is a zero discharge wetland. Water enters the wetland directly from the pretreatment facility. The effluent leaves the wetland system primarily by evapotranspiration. The wetland was sized too large in the initial design, and not enough water is currently available to fully develop the area.

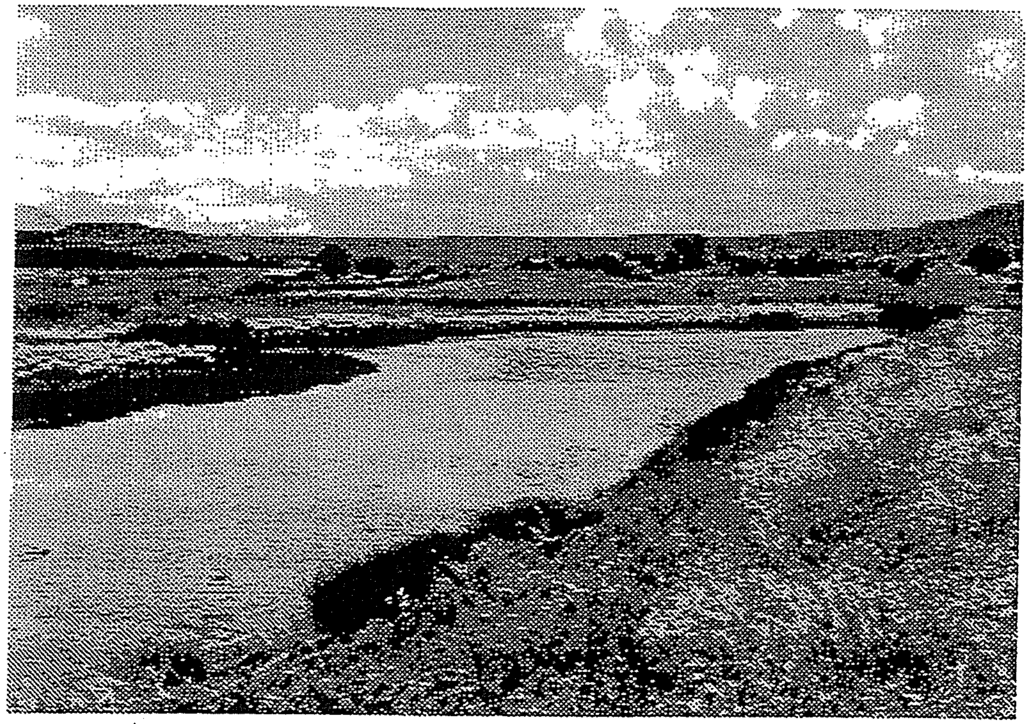


Figure 4-4. Springerville Marsh, Arizona. The 15 islands have attracted many waterfowl to the area.

Table 4-3. Springerville Marsh, Springerville, Arizona.

Construction Start Date:	August 1982
Operation Start Date:	March 1984
Construction Cost (year):	$152,000 (1982)
Operation Cost:	$909 AGF
	$5,000 City of Springerville
Constructed Wetland Area:	37 ha (90.35 ac)
Design Flow:	1,325 m^3/d (350,000 gpd)
Wastewater Source:	Municipal secondary effluent
Number of Cells:	5
Discharge Location:	No discharge

AGF = Arizona Game and Fish.

Public use of the wetland is minimal. Because the treatment facility is next to the wetland, it could pose some risk to public safety. Therefore, the public is allowed in only with permission of the treatment plant operators during normal business hours.

Bird use of this constructed wetland is high. Nesting surveys have indicated high use and reproduction, especially for waterfowl. Because of the wetland's proximity to a residential area, no hunting is allowed.

4.2.4 Sierra Vista Constructed Wetland, Sierra Vista, Arizona

4.2.4.1 Project Description

The Sierra Vista wetland is a pilot project sponsored by the City of Sierra Vista, the U.S. Bureau of Reclamation (USBR), and the National Biological Survey. Its purpose is to evaluate constructed wetlands for improving effluent quality and to compare several alternatives for reusing the improved effluent. The reuse alternatives are agriculture irrigation, groundwater recharge, municipal irrigation, and augmentation of flows in the San Pedro River. Prior to this pilot project, the effluent produced by the Sierra Vista Treatment Plant was used to irrigate a nearby alfalfa field.

To construct the wetland, two 1.4-ha (3.5-ac) cells were constructed in an existing 2.8-ha (7-ac) treatment pond. After the wetland's construction in April 1992, more than 100 volunteers planted 43,000 tubers. Planted species included hardstem bulrush (*Scirpus acutus*), three-square bulrush (*Scirpus americanus*), and yellow iris (*Iris pseudacorus*). After this initial planting effort, California bulrush (*Scirpus californicus*) and floating duckweed were also planted. Table 4-4 summarizes the Sierra Vista case history.

Table 4-4. Sierra Vista, Arizona.

Construction Start Date:	January 1992
Operation Start Date:	April 22, 1992
Construction Cost (year):	
Earthwork	$39,609 (1992)
Plants	$5,000 (1992)
Piping and Controls	$29,402 (1992)
Engineering	$20,000 (1992)
Constructed Wetland Area:	2.8 ha (7 acres)
Design Flow:	950 m^3/d (250,000 gpd)
Wastewater Source:	Municipal primary effluent
Influent Quality:	
BOD_5	84 mg/L
TSS	90 mg/L
Number of Cells:	2
Discharge Location:	Adjacent creek

4.2.4.2 Operational Performance

The 2-year-old Sierra Vista wetland is still developing. Performance will probably improve as vegetation grows. Table 4-5 summarizes operational data. The wetland already effectively removes nitrogen, phosphorus, and TSS. The data being gathered will be valuable for planning other constructed wetlands in Arizona. The Sierra Vista constructed wetland is attracting a variety of birds and is already a popular area for viewing nature.

4.2.4.3 Special Features/Issues

This wetland differs somewhat from the other case studies because it discharges to an adjacent creek. The use of water from treatment wetlands in Arizona holds great promise for restoring degraded riparian zones and other dewatered habitats. Numerous other opportunities for using reclaimed water exist in the arid climates of Arizona.

Table 4-5. Operational Data, Sierra Vista, Arizona.

Parameter	Inflow	Outflow
Fecal Coliform MPN/100ML	3,000	23
Nitrate-N (mg/L)	1.29	<.20
TKN (mg/L)	14.8	5.14
Phosphate (TP) (mg/L)	4.27	3.59
BOD_5 (mg/L)	84	13
TSS (mg/L)	90	18

MPN = Most probable number.
ML = Megaliter.

4.2.5 Incline Village Constructed Wetlands, Incline Village, Nevada

4.2.5.1 Project Description

The Incline Village, Nevada, wastewater treatment system includes final effluent treatment and disposal to a 173-ha (428-ac) constructed wetland (Figure 4-5). Prior to the wetland, effluent was discharged to the Carson River, which resulted in an unacceptable nutrient load to the river (CH2M HILL, 1980). Secondary wastewater is conveyed 30 kilometers by pipeline from the treatment plant near Lake Tahoe to the wetlands, through a vertical drop of 500 meters. A ranch located up the line from the wetlands has contracted to take the wastewater from the treatment plant during the summer. Thus, little water reaches the wetlands from April through August. Most of the 4,500 m^3/d (1.2 mgd) that reaches the wetlands evaporates in this arid climate, and a small fraction infiltrates to groundwater. The wetland was designed to dispose of the secondary wastewater and to establish wildlife habitat, and consequently no water quality permit was necessary (CWC, 1983).

Water management involves scheduling flow to eight wetland cells that divide into 21 subcells that connect via 20 outlet control structures, 14 inlet valves, and 40 inter-cell valves. In addition, at the operator's discretion, water from the treatment wetlands can be blended with water from a natural wetland complex fed by hot springs (CWC, 1983). Table 4-6 provides a summary of design criteria.

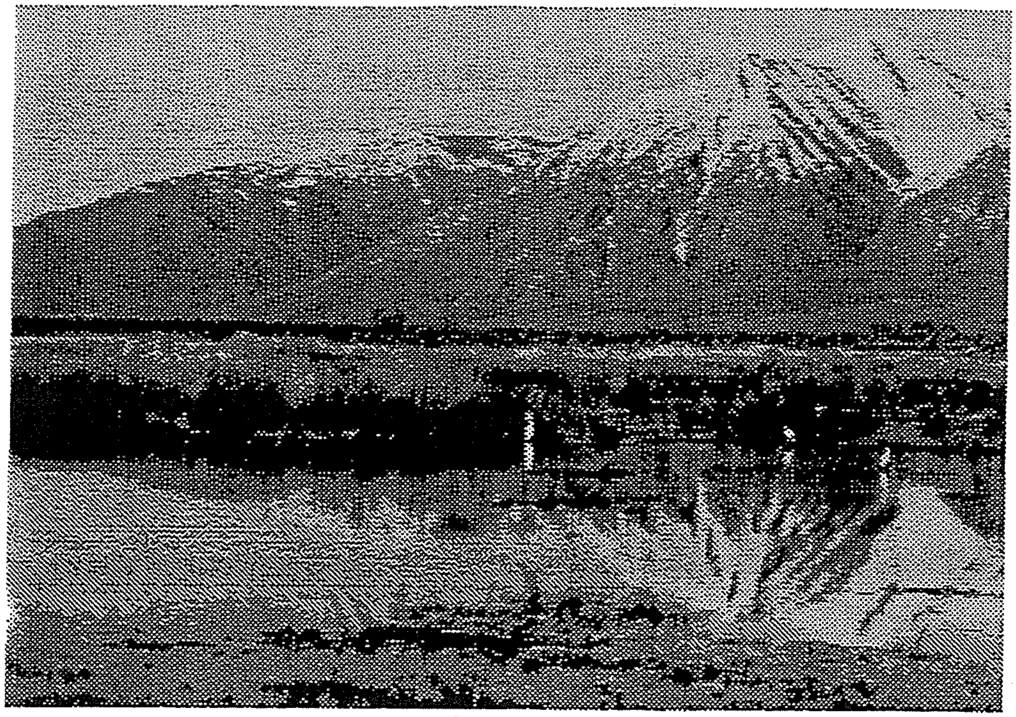


Figure 4-5. Incline Village Constructed Wetlands, Nevada. An active fishery exists, and record-sized fish have been caught at the site.

Table 4-6. Incline Village, Nevada.

Operation Start Date:	1984
Construction Cost (year):	$5,000,000 (1984)
Constructed Wetland Area:	
Total	156 ha (385 ac)
Cell 1	15 ha (37 ac)
Cell 2	13 ha (32 ac)
Cell 3	11 ha (27 ac)
Cell 4	9.5 ha (23 ac)
Cell 5 (overflow area)	47.5 ha (117 ac)
Cells 6 & 7 (floodplain area)	43 ha (106 ac)
Cell 8 (seasonal storage)	17 ha (42 ac)
Design Flow:	5,000 m^3/d (1.3 mgd)
Wastewater Source:	Municipal secondary effluent
Influent Quality:	
BOD_5	20 mg/L
TSS	20 mg/L
TDS	240 mg/L
TP	6.5 mg/L
TN	25 mg/L
Number of Cells:	8
Design Depth:	
Emergent marsh	15 cm (0.5 ft)
Open water	60-90 cm (2 to 3 ft)
Average	45 cm (1.5 ft)
Discharge Location:	No discharge

4.2.5.2 Operational Performance

The wetlands began operating in fall 1984 and have been successful thus far (Williams et al., 1987). Operating data measures water quantity, water quality, vegetation establishment, and habitat use. Detailed studies (Kadlec et al., 1987) of the hydrologic effects were conducted in 1985 and 1986, with special emphasis on evaporation. Water chemistry was reviewed intensively and supplemented in 1989-90, in conjunction with other regional wetland studies (Kadlec et al., 1990). Habitat and bird use were surveyed in 1991 and found to be compatible with the water disposal goals (McAllister, 1993; Heap, 1992).

Operation of the Incline Village constructed wetlands has been quite successful. The plant superintendent is pleased with the facility, and it is popular with the monitoring and maintenance personnel. The evaporative disposal goal has been met, even during the 100-year frequency rain event of February 1986. The wildlife habitat establishment goal has been met, with large numbers of both breeding and migratory waterbirds at the site.

Evaporation and infiltration were central to the project's design goals (Kadlec et al., 1987). As with other sites in the vicinity, the wetlands lose about 150 centimeters per year (cm/yr) of water to the atmosphere. However, the wetted surface area is not the entire diked area, because dryout occurs every summer. The absence of pumped water during the summer compounds the evaporative effect. Staff gages in Cells 6, 7, and 8 showed an infiltration water loss of 14 percent of the total water input in summer 1986. This estimate concurs with the preproject hydrogeological study (CH2M HILL, 1980).

There is no long-term trend in the concentration data for any of the six constituents in any cell or stream; that is, there is no apparent year-to-year variation. Nitrate, ammonium, phosphorus, and BOD_5 concentrations decrease as water passes through the wetlands (Kadlec et al., 1990). In contrast, chloride, conductivity, and total dissolved solids (TDS) increase along the flow path (Table 4-7). The commonly accepted method of mass balance

Table 4-7. Operational Data, Incline Village, Nevada, 1984-1989.

Water Quality

	NH_4-N (mg/L)	NO_3-N (mg/L)	TP (mg/L)	TDS (mg/L)	Chloride (mg/L)	BOD_5 (mg/L)
Influent	14.1	-	24	269	39	15.1
Effluent						
Cell 1D	2.33	13.1	6.84	1,339	86	11.4
Cell 2D	3.48	27.4	9.63	806	68	10.2
Cell 3D	1.98	24.2	6.83	1,147	88	10.4
Cell 4D	0.63	10.4	3.47	1,719	118	8.1
Cell 5A	0.65	2.7	1.37	1,993	105	7.7
Cell 5B	0.29	3.9	1.36	2,346	116	5.7
Cell 6	0.21	0.8	1.61	2,345	143	6.7
Cell 7	0.2	0.3	2.15	2,465	156	5.7
Cell 8	0.16	0.6	0.58	2,955	167	5.5

Water Budget

Inputs	**Flow (ac-ft/yr)**
Pumped	673
Groundwater Estimate	320
Precipitation	238
Hot Springs (diverted)	0
Total	1,231

Outputs	**Flow** (ac-ft/yr)
Evapotranspiration	782
Surface Discharge	0
Groundwater Estimate	449
Total	1,231

ac-ft x 0.00081 = m^3.

representation—inputs, outputs, and percent reduction—cannot be used because the system has no surface outflow. Because evaporative concentration takes place along the flow path, the chloride concentrations in the recharge cells were high, and a large fraction of pumped chloride goes to groundwater. Seasonally, the remaining chloride moved from dry deposits to surface water and back to dry deposits. Nevertheless, large reductions in nutrients and BOD_5

occur: nitrate decreases 98 percent, ammonium 98 percent, and phosphorus 97 percent. BOD_5 was reduced 63 percent, but not below the 5 to 6 mg/L range. In contrast, chloride increased more than fourfold and TDS increased more than tenfold, with passage to higher-numbered cells.

Shallow groundwater was monitored in six wells; five were 2 to 9 feet deep and one was about 44 feet deep. Groundwater was analyzed for temperature, conductivity, nitrate, and total phosphorus. The water contained considerable dissolved solids, as expected, and very small amounts of nitrogen and phosphorus. There do not appear to be trends in TDS: 1,670 mg/L in 1985 and 1986 and 1,660 in 1989. Chloride was 109 mg/L in 1985 and 1986 and 88 mg/L in 1989, which is a significant difference. Total phosphorus was 0.047 mg/L in 1985 and 1986 and 0.057 mg/L in 1989, probably not a significant difference. Wells 4 and 5, near Cells 4 and 7, showed 0.55 mg/L nitrate in 1985 and 1986, but only 0.05 mg/L in 1989.

4.2.5.3 Special Features/Issues

Initially, the vegetation of the wetlands was troublesome, with difficulties arising from hydrological and meteorological phenomena. It was too dry and windy for vegetation establishment. Some cells, primarily 1 through 4, were graded deeply into the ground, exposing subsoils not amenable to wetland vegetation. Using natural waters from the adjacent hot springs with the accompanying seed bank appears to be curing these problems. In other cells, dense vegetation has become established. The resulting detritus caused plugging of water control structures and had to be reduced by burning. Periodic, dense filamentous algal blooms occur in some cells.

Wildlife benefits of the wetlands have exceeded expectations. Large numbers of waterfowl and shorebirds (37 species identified from casual observation) use the site for nesting as well as resting during migration. An estimated 300 waterfowl nests are present per season. It is not unusual to see hundreds of waterbirds on the wetlands, even in the middle of winter. In turn, predator populations have thrived, including herons, coyotes, and several raptor species. Hunting of ducks and geese is permitted, under the management of the plant operator. Hunters lease blinds and decoys and an active fishery exists for herons and sport fishers. This project demonstrates the potential for multiple benefits from water treatment wetlands.

As mentioned above, salt exported to groundwater prevented salt buildup in the cells farthest downstream. This export is vital to continued ecosystem health, because without it, the end-of-the-line cells would become hypersaline. Such conditions are undesirable for wildlife management.

Mosquitoes have been identified in the wetlands, including *Culex tarsalis*, which is a vector for western equine encephalitis. There is a wide disparity in the perceptions of this situation among different regions of the United States. The biological control Bactimose™ has been suggested to treat the Incline Village wetland cells. Drawdown and dryout also can be effective and are conducted at this site at the optimal time.

4.2.6 Hemet/San Jacinto Multipurpose Constructed Demonstration Wetlands, Hemet, California

4.2.6.1 Project Description

The Hemet/San Jacinto Multipurpose Constructed Demonstration Wetlands is a cooperative effort by Eastern Municipal Water District (EMWD) and the USBR to evaluate and expand the use of reclaimed water. EMWD's water has been provided primarily by water imports. With the supply and availability of imported water increasingly uncertain, EMWD is considering alternatives such as reclamation and reuse of treated wastewater, groundwater, and water conservation. Reuse of treated wastewater involves further treatment in wetlands prior to injection or infiltration to recharge groundwater supplies. In addition, treatment wetlands with high quality wildlife habitat also serve to involve and educate the public about EMWD's overall reuse program. Table 4-8 provides a summary of the Hemet/San Jacinto project.

Table 4-8. Hemet/San Jacinto, California.

Construction Start Date:	January 1994
Operation Start Date:	1995
Construction Cost (year):	$1,060,000 (1994)
Constructed Wetland Area:	10 ha (25 ac)
Site Size:	18 ha (44 ac)
Wetland Types:	(a) Surface flow Wet meadow (moist soil test areas) (b) Surface flow Emergent marsh/open water (c) Surface flow Shallow emergent marsh
Design Flow:	3,785-18,900 m^3/d (1-5 mgd)
Wastewater Source:	Municipal secondary effluent
Number of Process Trains:	1
Number of Cells:	5 inflow; 8 moist soil test areas
Design Depth:	
Wet meadow	No standing water
Emergent marsh/open water	0.45-1.8 m (1.5-6 ft)
Shallow emergent marsh	3-10 cm (0.1-0.3 ft)
Discharge Location:	Reuse

The EMWD/USBR program is a 5-year study to develop design, construction, and operational criteria that will provide cost-effective and innovative alternatives for managing water resources in arid regions. A Wetlands Research Facility (WRF) was developed to research the ability of wetland treatment systems to attain tertiary treatment standards while providing wildlife habitat and public benefits. The WRF consists of two 0.2-ha (0.5-acre) nursery cells for wetland plant propagation, eight 15-m (50-ft) by 70-m (230-ft) research cells, and a reverse osmosis desalination unit with two saline vegetated marshes and two evaporation ponds. In 1994, construction was completed on a larger scale 10-ha (25-acre) demonstration wetland that will help evaluate removal efficiency, process limitations, and waterfowl use.

Because discharge from the demonstration wetlands returns to the WRF or to the saline marsh evaporate ponds, a National Pollutant Discharge Elimination System (NPDES) permit was not needed. All wetlands were constructed in highly disturbed upland areas, so no permits were necessary.

4.2.6.2 Operational Performance

The Hemet/San Jacinto wetlands are being monitored for water quality, plant establishment, wildlife use, aquatic macroinvertebrates, water-sediment interactions, and bioaccumulation. Preliminary analysis of data covering a 6-month period after vegetation establishment in WRF's research cells indicates that total nitrogen removal in emergent marsh/deep water/emergent marsh cells averaged 58 percent in contrast to 11 percent in densely vegetated wetland cells. Spikes in nitrogen and turbidity concentrations appear to coincide with large numbers of migrating red-wing blackbirds and are more evident in cells with open water habitat. Additional monitoring of the research cells is focusing on hydraulic residence times (HRTs), pollutant mass balance rates, evapotranspiration, and microbial dynamics.

4.2.6.3 Special Features/Issues

The demonstration wetland has islands of two sizes with different adjacent water depths to evaluate island design for wildlife use and effects on water flow paths. Vegetation is being transplanted from the experimental plant propagation cells to the larger-scale demonstration cells.

4.2.7 Santa Rosa Pilot Wetlands Creation Project, Santa Rosa, California

4.2.7.1 Project Description

The Santa Rosa Subregional Water Reclamation System Wetlands Creation Project was initiated to identify and evaluate three alternatives for wastewater reuse and discharge: irrigation, discharge to two different streams, and wetlands creation. A demonstration wetland was constructed in the Laguna de Santa Rosa watershed within an inactive reclaimed water storage reservoir on city-owned land known as the Kelly Farm (Figure 4-6 and Table 4-9). The demonstration project sought to identify design criteria to maximize fish and wildlife benefits, to determine expected water quality of discharge from a wetland receiving reclaimed water and stormwater, to evaluate the impact of reclaimed water on the wetland, and to provide wildlife and water quality data to key regulatory agencies, public groups, and individuals. The wetlands study program examines habitat design and management, hydraulic operations, and nuisance control.

Source: CH2M HILL

Figure 4-6. Santa Rosa Pilot Farm Wetlands, California. These wetlands further polish ammonia, nitrogen, and phosphorus from high quality influent wastewater.

Table 4-9. Santa Rosa, California.

Construction Start Date:	1989
Operation Start Date:	1990
Constructed Wetland Area:	4 ha (10 ac)
Site Size:	6 ha (15 ac)
Wetland Types:	(a) Surface flow Seasonal wetland (b) Surface flow Emergent marsh/open water (c) Surface flow Open water
Design Flow:	7,570 m^3/d (2 mgd)
Wastewater Source:	Municipal tertiary effluent and stormwater
Number of Process Trains:	1
Number of Cells:	5
Design Depth:	
Seasonal wetland	0-30 cm (0-1 ft)
Emergent marsh/open water	30-90 cm (1-3 ft)
Open water	2.7 m (9 ft)
Discharge Location:	Storage pond

The wetland's discharge returns to an adjacent reclaimed water storage pond. Because it does not discharge to a surface water body, an NPDES discharge permit was not necessary. Because the wetland cells were constructed in an existing lagoon, no other permits were needed.

4.2.7.2 Operational Performance

Highly pretreated wastewater and stormwater from a relatively undeveloped site are used to feed the pilot wetlands at Santa Rosa. Consequently, inflow pollutant concentrations are low. As summarized in Table 4-10, the wetlands provide some additional polishing of this high quality water. Although TSS remains essentially unchanged through the wetlands, ammonia demonstrates a 56 percent removal, total nitrogen a 22 percent removal, and total phosphorus a 12 percent removal, based on inflow-outflow concentrations. Metal concentrations also appear to be decreasing in the wetland system, except when stormwater additions occur.

Table 4-10. Operational Data, Santa Rosa, California, 1990-1993.

	TSS (mg/L)	NH_4-N (mg/L)	TN (mg/L)	TP (mg/L)
In	18.9	1.28	10.4	2.88
Out	20.6	0.56	8.15	2.52

In addition to water quality, vegetation and wildlife are monitored at Santa Rosa. The vegetative communities of the storage pond were found to shift to open water and emergent wetlands. The composition of the emergent wetlands changed from an existing cover of spike rush *(Eleocharis macrostachya)* to an increasing cover of tules, cattail, and smartweed (*Polygonum* spp.). An analysis of different tule planting techniques suggested that transplanted tule clumps spread twice as fast as tule single stems. Wildlife monitoring documented an increase in the total number of birds, especially among the wetland species.

4.2.7.3 Special Features/Issues

Mosquitos have been monitored in the Santa Rosa wetlands and not found to be a problem where mosquito fish (*Gambusia affinis*) are present.

An additional wetland system was constructed in 1991 at the La Franchi dairy to examine the potential of constructed wetlands to treat animal waste. Summer removal rates were measured at more than 70 percent for ammonia, less than 30 percent for phosphorus, and 55 percent for total organic carbon (TOC). Inflow TOC concentrations in dairy waste averaged more than 10,000 mg/L.

4.2.8 Carcoar Wetlands, Carcoar, Australia

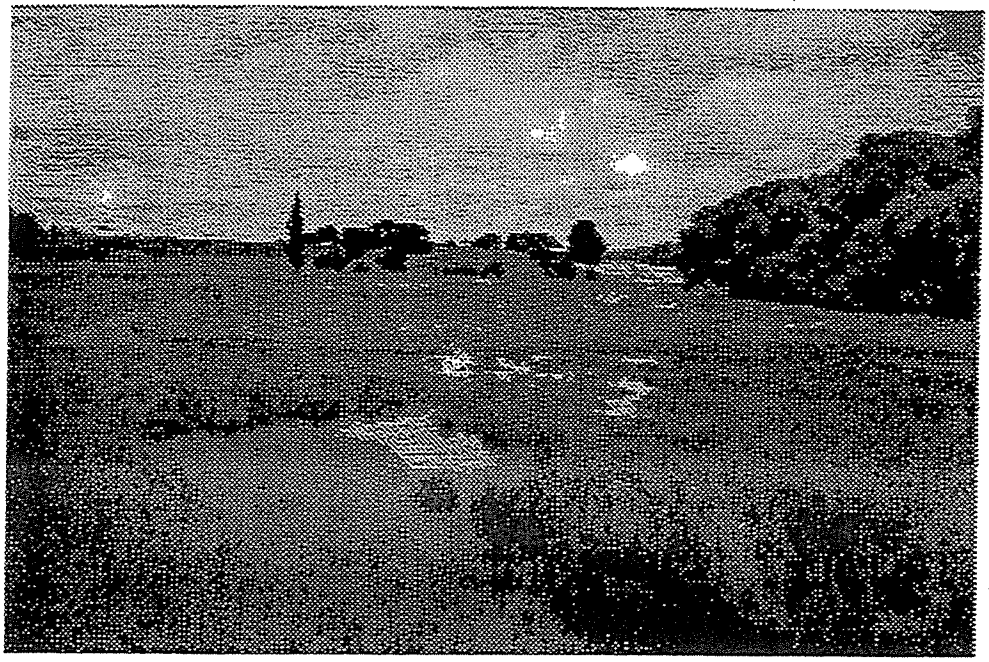
Carcoar Reservoir is a water storage reservoir on the Belubula River, near the town of Blayney in central western New South Wales, Australia. Water from the 37,000-megaliter (ML) (9,000-million gallons) reservoir is used for irrigation, stock, and domestic supplies. Activities on the reservoir include fishing and sailing. The impoundment has had a continuing history of water quality problems brought about by high nutrients in the Belubula River. In fact, blue-green algal blooms often occur in summer, and potentially toxic algal products have repeatedly restricted use of the water for stock and domestic consumption and for contact recreation. A water quality management plan has been developed for the watershed and its point sources, but many of the strategies cannot provide short-term relief. Consequently, the Department of Water Resources decided to construct a treatment wetland at the inlet to the reservoir to intercept phosphorus before it enters the storage area.

The Carcoar wetland has the following purposes:

- Remove nutrients
- Serve as a research site for large, in-stream constructed wetlands
- Provide a habitat for local fauna, environmental education, and community involvement

The wetlands are sited in the floodplain of the river. Water is delivered from a structure in a rock and rammed earth weir that spans the river just upstream of the wetlands. The weir raises water elevations by approximately 2 m (6.6 ft) to provide the hydraulic head necessary to divert flow to 9 ha (22 ac) of constructed marshes. Flows greater than 43,000 m^3/d (11.4 mgd) pass over the weir and bypass the wetlands, because short contact times would result otherwise. This permits treatment of 95 percent of the summer flows and 50 percent of the winter flows. An annual average of 70 percent of the river flow is treated.

The wetlands are formed by a series of levees with baffles to spread the water and avoid short-circuiting (Figure 4-7). The maximum depth is 1.2 m (3.9 ft), and the average depth is 48 cm (1.6 ft), yielding a storage capacity of 43 ML (11.4 million gallons). Thus, retention times range upward from a minimum of 1 day to more than 6 weeks in summer. The basins were planted with reed, but local water plants have appeared, principally bulrush and spike-rush.



Source: Robert Kadlec

Figure 4-7. Carcoar Wetlands, New South Wales, Australia. The wetland removes sediments and some nutrients from the river water before it enters the storage reservoir.

The Australian Trust for Conservation Volunteers, under supervision by the Department of Conservation and Land Management, planted the wetland. Local grade school and high school students help monitor, and the University of Western Sydney-Hawkesbury conducts research.

4.3 Subsurface Flow Constructed Wetlands

4.3.1 El Dorado School Wetlands, Santa Fe County, New Mexico

Very limited information was available for SSF constructed wetlands at Santa Fe County. Likewise, information on a SSF constructed wetland in Las Cruces was unavailable.

4.3.1.1 Project Description

A three-cell SSF constructed wetland was installed at the El Dorado School in Santa Fe County, New Mexico, in August 1990 to provide additional treatment of septic tank effluent prior to final surface discharge. The total wetland area for a 38 m^3/d (10,000 gpd) average flow is 1,020 m^2 (0.25 ac) for a design HLR of 3.7 cm/d (1.5 in/d). The gravel substrate is planted with common reed and bulrush.

4.3.1.2 Operational Performance

No operational performance data for the El Dorado School SSF constructed wetland were available.

4.3.2 Mesquite Constructed Wetlands, Mesquite, Nevada

4.3.2.1 Project Description

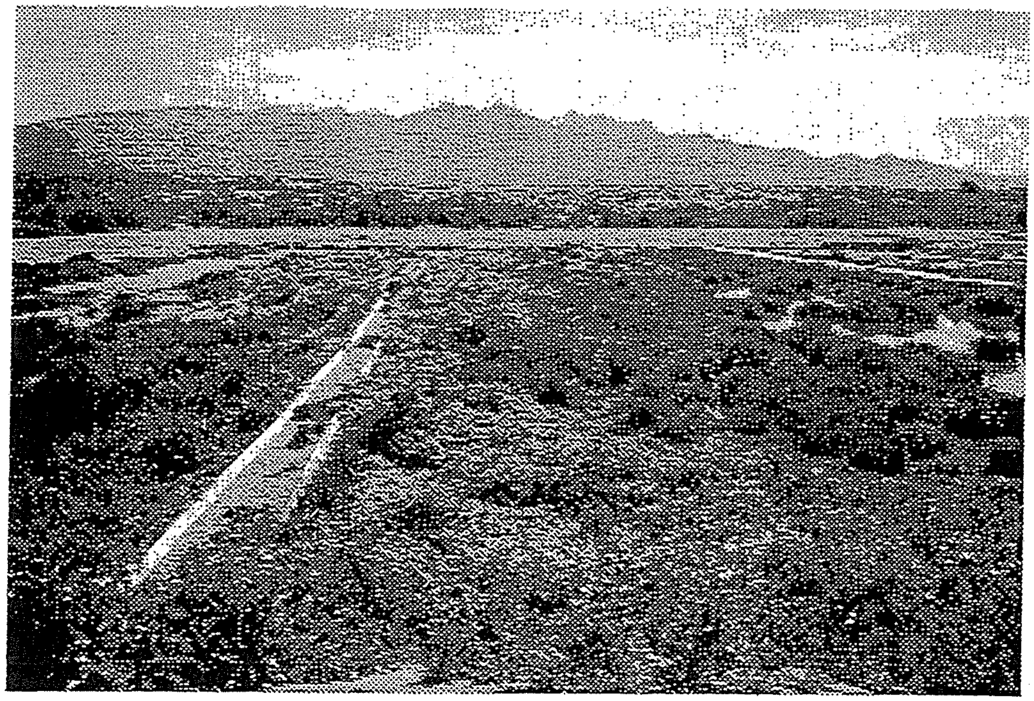
A subsurface flow constructed wetland was completed in 1992 to provide municipal effluent polishing at Mesquite, Nevada (Table 4-11). This SSF wetland treatment system consists of three wetland areas with a combined area of 1.9 ha (4.7 ac), each divided into four cells approximately 15 m (50 ft) long and 116 m (380 ft) wide arranged to operate in parallel. Native river-run gravel was used as a substrate in the wetland cells, and the design HLR is 16 cm/d (6.3 in/d). The wetland cells are planted with alkali bulrush (*Scirpus robustus*) (Figure 4-8).

Table 4-11. Mesquite, Nevada.

Operational Start Date:	1992
Construction Cost (1992):	
Distribution system	$95,000
Site work, recycle, pump station	200,000
Gravel media	170,000
Planting	50,000
Total	$515,000
Design Flow:	1,514 m^3/d (0.4 mgd)
Design Area:	1.9 ha (4.7 ac)
BOD_5 Loading:	78 kg/ha/d (70 lb/ac/d)
HRT:	3.3 d
HLR:	16 cm/d (6.3 in/d)
Media Depth:	81 cm (32 in)
Media Size:	0.9-2.5 cm (0.375-1 in)
Media Porosity:	33%
Hydraulic Conductivity:	512 m/d (1,680 ft/d)
Discharge Location:	Reuse
Design Area:	1.9 ha (4.7 ac)
BOD_5 Loading:	78 kg/ha/d (70 lb/ac/d)
HRT:	3.3 d
HLR:	16 cm/d (6.3 in/d)
Media Depth:	81 cm (32 in)
Media Size:	0.9-2.5 cm (0.375-1 in)
Media Porosity:	33%
Hydraulic Conductivity:	512 m/d (1,680 ft/d)\
Discharge Location:	Reuse

4.3.2.2 Operational Performance

Performance data for June 1992 through May 1993 were available for the Mesquite Constructed Wetlands (Crites et al., 1993). Average inflow and outflow concentrations for the Mesquite SSF wetlands are summarized in Table 4-12. Effluent concentrations for BOD_5, TSS, and nitrogen were typically highest during the winter months.



Source: Ron Crites

Figure 4-8. Mesquite Wetlands, Mesquite, Nevada. *The subsurface flow wetland provides final polishing of municipal wastewater.*

Table 4-12. Operational Data, Mesquite, Nevada, June 1992 - May 1993.

Parameter	Influent (mg/L)	Effluent (mg/L)	Percent Removal
BOD_5	64	29	55
TSS	57	13	77
Ammonium N	16.4	10.2	38
TKN	29.1	15.6	46
Total N	31.6	16.4	48
Total P	7.4	6.2	16

4.3.2.3 Special Features/Issues

The Mesquite SSF wetlands construction cost was $515,000 or about $270,818/ha ($109,600/ac). The major portion of this cost was attributed to the cost of the gravel media and earthwork.

The Mesquite constructed wetlands were designed to operate with a continuous 100 percent recycle flow. The recycle is intended to result in better plug flow and to maintain healthy plant growth during dry conditions. The recycle option has generally not been used.

4.4 Floating Aquatic Plant Systems

4.4.1 Pima County Constructed Ecosystems Research Facility, Pima County, Arizona

4.4.1.1 Project Description

Construction of the Pima County Constructed Ecosystems Research Facility was completed in late 1988, and system operation began in January 1989 (Table 4-13). The pilot facility is adjacent to the Roger Road Wastewater Treatment Facility and receives secondarily treated municipal effluent. The pilot facility consists of six ponds and a laboratory (Figure 4-9). The earthen ponds are lined and have a total surface area of 3.3 ha (8 ac). Ponds 1 through 5 are 0.05 ha (0.12 ac) each and 140 cm (4.7 ft) deep. Pond 6 is 0.08 ha (0.2 ac) and 260 cm (8.7 ft) deep. During operation with water hyacinths, the water depth was controlled at 90 cm (3 ft). Pond 5 is covered by a greenhouse.

Influent flows to the ponds ranged from 136 to 142 m^3/d (36,000 to 38,000 gallons per day [gpd]) from 1989 to 1991, and the reported HLR was 32.5 cm/d (12.8 in/d) from 1990 to 1991. Primary wastewater was discharged to Pond 6 at a flow rate of 136 m^3/d (36,000 gpd) for an effective HLR of about 17.7 cm/d (7 in/d).

Beginning in 1992, the system operated in a new mode after conversion of Pond 1 to a combination duckweed and SSF wetland system. The wetland portion of the cell was planted with cattail (*T. domingensis*), bulrush (*S. olneyi*), giant reed (*Arundo donax*), black willow (*Salix nigra*), and cottonwood (*Populus fremontii*). The gravel fill in the raceway consists of 60

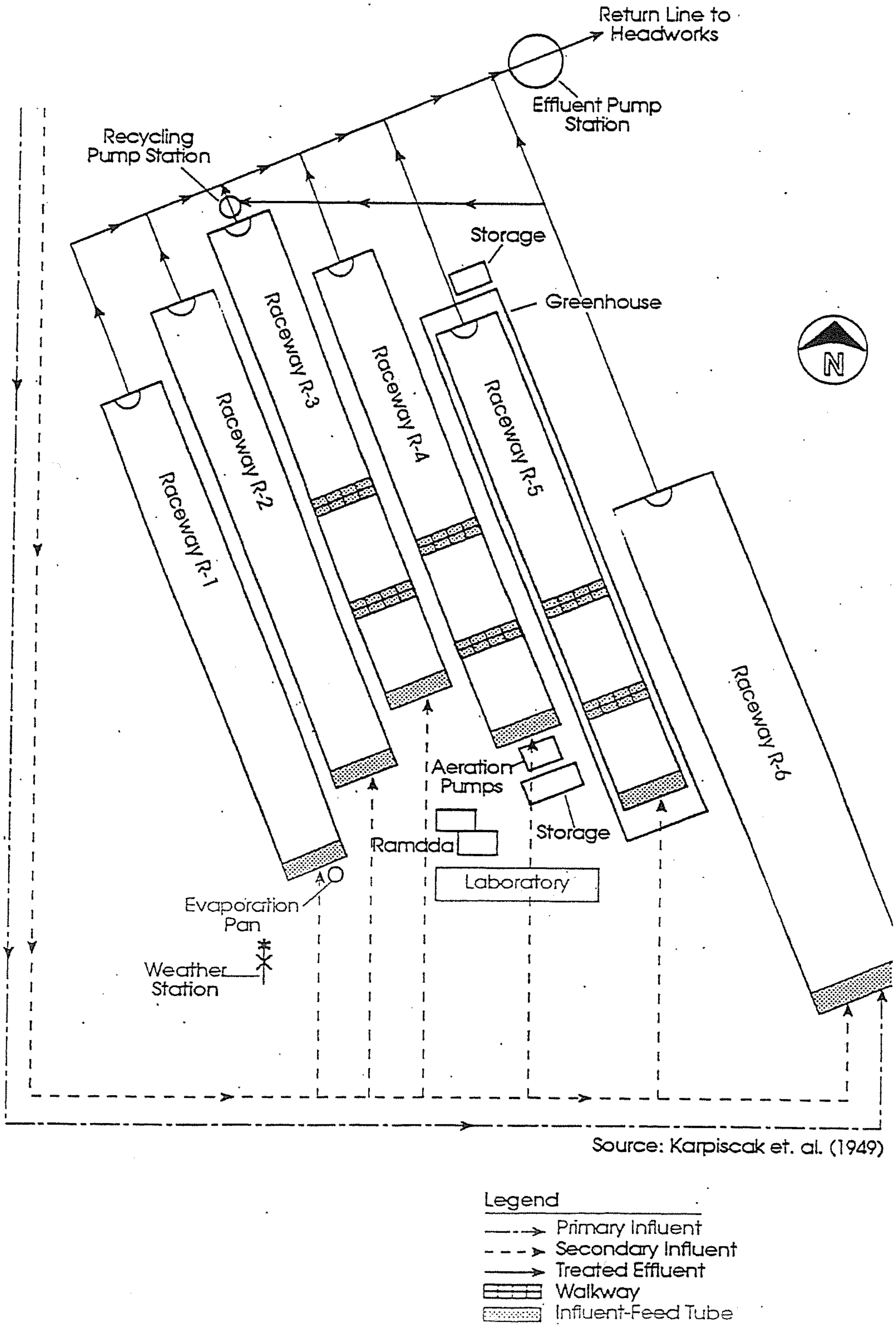


Figure 4-9. Floating Aquatic Plant Research Project at Pima County, Arizona. This research facility receives secondarily treated municipal effluent; nitrate nitrogen removal efficiency has been about 90 percent.

cm (2 ft) of coarse material (2 to 2.5 cm) overlain by pea gravel. Soil was placed inside rock walls for tree planting. Also at this time, Pond 6 was converted from water hyacinth to duckweed.

Table 4-13. Pima County, Arizona.

Operation Start Date:	1989	
Constructed Wetland Area:	3.3 ha (8 acres)	
Design Flow:	136-142 m^3/d	
Wastewater Source:	Municipal secondary effluent	
Influent Quality:		
BOD_5	20 mg/L	
TN	22.9 mg/L	
Cell Design:		
Number of cells	6	
Depth	Ponds 1-5	140 cm (4.7 ft)
	Pond 6	260 cm (8.7 ft)
Cell areas	Ponds 1-5	0.05 ha (0.12 ac)
	Pond 6	0.08 ha (0.2 ac)
Design Depth:	90 cm (3 ft)	
Discharge Location:	Reuse	

4.4.1.2 Operational Performance

Average performance of the five water hyacinth ponds receiving secondary influent resulted in a concentration reduction for BOD_5 from about 20 to 7 mg/L for an average percent removal efficiency of 64 percent. Influent TSS concentrations were not reported, but outflow concentrations were typically less than the detection level of 5 mg/L and always less than 10 mg/L during the water hyacinth tests. Nitrate nitrogen concentrations were reduced by about 90 percent, resulting in low or undetectable concentrations in the pond outflows. Ammonia nitrogen reduction efficiency was much less, about 14 percent, and total nitrogen was reduced by about 40 percent.

Table 4-14 summarizes operational results from the Pima County pilot facility from August 1992 to January 1993 when constructed wetlands were compared to hyacinth and duckweed systems. During this 6-month period, lowest effluent concentrations for BOD_5, ammonia nitrogen, and total nitrogen were observed for the hybrid and water hyacinth systems, and lowest nitrate+nitrite nitrogen outflow concentrations were observed for the duckweed system.

Table 4-14. Operational Data, Pima County, Arizona, Pilot Wetland and FAP Ponds, August 1992 to January 1993 (Karpiscak et al., 1994).

		Concentration (mg/L)							
	HLR	BOD_5		NO_3+NO_2-N		NH_3-N		TN	
Test Unit	(cm/d)	IN	OUT	IN	OUT	IN	OUT	IN	OUT
Ecosystem (duckweed/wetland)	16.7	23	5.7	5.31	0.65	15.2	13.3	22.9	14.2
Hyacinth	20.5	23	7.2	5.31	0.26	15.2	12.7	22.9	13.4
Duckweed	11.0	23	11.0	5.31	0.17	15.2	16.8	22.9	18.1

cm/d x 0.39 = in/d.

4.4.2 San Diego Water Hyacinth Facility, San Diego, California

4.4.2.1 Project Description

In 1981, the City of San Diego began to test the use of water hyacinths for secondary treatment of municipal wastewaters in a 114 m^3/d (30,000 gpd) pilot facility. The project also included a biomass digestion facility to test methane production from the harvested floating aquatic plants. In 1984, this facility expanded to include six water hyacinth treatment ponds (Figure 4-10). According to U.S. EPA (1988), additional expansions of this test facility were planned for 1989 and later, ultimately resulting in a full-scale system capable of treating a flow of 3,785 m^3/d (1 mgd).

Source: George Tchobanoglous

Figure 4-10. San Diego, California, Water Hyacinth System. Promising results led to an expansion of this facility to treat municipal wastewater.

The water hyacinth facility was constructed with the following goals:

- Demonstrate that it could meet a 30 mg/L effluent limit for BOD_5 and TSS
- Determine if the FAP effluent was of sufficient quality for subsequent advanced wastewater treatment
- Determine if the hyacinth plants could be used for methane production and energy recovery
- Examine the public health and nuisance potential of a large-scale water hyacinth wastewater treatment system

Table 4-15 summarizes design criteria for the San Diego pilot water hyacinth facility. The six water hyacinth earthen ponds used in the Phase I and II studies were clay-lined and measured 8.5 m x 126 m x 120 cm deep (28 x 413 x 4 ft) (area = 0.11 ha, 0.27 ac). The ponds were configured to operate in series or in parallel; in 1986, they were modified to operate in a step-feed mode (Figure 4-11). Later, aeration was added to the ponds to help eliminate odor problems associated with high sulfate levels in the wastewater.

Table 4-15. Design Criteria Summary for San Diego, California, Water Hyacinth Pilot Facility (U.S. EPA, 1988).

Pond Configuration	6 earthen ponds Clay lined Trapezoidal cross sections Plug-flow Step-feed with recycle	
Pond Dimensions	Length	122 m (400 ft)
	Width	9.8 m (32 ft) (top), 13.6 m (45 ft) (bottom)
	Area	0.1 to 0.11 ha (0.25 ac)
	Depth	up to 1.4 m (4.6 ft)
Design Loadings	HLR	5.8 to 27.7 cm/d (2.3 to 11 in/d)
	BOD_5	123 to 359 kg/ha/d (110 to 320 lb/ac/d)

4.4.2.2 Operational Performance

With influent BOD_5 and TSS concentrations greater than 100 mg/L, effluent concentrations were typically less than 30 mg/L. Step-feeding the influent to the water hyacinth ponds enhanced overall treatment but also resulted in anaerobic conditions along the length of the cells, creating the need for supplemental mechanical aeration. At high recirculation rates, turbidity of the effluent increased, resulting in high TSS in the effluent and excessive chlorine demand in the final disinfection process. TSS was generally within limits at a recirculation ratio up to 5:1.

DO decreased to less than 1.2 mg/L, resulting in significant odor problems and the need to install a ferric chloride feed system and aeration. Low DO levels led to poor mosquito fish survival and poor mosquito larval control. Low DO combined with low temperatures in the winter resulted in the need for additional mosquito control measures (*Bacillus thurengensis* and Golden Bear Oil 1111).

4.4.2.3 Estimated Costs

On the basis of the pilot studies, San Diego estimated that its full-scale water hyacinth facility (3,785 m^3/d) (1 mgd) would have a capital cost of about $2.18 million and an annual operation and maintenance cost of $494,000 (in 1986 dollars). Anaerobic digestion of the hyacinths might generate methane with an energy equivalent to about 2 million British thermal units (BTU) annually; however, the capital and operation and maintenance costs do not include the costs associated with this digestion facility.

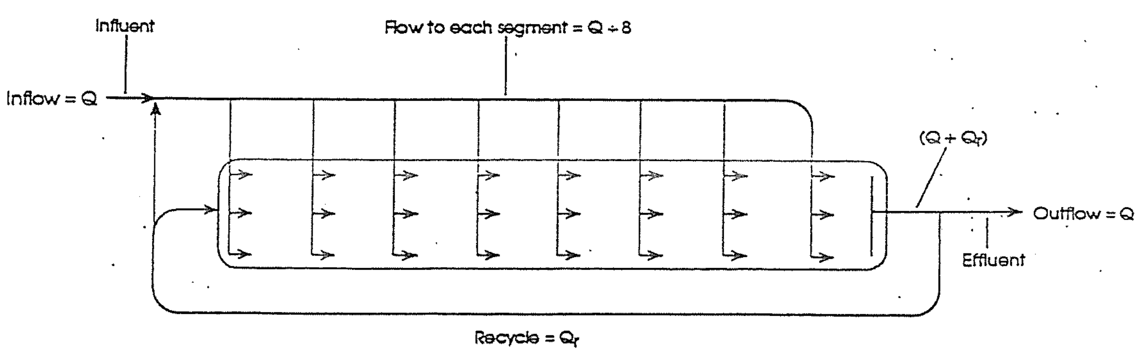


Figure 4-11. Step-Feed Hyacinth Pond at the San Diego, California Pilot Facility. The step-feed design improved the system's performance overall but resulted in anaerobic conditions that required additional aeration.

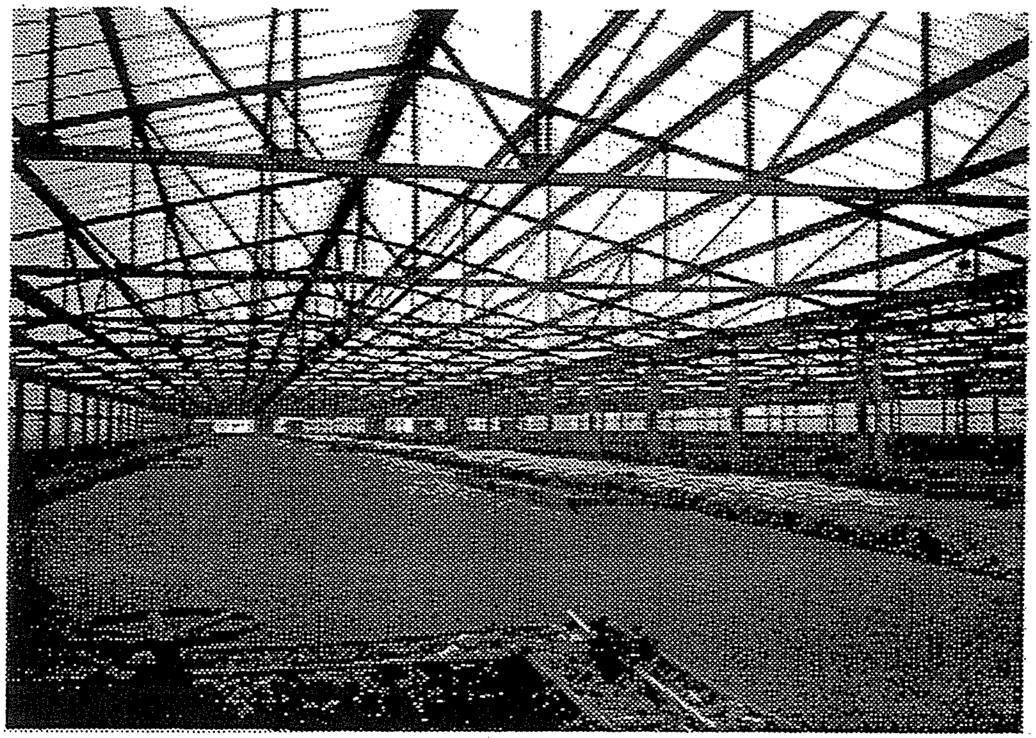
4.4.3 Hornsby Bend Facility, Austin, Texas

4.4.3.1 Project Description

The City of Austin used water hyacinths seasonally to upgrade lagoon effluent from 1977 until 1990. In February 1986, the city's Hornsby Bend facility expanded FAP technology to include three water hyacinth ponds that were entirely enclosed in a 2-ha (4.9-ac) glass greenhouse (Table 4-16). The water hyacinth cells had a total surface area of 1.6 ha (4 ac), a length of 265 m (870 ft), and ranged in size from 0.48 ha to 0.64 ha (1.2 to 1.6 ac). Basin depths ranged from 90 cm (3 ft) upstream to 150 cm (5 ft) downstream. The design flow rate was 7,570 m^3/d (1.5 mgd) for an average HLR of 47 cm/d (18.5 in/d). This system provided additional polishing of sludge lagoon supernatant to meet discharge standards of 30 mg/L for BOD_5 and 90 mg/L for TSS on a year-round basis. The system was converted largely to a duckweed cover in 1990 (Figure 4-12).

Table 4-16. Hornsby Bend Facility, Austin, Texas.

Operation Date:	1977 - 1990
Construction Cost:	$1.2 million ($750,000/ha)
Constructed Wetland Area:	1.6 ha (4 ac)
Design Flow:	7,570 m^3/d
Wastewater Source:	Sludge lagoon supernatant
Influent Quality:	
BOD_5	131 mg/L
TSS	142 mg/L
Cell Design:	
Number of cells	3
Plant types	Water hyacinth converted to duckweed
Length	265 m
Width	
End basins	18.1 m (0.48 ha)
Center basins	24.2 m (0.64 ha)
Depth	0.9-1.5 m (3-5 ft)
Total volume	17,000 m^3
Discharge Location:	River



Source: City of Austin

Figure 4-12. City of Austin's Hornsby Bend Enclosed Duckweed System. In 1990, the vegetation in the ponds in this 2-ha greenhouse was changed from water hyacinth to duckweed.

The FAP system was designed for natural mosquito control through the use of predator species such as mosquito fish, grass shrimp (*Palemonetes kadiakensis*), and several species of frogs. Eight open water exclosures are located in each of the FAP cells to maintain oxygenated habitat for the fish and shrimp. A 3.4-m (11-ft) cascade provides passive aeration to the effluent before final discharge.

4.4.3.2 Operational Performance

Performance data from a one-year period from 1987 to 1988 have been published for the Hornsby Bend water hyacinth facility (Table 4-17). Effluent pH was found to be lower than the influent pH with monthly averages between 7.1 and 7.8. Influent BOD_5 averaging 131 mg/L was reduced to an average outflow concentration of 36 mg/L. Average monthly TSS concentrations were reduced from 142 to 28 mg/L. Approximately 77 percent of this effluent TSS is organic as measured by the volatile suspended solids test. Influent and effluent ammonia nitrogen concentrations for the water hyacinth facility have been high, with monthly average effluent concentrations exceeding inflow concentrations during some months apparently because of mineralization of organic nitrogen.

Table 4-17. Operational Data, Austin, Texas, 1987-1988 (U.S. EPA, 1988)[a].

	pH		BOD_5 (mg/L)		TSS (mg/L)		VSS (mg/L)		NH_3-N (mg/L)	
Date	Inf	Eff	Inf	Eff	Inf	Eff	Inf	Eff	Inf	Eff
9/87	8.4	7.1	97	30	140	31	90	28	22.9	38.6
10/87	8.3	7.8	39	11	120	19	169	22	26.5	43.0
11/87	8.3	7.8	153	9	245	21	240	17	26.1	39.3
12/87	8.2	7.7	106	14	142	24	111	14	41.9	39.1
1/88	8.1	7.6	79	18	127	17	96	16	121.1	31.0
2/88	8.1	7.7	84	45	84	36	71	12	95.6	36.4
3/88	8.1	7.6	-	-	155	41	91	37	77.6	42.0
4/88	7.9	7.6	357	139	182	47	180	49	76.8	42.5
5/88	7.9	7.4	143	34	121	26	68	8	43.5	21.9
5/88	8.0	7.7	156	30	117	30	79	23	47.0	33.9
7/88	8.1	7.7	99	28	132	19	104	12	24.7	37.4
Average	8.1	7.6	131	36	142	28	118	22	54.9	36.8

[a]Monthly average of approximately 12 samples (composites) per month.

Inf = Influent.

Eff = Effluent.

VSS = Volatile suspended solids.

4.4.3.3 Estimated Costs

The estimated capital cost for the Hornsby Bend water hyacinth system was $1.2 million for a per hectare cost of $750,000.

4.5 Summary of Constructed Wetland and FAP Systems in Arid Lands

Table 4-18 summarizes key information from the 13 wetland and FAP treatment system case histories presented in this report. These projects demonstrate that constructed SF wetlands can provide both effective treatment and valuable wildlife habitat areas in Arizona.

SSF constructed wetlands and FAP treatment systems can provide effective treatment in Arizona, but because of their higher construction and operational costs and their lack of wildlife habitat and public use values, they are appropriate treatment alternatives at a much smaller group of sites in the state.

Table 4-18. Summary of Arid Climate Systems Discussed in this Section.

Location	Type	Start	Goal	Wastewater	Inflow (m^3/d)	Discharge
Show Low, AZ	SF	1979	Effluent disposal and wildlife habitat	Municipal	5,375	None
Pinetop-Lakeside, AZ	SF	1980	Effluent disposal and wildlife habitat	Municipal	7,570	None
Springerville, AZ	SF	1984	Effluent disposal and wildlife habitat	Municipal	1,325	None
Sierra Vista, AZ	SF	1992	Evaluate for reuse	Municipal	950	Creek
Incline Village, NV	SF	1984	Effluent disposal and wildlife habitat	Municipal	5,000	None
Hemet, CA	SF	1995	Evaluate for reuse	Municipal	3,785-18,900	Reuse
Santa Rosa, CA	SF	1990	Evaluate for reuse	Reclaimed water and stormwater	7,570	Reuse
Carcoar, Australia	SF		Clean before water-supply reservoir	High-nutrient river water		Water storage pond/reservoir
Santa Fe, NM	SSF	1990	Advanced treatment	Septic tank effluent	38	Surface water
Mesquite, NV	SSF	1992	Advanced treatment	Municipal	1,514	Reuse
Pima County, AZ	FAP	1989	Advanced treatment	Municipal	136-142	Reuse
San Diego, CA	FAP	1981	Evaluate treatment technology	Municipal	114	Reuse
Austin, TX	FAP	1977-1990	Advanced treatment	Municipal	7,570	River

SECTION 5.0

Design Principles for Constructed Wetland and Floating Aquatic Plant Treatment Systems

5.1 Introduction

Wetlands and FAP systems have been constructed to treat wastewaters for at least 20 years. During this time, most designs have been based on review of operational data from existing treatment wetlands treatment systems or from previously constructed pilot wetland and FAP treatment systems. In many cases, rule-of-thumb techniques have been employed to try to avoid the need for careful analysis of treatment data from operational systems. Wetland designers assumed that if Rule 1 works at System A, then Rule 1 should work at Systems B and C. If a rule-of-thumb did not work at System B, then the designer simply made System C bigger without an understanding of the wetland's limitations. Unfortunately, non-quantitative design techniques are imprecise and result in either over-design (and unnecessary expense) or under-design (which leads to permit violations and disillusionment with the technology).

Substantial time and money have been spent on building and monitoring pilot and full scale constructed wetland and FAP treatment systems. As described in Section 3, operational data can be analyzed to help design new wetland systems. However, this data collection, summarization, and analysis is laborious and has not been completed for every aspect of wetland and FAP design. Consequently, the design basis for some types of treatment systems is better than for other types of systems. In particular, the North American Wetland Treatment System Database and subsequent efforts have provided a solid basis for design of most constructed SF and SSF wetland treatment systems. A similar effort has not yet been completed for FAP systems, although private companies are making efforts to refine design criteria for proprietary duckweed systems (Lemna, 1994). At this time, designers of FAP treatment systems will need to rely more on independent data reviews and crude rule-of-thumb methods than will constructed wetland treatment system designers.

This section is not intended to be a comprehensive design handbook. Rather, it provides a basis for reviewing designs that have been based on a variety of more detailed design techniques. Design criteria for Arizona systems should be based on permitted discharge limits, good engineering practice, and ADEQ Engineering Bulletins (such as No. 11), when appropriate. The constructed wetland and FAP treatment system designer may wish to consult the following references for more information:

- Kadlec and Knight (in press) - comprehensive basis for design of constructed wetlands (available late 1995)
- Reed et al. (1988) - collection of natural system design techniques with chapters devoted to constructed wetlands and aquaculture (FAP) systems
- U.S. EPA (1993) - technology assessment of SSF constructed wetlands
- Steiner and Watson (1993) - Tennessee Valley Authority's design, construction, and operation guidelines for small (including individual residence) SSF constructed wetlands

- WPCF (1990) - collection of natural system design techniques with chapters on wetlands and FAP systems

- Tchobanoglous and Burton (1991) - wastewater treatment plant design with chapters on wetlands and FAP systems

- U.S. EPA (1988) - design manual for constructed wetlands and FAP treatment systems

- Hammer and Kadlec (1983) - early design manual for natural wetland treatment systems

5.2 Constructed Wetlands

Table 5-1 provides a checklist of design considerations that are important for constructed wetlands. The following sections describe these specific elements of constructed wetland treatment system design:

- Site selection
- Treatment goals
- Size and depth
- Hydraulics and water control
- Vegetation
- Basin, substrate, and liners

5.2.1 Site Selection

A site evaluation is critical before design and construction of a treatment wetland. Possible site constraints include topography, depth to bedrock, existence of natural wetlands, presence of protected species, and significant cultural resources. A site-specific study can help to minimize project cost and permitting constraints.

Table 5-1. Checklist for Constructed Wetland and FAP System Review.

The following items should be considered during review of proposals for constructed wetland and FAP treatment systems:

1. Site Constraints

Climatic Factors	Maximum and minimum monthly temperature Rainfall and evaporation Ice and snow cover
Topography	Minimize cut and fill Minimize erosive slopes Water Courses/Drainage - Site drainage - 100-year flood protection
Geology/Soils	Absence of bedrock near surface Soil permeability Soil erodibility Geotechnical stability Presence/absence of faults
Aquifers	Water sources susceptible to contamination Salt accumulation Groundwater flows and depths
Biological	Section 404 wetlands jurisdiction Threatened or endangered species
Socioeconomic	Potential for nuisance conditions Land ownership/adjacent land uses Cultural resources

2. Treatment Goals

Constructed Wetlands	
Secondary treatment (SSF systems only)	Minimum of primary pretreatment
Advanced treatment (BOD_5, TSS, NH_4-N, TN, and TP reduction)	Minimum of secondary pretreatment
Disinfection	Chlorination and dechlorination Other alternatives to be considered
FAP Systems	
Secondary treatment	Minimum of primary pretreatment Less than 80 kg BOD_5/ha/d Less than 6 cm/d HLR Aeration or step-feed as necessary to control odors and mosquitoes
Advanced treatment	Minimum of secondary pretreatment Less than 10 cm/d HLR

Table 5-1. (Continued)

3. System Sizing	
Constructed Wetlands	Use sizing equations in Table 5-3
FAP Systems	Use rule-of-thumb methods in Table 5-4
4. Other Design Criteria	
Constructed Wetlands	
Water depth (SF only)	15 to 60 cm (0.5 to 2 ft) with water level control
Bed depth (SSF only)	30 to 90 cm (1 to 3 ft) with water level control
Substrate	Loamy topsoils in SF systems Coarse sand or gravel in SSF systems
Basin design	Lined in leaky soils or for secondary treatment Minimum two parallel systems Slight bed slope for drainage Berm freeboard for storm events and substrate accretion Emergency overflows for berm protection Width is 0.4 to 2 $m/m^3/d$ of flow (SSF only)
Water control	Effective inflow distribution Adjustable outlet weirs
FAP Systems	
Water depth	0.3 to 1.5 m (1 to 5 ft) (water hyacinth) 1.5 to 2.0 m (5 to 7 ft) (duckweed)
Water control	Inflow distribution Diffuse outflow Adjustable outlet weirs
Basin design	Lined for groundwater protection Minimum two parallel systems Basin area and dimensions should reflect plant species harvesting technology Floating baffles to control plant cover Emergency overflows for berm protection Berm freeboard for storm events
Post aeration	As necessary to meet effluent limitations

5. Regulatory Issues

Aquifer Protection Permit
National Pollutant Discharge Elimination System Permit
Environmental Assessment/Environmental Impact Statement
Section 404 Wetland Permit
Local Permits

Constructed wetland treatment systems can be built in any geographical area of Arizona where sufficient land is available. Constructed wetlands need to incorporate setback requirements that are stated in ADEQ's Engineering Bulletins 11 (page VI-2) and 12. Wetland treatment systems must be relatively level to ensure even flow distribution and minimize earthwork expenses. A site should be selected with minimal natural slopes, minimum bedrock within several meters of the ground surface, and suitable onsite soils for berm construction. Less favorable sites will increase wetland construction costs. A recommended minimum depth for work over bedrock is to have from 30 to 60 cm (1 to 2 ft) of soil between the wetland bottom and bedrock to reduce seepage.

Climatic factors are not prohibitive but do affect the required wetland treatment system area as discussed below. Constructed wetland sites should be selected so they do not present a nuisance to surrounding land uses. Properly designed constructed wetlands do not have odor or mosquito problems and can be located adjacent to residential areas. SF constructed wetlands frequently attract waterfowl and other birds, so they should not be located within prohibited zones around airports.

Constructed wetlands should not be sited in floodplains or in other seasonally flooded areas (jurisdictional wetlands) unless permit and operational constraints have been addressed. In some cases, a study of the project's net ecological benefits may show that a treatment wetland located in an existing infrequently-flooded area may enhance overall environmental and public values.

5.2.2 Treatment Goals and Pretreatment

Constructed SF wetlands can provide tertiary treatment of municipal wastewaters. Because of the potential to develop nuisance conditions (odors, mosquitoes, and poor plant growth) under high organic loading rates, constructed SF wetlands are not recommended for primary or secondary treatment of municipal wastewaters. On the other hand, SSF constructed wetlands can be designed for secondary or for tertiary wastewater treatment.

Since the water surface is below ground level in properly designed SSF systems, nuisance conditions caused by excessive anaerobic conditions are less likely to be an issue.

Tertiary treatment functions typically provided by constructed SF wetlands include further reductions in concentrations of BOD_5, TSS, ammonia nitrogen, nitrate+nitrite nitrogen, total nitrogen, and total phosphorus. As discussed below, HLR and influent quality greatly affect wetland effluent quality. Typical goals for constructed SF wetland treatment systems include one or more of the following:

- Further reduction of BOD_5 and TSS concentrations beyond secondary treatment
- Nitrification of ammonia nitrogen to nitrate
- Denitrification of nitrate nitrogen with concurrent reduction of total nitrogen concentration
- Reduction of total phosphorus concentration
- Reduction of other parameters including fecal coliforms, metals, organics, and whole effluent chronic toxicity

SSF constructed wetlands are generally designed to provide secondary or tertiary effluent quality. Typical treatment goals that might be part of a SSF constructed wetland treatment system design include the following:

- Secondary treatment of screened and settled primary or septic tank effluent
- Further reduction of BOD_5 and TSS concentrations beyond secondary treatment

- Denitrification of nitrate nitrogen in a previously nitrified wastewater SSF constructed wetlands are not particularly cost-effective for nitrification or for phosphorus removal because they have essentially the same removal rates for ammonia nitrogen and phosphorus as SF wetlands and typically cost 5 to 10 times more. Generally, SSF systems are preferred over SF systems only for small-scale applications (single and multi-family or school), or when the designer wishes to intentionally discourage the use of the wetlands by wildlife.

Influent quality expected for a constructed wetland can be based on actual measured quality from an existing pretreatment system or can be estimated based on typical published values. Tchobanoglous and Burton (1991) provide typical water quality information for primary and secondary municipal wastewaters, and Canter and Knox (1985) provide a review of typical septic tank effluent quality.

5.2.3 System Sizing

Because wetland design methods are still being developed, a clear consensus on sizing guidelines is not yet available. Some of the published sizing guidelines are inaccurate or not robust enough to work in every case. Some constructed wetland treatment designs have been based on incorrect hydraulic and kinetic models that overestimate treatment performance. Until recently, empirical methods using operational data provided the best guidance for system sizing. Although rule-of-thumb methods can help develop conservative sizing guidelines, they are not useful for optimizing wetland treatment areas for specific applications.

Table 5-2 presents general design guidelines for constructed wetland treatment systems from WPCF (1990). These numbers are helpful, but the information is not specific enough for cost-effective design. The volumetric-based first-order wetland design equation (based on hydraulic residence time) in WPCF (1990) and elsewhere (Reed et al., 1988; U.S. EPA, 1988; U.S. EPA, 1993) does not accurately explain a variety of operational wetland data.

The idea that more time in the wetland is good for improving water quality is intuitively very appealing. Early in the history of the technology, there was success for TSS and BOD_5 reduction in wetlands that had 7-10 days of nominal detention. The urge to replicate this range is therefore strong, but clearly this basis is inadequate for other constituents and may represent over-design for TSS and BOD_5. This attribute of the wetland must be coupled with a knowledge of the irreducible background concentration of the contaminant, as well as other design factors.

Depth is one primary controlling factor for nominal detention time and wetland area is the other. The relationship between these variables includes the water void fraction and can be described by the equation:

$$\tau_{nom} = \frac{\varepsilon AH}{Q}$$

where	A	=	wetland area, m^2
	H	=	water depth, m
	ε	=	water column void fraction
	t_{nom}	=	nominal detention time, d
	Q	=	water flow, m^3/d

The activity of the wetland in pollutant removal is associated with the immersed sediments and biota. These reactive surfaces dominate the removal processes for all biologically active substances. As a consequence, the rate of removal depends highly on vegetation density: a bare soil, shallow pond has the minimum efficiency; a densely vegetated, fully littered wetland of the same depth has a higher efficiency.

Table 5-2. Summary of Wetland Treatment System Design Criteria (WPCF, 1990).

	Constructed	
Design consideration	Surface Flow	Subsurface Flow
Minimum size requirement, ha/1,000 $m^3 \cdot d$	3-4	1.2-1.7
Maximum water depth, cm	50	Water level below ground surface
Bed depth, cm	Not applicable	30-90
Minimum aspect ratio	2:1	Not applicable
Minimum hydraulic residence time, days	5-10	5-10
Maximum hydraulic loading rate, cm/d	2.5-5	6-8
Minimum pretreatment	Primary; secondary is optional	Primary
Configuration	Multiple cells in parallel and series	Multiple beds in parallel
Distribution	Swale; perforated pipe	Inlet zone (>0.5 m wide) of large gravel
Maximum loading, kg/ha·d		
BOD_5	100-110	80-120
TN	60	60
Additional considerations	Mosquito control with mosquitofish	Allow flooding capability for weed control

ha x 2.47 = ac
m^3/d x 0.000264 = mgd
cm/d x 0.394 = in/d
kg/ha/d x 0.892 = lb/ac/d

If the detention time is increased by deeper submergence of these active components, at constant wetland area, no further removal activity is observed. In contrast, increasing the area of the wetland while retaining a constant volume does in fact increase the biotic material in contact with the water, and act to provide more detention time.

Cooper (1990), Brix (1990), and Kadlec and Knight (in press) have developed area-based, first-order wetland design models to predict treatment area requirements. Kinetic constants in these models were based on information from wetland systems in Great Britain, Denmark, and in the North American Wetland Treatment System Database. Rate constants presented in this guidance manual are derived from the North American Database and represent average conditions for various wetland designs. These rate constants are based on geographically-diverse treatment wetlandsand are considered to be relevant to Arizona conditions until more local performance data become available.

Area-based, first-order design models allow realistic calculation of the wetland area necessary to reduce an average inflow pollutant concentration, C_1, to an average outflow concentration, C_2, at a given average flow rate, Q. In addition, the models for BOD_5 and TN correct for the inevitable internal production of particulate and dissolved organic BOD_5 and TN. These natural processes result in a background BOD_5 concentration, C^*, equal to about 5.8 mg/L, and a background TN concentration of about 0.4 mg/L. Background TSS concentration is a function of inflow TSS concentration as shown in Table 5-3. Conservative design mustassume that pollutant concentrations will not be consistently lowered below these irreducible, background concentrations (C^*).

Table 5-3 summarizes the design equations and preliminary rate constants developed by Kadlec and Knight (in press). The rate constants for NH_4-N and NO_3+NO_2-N assume that nitrogen will change forms in the wetlands. Design for either of these parameters should assume that C_1, the design inflow concentration, is approximately equal to the inflow concentration of total nitrogen minus 0.4 mg/L. Wetland rate constants are empirically derived and will be refined as additional operational data become available.

The models in Table 5-3 predict that annual average removal rates and actual outflow concentrations will vary around these averages. Two methods are available to ensure that the wetland size is adequate to treat wastewater to comply with regulatory criteria that are frequently given as monthly maximum averages. The first method is to use the temperature correction factors given in Table 5-3 and to design for the coldest month. The second method is to convert monthly limitations to annual averages by using observed ratios from wetland treatment systems. For the wetland treatment systems in the Database, typical ratios between annual average and maximum month are 0.59 for BOD_5, 0.53 for TSS, 0.4 for NH_4-N, 0.4 for NO_3+NO_2-N, 0.67 for TKN, 0.62 for TN, and 0.56 for TP. In the case of a monthly maximum limit, this monthly maximum value should be multiplied by the above ratios to determine the value of C_2 for the equation in Table 5-3.

Table 5-4 presents an example of sizing a constructed SF treatment wetland to polish a facultative lagoon effluent prior to discharge. In this example, wetland area is controlled by the TN discharge limit, and there is an indication that consistent compliance with the desired TSS limit may be unrealistic for a constructed wetland.

5.2.4 Hydraulic Design

Some wetland treatment systems, both SF and SSF, have failed because of hydraulic problems. The wetland must be able to convey the design flow without overtopping either the berms or the media.

There is not a long history of research and development related to overland flow in wetlands. Mathematical descriptions are often adaptations of open channel flow formulae. These are discussed in detail in a number of texts, for example French (1985). The general approach uses mass, energy, and momentum conservation equations coupled with an equation for frictional resistance. A Manning's coefficient based on vegetated channel flow, must be coupled with the free surface water mass balance to compute the head loss through the wetland.

Table 5-3. First-Order, Area-Based Constructed Wetland Sizing Model.

General Model:

$$J = k\,(C - C^*)$$
$$k = k_{20}\,\theta^{(T-20)}$$
$$C^* = C^*_{20}\,\theta^{(T-20)}$$

where:

J	=	removal rate (g/m^2/yr)
k	=	first-order, area-based rate constant (m/yr)
k_{20}	=	rate constant at 20°C (m/yr)
C	=	pollutant concentration (mg/L)
C^*	=	irreducible background concentration (mg/L)
T	=	temperature, °C
θ	=	temperature coefficient

Wetland Area (based on modified plug flow hydraulics):

$$A = -\frac{Q}{k}\left[\ln\left(\frac{C_2 - C^*}{C_1 - C^*}\right)\right]$$

where:

A	=	wetland area (m^2)
Q	=	wastewater flow (m^3/yr)
C_1	=	inflow concentration (mg/L)
C_2	=	outflow concentration (mg/L)

Model Parameter Values (at 20°C):

		BOD	TSS	NH_4-N	NO_3+NO_2-N	TN	TP
Surface Flow							
k, m/yr		35	1000	18	35	22	12
	θ	1.00	1.00	1.04	1.09	1.05	1.00
C^*, mg/L		6	5.1+0.16C_1	0.0	0.0	1.5	0.02
	θ	—	1.065	---	---		1.00
Subsurface Flow							
k, m/yr		180	1000	34	50	27	12
	θ	1.00	1.00	1.04	1.09	1.05	1.00
C^*, mg/L		6	4.7+0.09C_1	0.0	0.0	1.5	0.02
	θ	---	1.065	---	—		1.00

Table 5-4. Constructed Wetland Sizing Example.

Project Goal: Upgrade an existing facultative lagoon effluent to allow for either surface water or groundwater discharge.

Existing effluent flow and quality (annual averages):

Flow	-	5,680 m^3/d (1.5 mgd)
BOD_5	-	30 mg/L
TSS	-	60 mg/L
TKN	-	15 mg/L
NO_3-N	-	5 mg/L

Final discharge limits (maximum month):

BOD_5	-	15 mg/L
TSS	-	15 mg/L
TN	-	10 mg/L

Determine minimum wetland size:

A. Define annual average design goals based on maximum month/annual average ratios:

BOD_5	=	15 x 0.59	=	8.8 mg/L
TSS	=	15 x 0.53	=	7.9 mg/L
TN	=	10 x 0.62	=	6.2 mg/L

B. Calculate areas for each parameter assuming average temperature is 20° C (68°F):

$$A = \frac{-Q}{k}\left[\ln\left(\frac{C_2 - C^*}{C_1 - C^*}\right)\right]$$

Q = 2,073,200 m^3/yr (1.5 mgd)

Parameter	Concentration (mg/L) C_1	C_2	C^*	K_{20} m/yr	Estimated Area ha	acres
BOD_5	30	8.8	6	35	12.7	31.4
TSS	60	7.9	14.7	1,000	–	–
TN	20	6.2	1.5	22	12.9	31.9

C. These results indicate that a constructed wetland may not be able to achieve the maximum monthly limit for TSS; however, examination of Table 3-3 and estimation of the area necessary to produce an annual average TSS of 15 mg/L (0.35 ha or 0.86 ac) indicates that a wetland sized for BOD_5 or TN compliance, will produce background concentrations of TSS.

The minimum wetland design area is set by TN at 12.9 ha (32 ac).

The general approach for SSF constructed wetland design uses Darcy's law of friction combined with the water mass balance. Some designers fail to use the mass balance, and errors result.

The idea of flowing water through a planted bed of porous media seems simple enough; yet numerous difficulties have arisen in practice. Gravel bed SSF wetlands in the United States frequently flood. The two probable causes are clogging of the media with particulates and improper hydraulic design. The same appears to be true for other countries as well (Brix, 1994), especially in SSF wetlands with a soil medium. The underlying cause of such hydraulic failure is the ad hoc procedure of designing to guessed values of hydraulic parameters. The SSF constructed wetland technology has been rescued by the fact that the hydraulically failed mode of flooded operation is the SF wetland. However, high construction cost for SSF compared to SF wetlands makes proper hydraulic design essential to obtain any advantage from the SSF constructed wetland alternative.

5.2.5 Water and Bed Depth

Water depth in SF constructed wetland treatment systems affects the survival and reproduction of plants, the effective hydraulic residence time, and the ability of oxygen to diffuse from the atmosphere to microbial populations. Normal water depths in wetland treatment systems range from about 15 to 60 cm (0.5 to 2 ft). When combined with high organic loadings, greater depths provide poor root oxygenation and poor plant growth. For example, a constructed wetland receiving tertiary wastewater might maintain good plant growth (and DO) at a water depth between 60 and 90 cm (2 to 3 ft), but a constructed wetland receiving secondary wastewater may have difficulty maintaining plant populations at 30 cm (1 ft). Generally, water depth in SF constructed wetlands should be adjusted to optimize plant growth as long as treatment goals are being accomplished. The constructed wetland outlet structure should allow control of water depths from zero up to the maximum design depth.

Bed depth of SSF constructed wetlands is typically the most important factor in system cost. WPCF (1990) recommends a bed depth of 30 to 90 cm (1 to 3 ft). European designers who have applied this technology to hundreds of systems (Cooper, 1990) recommend a bed depth of about 60 cm (2 ft). Green and Upton's (1994) estimate of a bed width requirement of about 0.4 m per m^3/d of flow for tertiary treatment is based on a bed depth of 60 cm (2 ft) and the use of 5 to 10 millimeters (mm) (0.2 to 0.4 in) gravel with a bed slope less than 5 percent and a steady state hydraulic conductivity of 1×10^{-3} m/s. Recommended bed widths for secondary treatment of settled wastewater are wider at 0.85 to 2 m per m^3/d (Cooper, 1990). Bed length can be determined by using the required bed area calculated from the equations in Table 5-3 divided by the required bed width. For example, for an inflow of 300 m^3/d (80,000 gpd) of secondary wastewater and a bed area of 0.5 ha (1.2 ac) for tertiary treatment, the recommended bed width would be about 120 m (393 ft) and the bed length would be about 42 m (138 ft).

5.2.6 Wetland Substrate

SF constructed wetlands typically use native soils as a substrate for plant growth. Treatment wetlands can be constructed on almost any soil type and on gravel, but preferred soils are loams and sands because of the ability of plants to develop extensive root systems and to propagate through rhizome development. Loamy soils are advantageous because of their fertility and texture. Clays may have excellent fertility but their texture hinders root penetration and diffusion of oxygen and other gases to and from the roots. Preferred wetland construction includes from 15 to 30 cm (0.5 to 1 ft) of loamy or sandy topsoil within the wetland to provide a suitable rooting medium for the wetland plants.

Substrate conditions are critical to the design of SSF wetlands. SSF wetlands have been constructed with substrates ranging from coarse sands (rarely loams) to pea gravels with diameters less than 1 cm (0.4 in) to large rocks (up to 10 to 15 cm [4 to 6 in] diameter). Excessive fines associated with SSF substrate can result in hydraulic failure and should be avoided. Media permeability must be determined to correctly design the cross-sectional area to avoid surface flow.

5.2.7 Wetland Liner Requirements

Underlying soil permeability must be considered in the design of a constructed wetland. The most desirable soil permeability is less than 10^{-6} to 10^{-7} m/s (0.14-0.014 in/hr). Lining is sometimes needed to decrease soil permeability and thus reduce seepage losses through the bottom of the wetland. Lining can consist of installing artificial materials, such as a geomembrane, or placing a layer of less permeable soils in the bottom of the wetland. Mechanical compaction of existing or imported soils can also be effective in creating a less permeable barrier to seepage.

Generally, liners will be required for constructed wetlands receiving primary wastewaters (including SSF systems receiving septic tank effluents), but not for systems receiving secondary or tertiary quality wastewaters. Systems designed with multiple cells may only require liners in those cells receiving primary effluent. If the effluent discharged from one cell to another is of secondary quality then a liner may not be required in the downstream cells.

Constructed wetlands may also be lined to prevent excessive loss of wastewater that is intended for some other beneficial use such as landscape irrigation or wildlife habitat. In these cases, lining may be partial to reduce infiltration through particularly permeable site soils and may be accomplished by adding less permeable subsoils or topsoils to portions of the site.

Need for an engineered liner is a determination that will be made on an individual project basis. A liner may add significant cost, and, in some instances, may hamper performance of the system. The regulatory constraints that may bear upon this decision stem from requirements of the Aquifer Protection Permit (APP) Program. To receive an APP, facilities must meet two basic requirements—that the design use the Best Available Demonstrated

Control Technology (BADCT) and that the discharge meet Aquifer Water Quality Standards (AWQS) at the point of compliance downgradient of the facility. Therefore, a liner is a required design component for a facility if it is common practice to line facilities of this type. Also, even if BADCT does not require a liner, some facilities might still need a lined system or a partially lined system to demonstrate that AWQS will be met downgradient. At sites where site characteristics can be demonstrated to perform hydrologically like a liner, no liner would be required.

5.2.8 Water Control

Constructed wetland treatment systems transform and assimilate pollutants on an aerial basis. In other words, the populations of plants and associated attached microbes that use pollutants for energy and nutrients depend more on the surface area of the wetland than on the depth of the surface water or subsurface substrate. This dependency results from the area basis of the major energy and material inputs to wetlands (sunlight, wind, and oxygen diffusion). Thus, treatment performance is tied closely to effective distribution of wastewater to all parts of the wetland area. Influent flow distribution, internal flow control, and diffused outlet design are essential to optimize treatment in constructed wetlands.

A variety of methods are available to distribute influent wastewater to treatment wetlands (Figure 5-1). Specific techniques include gated distribution header pipes, level-spreader swales or deep zones, multiple inlet ports from a gravity or pressurized pipe, and low-head sprinkler systems. The important element in the design is flexibility to adjust flows between ports or inlet locations so that slight inaccuracies during construction can be corrected following startup.

Flow tends to channelize in shallow constructed wetlands. Because shallow water may be desired to enhance plant cover, design should provide methods to maintain relatively even flow distribution across the width of the constructed

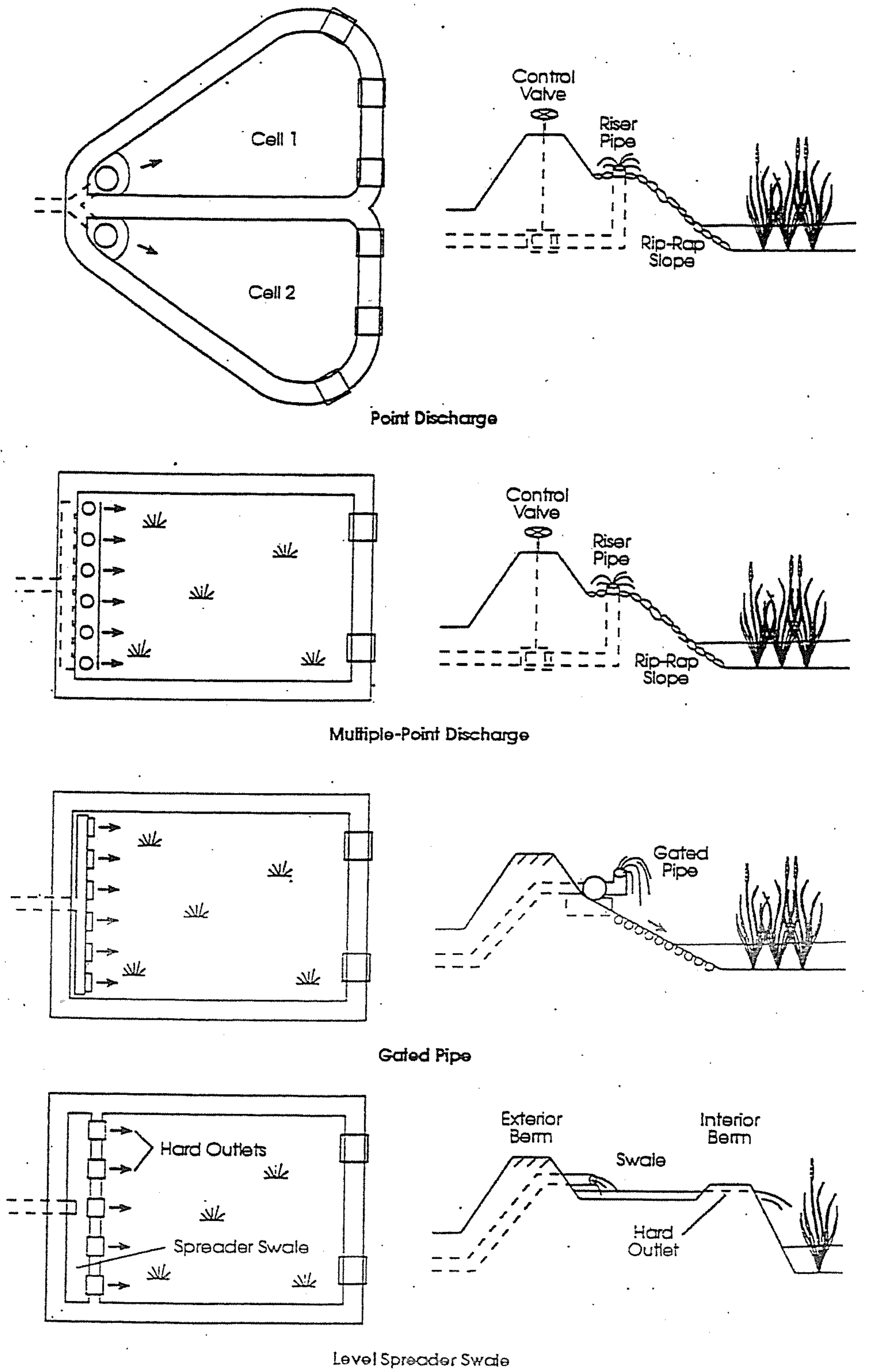


Figure 5-1. Influent Flow Distribution Structures for Constructed Wetlands. Even flow distribution is essential to optimize treatment performance.

wetland cells. Deep zones perpendicular to the flow path can help maintain good flow distribution along the length of the wetland (Knight and Iverson, 1990). These perpendicular deep zones also enhance treatment by increasing hydraulic residence time and provide habitat for some wildlife. Even flow distribution also can be achieved with high length-to-width ratios (greater than about 5:1) or internal baffles or berms that effectively increase length-to-width ratios.

Outlet structures also can enhance distribution. In SF constructed wetlands, multiple outlet weirs or a terminal, transverse, deep channel will recollect distributed flows. In SSF wetlands, a perforated outlet pipe at the bottom of the gravel substrate adjacent to the outlet effectively recollects flows.

Outlet structures must also provide flexibility to regulate water depths within the constructed wetland. For SF systems, a moveable weir or removable stoplogs are commonly used to change water levels. In SSF systems, water depth in the bed substrate is frequently controlled by use of a swivel elbow on the outflow drain pipe located within an excavated basin adjacent to the wetland outlet.

5.2.9 Basin Configuration

All constructed wetland treatment systems should have a minimum of two parallel treatment cells or trains of cells in series (Figure 5-2). This redundancy ensures continued operation during maintenance. For larger systems, additional parallel flow systems are preferable to minimize the loading placed on operational cells when one portion of the system is temporarily removed from service.

There is no apparent upper limit on the size of wetland cells. Individual cells larger than 300 ha are in use at some constructed wetlands in the U.S. Site topography may limit cell size because of excessive earthwork necessary to

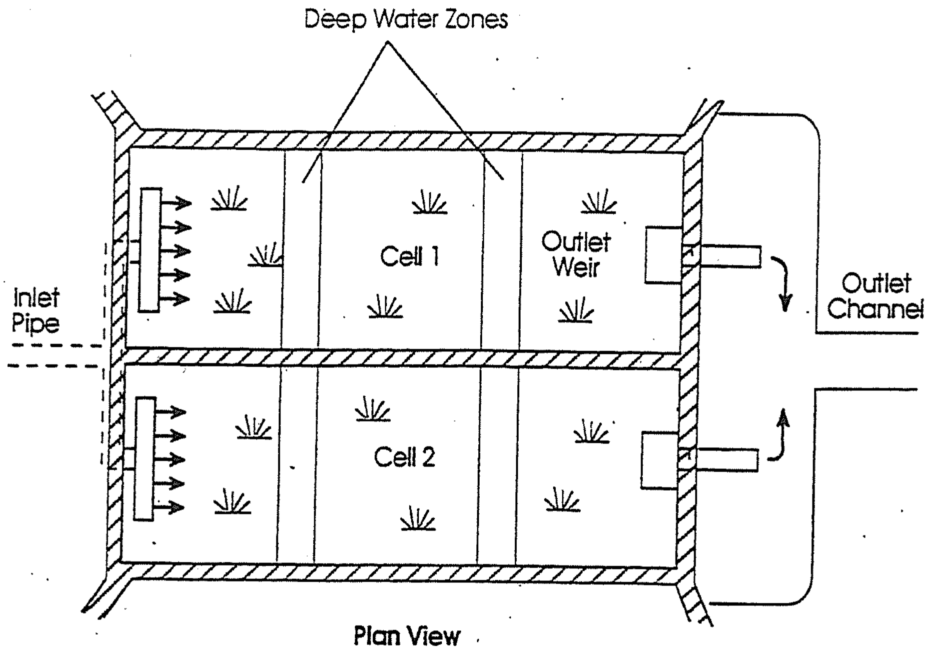


Figure 5-2. Typical Configuration of a Constructed Surface Flow Wetland Treatment System. Parallel basins provide the ability to shut off a portion of the system for maintenance.

create large wetland cells. Terraced cells may be the best approach to construct wetlands on sites with excessive natural slopes.

High length-to-width ratios in wetland cells may be useful in terms of minimizing short circuiting but have the disadvantage of increasing wetland cost by increasing the ratio of berm volume to wetland treatment area (Knight, 1987). Length-to-width ratios of 1:1 to 2:1 are acceptable in SF constructed wetlands as long as internal flow distribution structures such as perpendicular deep zones or low parallel berms parallel to the flow direction are included. Length-to-width ratios in SSF wetlands are based on required inlet width and system area (see 5.2.5), and are often less than 1:1.

Berm heights above the maximum design water level must be sufficient to store direct and indirect rainfall and to allow for gradual filling of the constructed wetlands with solids. Solids accumulation rates in wetlands depend on the amount of inorganic solids entering the wetland and on internal productivity of the wetland plants. Typical solid accumulation rates are less than 0.5 cm/yr (0.2 in/yr) with rates up to 1 cm/yr (0.4 in/yr) possible in inlet areas. Internal deep zones within the wetland can provide a sump for solids so that solids accumulation will not factor into determining berm freeboard.

For wastewaters with high concentrations of mineral or stabilized organic solids, pretreatment wetland cells or ponds should be used. These pretreatment cells can be designed to be emptied of solids on a periodic basis if necessary to protect the overall system from excessive sedimentation. Based on maximum solids accumulation rates, a 30 cm (1 foot) freeboard height would provide from 30 to 60 years of solids storage in a constructed wetland. The need for solids removal is unlikely in most constructed wetlands. However, if residual solids are anticipated to accumulate in a constructed wetlands the designer should plan for testing, removal, and environmentally sound disposal during design. In general, any solid that might accumulate in a wetland could be treated in the same manner as other wastewater residuals.

Berm freeboard in constructed SF and SSF wetlands should generally equal or exceed about 30 cm (1 ft) to accommodate rainfall and filling. A wave action analysis should be utilized to determine berm height in larger wetland impoundments with open water areas. In addition, emergency overflow points will allow safe passage of flood flows caused by excessive rainfall or blocked outlets without loss of berm integrity. Overflow points should route excessive waters to the area of least potential impact.

Side slopes are based on geotechnical constraints related to soil compaction and erosion potential. Side slopes in the range of 2:1 (horizontal:vertical) to 3:1 are generally satisfactory for constructed wetland berms.

5.2.10 Post Aeration

SF and SSF constructed wetland typically have wetland outflow DO concentrations below saturation. Post aeration must be provided when necessary to meet standards to discharge to classified surface waters. Post aeration can be provided by a passive, cascade system of adequate height and width, or by mechanical aeration. Post aeration requirements to meet specific numerical limits can be calculated using standard wastewater design texts such as Tchobanoglous and Burton (1991).

5.2.11 Vegetation

The most commonly used plant species in constructed wetlands designed for water quality improvement are cattails, bulrush, and common reed (*Phragmites communis*). All three of these species have very high colonization and growth rates, establish high surface area that continues through the winter dormant season, have high pollutant treatment potential, and are very robust in continuously flooded environments. Of these three plant groups, bulrush provides the greatest overall wildlife benefit, but cattails also provide habitat for nesting and roosting birds. Common reed has very little habitat value but is an extremely robust wetland plant. Other plant species that can be used in constructed wetlands to enhance ecosystem diversity and to create greater wildlife value are discussed in Section 6 and are listed in Appendix A.

All three of the major plant groups can be propagated from field-harvested or nursery-grown plant stock (rhizomes or seedlings). Because plant propagation is frequently the least successful aspect of project implementation, applicants should use experienced subcontractors. Maintaining wet soils without excessive flooding is critical to success during initial plant propagation.

5.2.12 Public Access

Public access to treatment wetlands should be controlled. The appropriate level of control depends on pretreatment, including disinfection for pathogen removal. Constructed SF and SSF treatment wetlands receiving less than disinfected secondary quality wastewaters should be fenced with no allowable public access. If pretreatment results in the equivalent of disinfected secondary quality, public access can be allowed as long as signs are posted to warn visitors of the water's source. An example sign might be:

Warning

These Wetlands Contain Reclaimed Wastewater

Please Avoid Body Contact

5.3 Floating Aquatic Plant Systems

Design of FAP treatment systems is based generally on a review of empirical data from operating systems and on rule-of-thumb methods. This section summarizes design criteria for FAP treatment systems including information about site selection, pretreatment, system sizing, water control, basin configuration and lining, post aeration, and vegetation selection and disposal.

5.3.1 Site Selection

FAP treatment systems can be used for wastewater treatment in any climatic area of Arizona; however, climatic conditions influence plant species selection as indicated below. Siting considerations for FAP systems are the same as those for lagoon systems. A proposed site should be relatively level with minimal bedrock near the ground surface. A proposed site should not be near any potable drinking wells and should allow enough land area for a fenced buffer area.

5.3.2 Pretreatment

FAP treatment systems typically provide either secondary or tertiary treatment. Pretreatment prior to a secondary FAP system would be primary (screening and primary sedimentation). Pretreatment prior to a tertiary FAP system would be secondary or higher.

5.3.3 System Sizing

Depending on treatment goals, FAP systems can operate in either aerated or non-aerated modes (U.S. EPA, 1988). Aeration may be added to achieve a higher loading and assimilation rate with a minimal FAP pond area. Nonaerated systems handle low organic loadings (less than about 80 kg BOD_5/ha/d [70 lb/ac/d]). Anaerobic FAP systems result from higher organic loading rates and may also result in odors and mosquito problems.

Table 5-5 summarizes FAP design criteria from WPCF (1990). HLRs as high as 120 cm/d (47 in/d) have been used in FAP systems but are not recommended. For secondary treatment, an HLR range from 2 to 6 cm/d (0.8 to 2.4 in/d) is recommended for water hyacinth FAP systems (WPCF, 1990). HLRs for tertiary treatment with aeration may be as high as 10 cm/d (4 in/d). HLRs for duckweed FAP systems have generally ranged from 0.5 to 2 cm/d (0.2 to 0.8 in/d) for secondary treatment and from about 4 to 10 cm/d (1.6 to 4 in/d) for tertiary treatment. Reed et al. (1988) published empirical design models for sizing water hyacinth FAP systems to meet specific effluent goals for nitrogen and phosphorus. These models account for the overall loss of nutrients in FAP systems due to sedimentation and plant uptake/harvesting.

Equation 5-1 estimates the design HLR necessary to achieve average effluent total nitrogen goals:

$$L_N = (760)/(1-N_e/N_0)^{1.72}$$

where

L_N	=	HLR, limited by nitrogen removal, m^3/ha/d
N_e	=	effluent total nitrogen concentration, mg/L
N_0	=	influent total nitrogen concentration, mg/L

This empirical equation assumes at least 80 percent plant cover and routine harvesting. Equation 5-1 is based on minimal data from only a few systems and does not allow for normal variation in effluent quality. Thus, this empirical expression should be used with some caution during design. The equation provided by Reed et al. (1988) for total phosphorus removal in water hyacinth ponds is not reproduced here because of its limited usefulness.

Table 5-5. Summary of Floating Aquatic Plant System Design Criteria (modified from WPCF, 1990; EPA, 1988).

	Water Hyacinth			Duckweed	
Design Criteria	Secondary Nonaerated	Secondary Aerated	Nutrient Removal Nonaerated	Secondary	Nutrient Removal
Pretreatment Screened	Screened	Secondary	Fac. Pond	Fac. Pond	
Influent BOD_5 (mg/L)	130-180	130-180	30	40-60	40-60
BOD_5 loading rate (kg/ha•d)	40-80	150-300	10-40	22-28	22-28
Water depth (m)	0.5-0.8	0.6-0.9	0.9-1.4	1.5-2.0	1.5-2.0
HRT (days)	10-36	4-8	6-18	20-25	20-25
HLR (cm/d)	2-6	5-10	<8	2-10	2-10
Harvest schedule	Twice Seasonally	Monthly	Continuous	Monthly	Weekly
Effluent quality (mg/L)					
BOD_5	<30	<15	<10	<30	<10
TSS	<30	<15	<10	<30	<10
TN	<15	<15	<5	<15	<5
TP	<6	<6	<1-2	<6	<1-2

kg/ha/d x 0.892 = lb/ac/d
m x 3.28 = ft
cm/d x 0.394 = in/d

Soluble pollutant reductions occur in FAP systems as a result of microbial populations colonizing plant roots and accumulated solids on the bottom of the cell. For this reason, increasing water depth does not have a proportional affect on treatment system performance. Recommended water depths for water hyacinth FAP systems range from about 30 to 150 cm (1 to 5 ft). Water depth in duckweed systems is typically deeper at 150 to 200 cm (5 to 6 ft).

5.3.4 Water Control

Since FAP systems are ponded, flow may be distributed from and collected with simple structures. Inflow must be evenly distributed along the entire inlet side, and single or multiple weirs can regulate water depth and outflows at the outlet. Short-circuiting is a potential problem in irregularly shaped basins, so most FAP systems are rectangular. High length-to-width ratios are expensive to construct and should not be necessary if inlet and outlet devices collect and distribute flows over the width of the ponds. Short-circuiting and ineffective use of the pond volume might occur in systems that incorporate point inlet and outlet devices and low length-to-width ratios.

Flow baffles or submerged curtains can enhance plug-flow in nearly square basins and in retrofits of existing lagoons. These curtains are an integral part of the Lemna Corporation's patented design process.

Outlet structures should allow water level control including the ability to completely drain the basins for maintenance.

5.3.5 Basin Design

Wind velocity is an important factor in FAP basin sizing unless floating baffles are used to maintain plant cover. Proprietary Lemna systems use a floating grid to maintain plant cover in large basins (see Figure 3-4). Although water hyacinth plants are less susceptible to movement by wind, the potential for poor coverage exists. Floating baffles can be used, but pond size is usually limited to less than 0.4 ha (1 ac) to reduce wind effects on plant cover.

A minimum of two parallel systems should be provided in all FAP designs. Additional parallel systems are appropriate for larger applications. To maintain manageable pond sizes to harvest plants from shore, parallel FAP systems can be divided into cells in series. If floating plant harvesters are used, larger ponds are acceptable.

5.3.6 Basin Lining

FAP treatment system basins should be lined when effluent may leak and violate aquifer standards. In most instances, FAP basins that receive primary quality influent and provide secondary treatment must be lined. FAP systems receiving secondary quality effluent do not need to be lined as long as they meet aquifer protection standards. FAP basins may also need to be lined to conserve water that would otherwise be lost for some planned reuse following treatment.

5.3.7 Post Aeration

Water exiting FAP systems receiving high organic loadings invariably has low DO. Post aeration must be provided to meet standards to discharge to classified surface waters. Post aeration can be provided by use of a passive, step system of adequate height and surface area or by mechanical devices. Aeration requirements can be calculated based on standard wastewater design texts such as Tchobanoglous and Burton (1991).

5.3.8 Vegetation

Two plant groups are commonly used in FAP treatment systems. Water hyacinths have been used for over 20 years but have lost favor because they do not tolerate frost and are susceptible to pathogens and micronutrient deficiencies. Water hyacinths should not be used as a single-species cover for FAP systems that are prone to annual frosts unless a greenhouse or other frost-protection system can be provided. Water hyacinths are an exotic species and adequate controls must be in place to prevent their release to susceptible surface waters.

Various species of duckweed and related small, floating plants in the genera *Lemna*, *Spirodella*, *Wolffiella*, and *Wolffia* are found in natural wetlands and aquatic habitats throughout the United States. Duckweed plant associations have greater genetic variability and cold hardiness than water hyacinth monocultures and may be more appropriate for FAP systems in Arizona. While duckweed is a normal component of many constructed wetland treatment systems and existing lagoons, the use of duckweed in a managed system of floating grids and submerged baffles is a patented process controlled by a private corporation. This private company typically provides design, implementation, and operating assistance with duckweed applications.

5.3.9 Harvesting and Plant Disposal

FAP treatment systems are generally harvested. Unharvested populations of water hyacinths and duckweed tend to become infested with pathogens and to naturally senesce, resulting in poor growth, reduced cover, and poor treatment performance. Harvesting is required to keep these plants growing and healthy. Harvesting also removes nutrients. Although total nitrogen removal can occur in some FAP systems with infrequent harvesting, total phosphorus removal is minimal without harvesting, and neither nitrogen or phosphorus removal are reliable without frequent and regular harvests.

Considerations for plant harvesting and disposal are integral to FAP system design. Basins must be relatively small (less than 0.4 ha [1 ac]) to allow harvesting from the shore. Rather sophisticated floating harvesters are available from proprietary dealers.

Plant disposal is a major operation in FAP systems. Water hyacinth plants must be dewatered prior to composting, methane generation, or land filling. Duckweed can generally be dewatered during harvesting and then disposed of via composting or land application.

5.4 Combined FAP/Wetland Systems

There may be some locations in Arizona where a combination of the FAP and constructed wetlands technologies may provide the most cost effective approach for wastewater management. FAP systems are generally more suitable for providing secondary treatment and can be used for pretreatment prior to discharge to a SF constructed wetland. The typical application for this combination of technologies might involve an upgrade of an existing conventional lagoon to a FAP system, followed by a SF constructed wetland for tertiary treatment.

SECTION 6.0

Constructed Wetland Design for Ancillary Benefits

6.1 Fish and Wildlife Enhancement

Constructed treatment wetlands improve water quality by assimilating and transforming sediments, nutrients, and potentially toxic chemicals. In addition to these primary functions, treatment wetlands can incorporate secondary benefits such as photosynthetic production, secondary production of fauna, food chain and habitat diversity, energy export to adjacent ecosystems, and aesthetic, recreational, and educational activities. These additional benefits can be especially important in Arizona, where only a fraction of natural wetland area still exists (Brown, 1985). As a project's concept broadens to include wildlife viewing and educational opportunities, local communities benefit, too.

Although the potential for treatment wetlands to create wildlife habitat is still being studied, they do seem to act as oases for wildlife in arid climates. For example, 121 bird species have been recorded at the Show Low wetlands. Thirteen of those species are threatened, endangered, or sensitive (Wilhelm et al., 1989). Four of these species of special concern nest in the wetlands.

This section describes how SF wetlands can be designed to enhance ancillary benefits. Subsurface flow and FAP systems have little potential for secondary benefits and are not covered here. Habitat diversity is key to creating attractive wildlife habitat. Landform, water depth, vegetation, and animal species influence habitat diversity and are discussed below.

6.1.1 Landform

Landform includes the size and shape of the wetland basins, dikes, and channels. After the necessary area for water treatment is determined during design, opportunities for diversity should be considered. These may include adding wetland area, providing irregular shorelines, varying water depths to create open water, creating islands, and excavating channels between ponds. Any large rocks in the area can be considered for resting sites for waterfowl. Taking advantage of natural opportunities on the site can benefit the project and keep costs down.

6.1.2 Water Depth

Water depth will determine types of habitat. Shallow water areas less than 30 cm (1 ft) deep are attractive to wading birds. Deeper water areas will attract birds that dive to feed. The wetland vegetation depends highly on water depth. Shallow areas allow emergent plants to grow, while submergent plants prefer deeper water.

Water depths that are held relatively constant are conducive to developing breeding habitat. Waters that are shallow and even dry up at times produce feeding areas for migrating birds, including shorebirds. Constructed wetlands design can incorporate features that benefit both breeding and feeding requirements. Arizona has never been considered a productive breeding ground for waterfowl. However, the state does provide important habitat for migratory birds from the intermountain area (Utah, Idaho, Wyoming, Colorado, and

Montana). Good foraging conditions in Arizona can improve nesting success in these other states (Fredrickson and Dugger, 1993).

6.1.3 Vegetation

Wetlands constructed for wastewater treatment provide a potential refuge for native wetland plants. That communities place a high value upon the use of native plants for habitat creation and restoration is reflected by recent efforts to control exotic plants and restore native plant associations. While plant species most tolerant of effluent conditions should be used in treatment wetlands, consideration should also be made of using plants that have high wildlife food value and are native or naturalized in the project area.

Vegetation provides the structure of a created wetland. If left on its own, a wetland will become vegetated; however, this process may take longer than is wanted and may result in a less desirable plant community. Progress can be speeded up by seeding or planting wetland plants found in the project area. Ideally, wetland plants could be transplanted from a nearby wetland. The needs of the plants must be considered during planting. For example, spike rush (*Eleocharis* spp.) should go in the most shallow water areas, while hard stem bulrush (*Scirpus acutus*) can grow in water up to 1 m (3.3 ft) deep.

By knowing the mature height of the various emergent plants, a shoreline can be vegetated to provide tall cover for hiding and short cover for waterfowl loafing. Plants such as bulrush can hem in cattail to keep it from spreading too rapidly. Wetland plants are best transplanted in the spring after growth is beginning. Although they can be held for long periods under cool conditions, they should be dug and transplanted the same day.

Upland areas and dikes also need to be vegetated to avoid erosion. Tall grasses that establish quickly are most desirable. Other species known to be desirable for wildlife and non-invasive may be needed to occupy the site while slower-growing species take over.

Herbaceous plants, shrubs, and trees can also help diversify a constructed wetland. Existing trees that sustain flooding are especially desirable for roosting and nesting sites. When they do not occur or are in short supply, transplanting trees or putting up artificial structures is desirable. Trees such as willows can be effective screens adjacent to dikes to keep birds from being disturbed by human activity. Trees should not be planted on dikes because of the potential for roots to compromise the integrity of the structure.

Submergent vegetation grows in the water column in wetlands if the water is clear enough to allow light penetration. Submergents such as pondweed (*Potemegeton* spp.) and water milfoil (*Myriophyllum* spp.) enhance the habitat when conditions allow their growth. They provide food for waterfowl and productive habitat for macroinvertebrates.

Woody native plants have been demonstrated to have a much higher habitat value for native birds than some exotic plants. As research is beginning to demonstrate, the introduction of the exotic salt cedar (*Tamarix* spp.) has altered riparian communities and lowered their value to wildlife. Other research efforts in urban habitats in Tucson have also demonstrated that habitat values for territorial breeding birds are significantly higher in areas dominated by native plant species than those dominated by exotic plants (Mills et al., 1989).

While the data cited above reflect the importance of indigenous plant species for breeding birds, a group with a large public constituency, it is only one component of the diverse array of wildlife that use riparian and wetland areas. Not all wildlife species respond to exotic plants in the same manner as territorial breeding birds. Planting grain crops to enhance habitat values for migratory waterfowl, for example, has been well documented. For many other groups of wildlife, little information is available.

When deciding on the use of natives versus exotics for a constructed wetland, it is important to remember that once introduced, undesirable, invasive species can be very difficult, if not impossible, to remove. The use of exotics also creates the potential to have significant, adverse impacts to native plant communities outside of the constructed wetland on a local or regional level, should they escape (for example salt cedar, kudzu [*Pueraria lobata*] and water hyacinth). On the other hand, indigenous species may be slow to cover berm areas that are highly susceptible to erosion. Cover grasses such as western wheatgrass (*Agropyron smithii*) can be used to provide rapid ground cover until more desirable species take over.

Selected Arizona wetland and riparian plants are listed in Appendix A to facilitate the selection and use of native species. This list illustrates the diversity of indigenous plants that can be used in wetlands constructed for wastewater treatment. It includes species such as cattail and bulrush that have long been associated with wetland wastewater treatment systems, and plants whose efficacy for wastewater treatment have not been demonstrated. This list includes general information regarding the geographic distribution within the state, frequency of occurrence, typical hydrologic regime, soil preference, and elevation. The availability of these plants in nurseries cannot be guaranteed. During the early planning phases of a constructed wetland project, after funding and construction schedules are known, it would be prudent to contract with a native plant nursery in advance to grow those plants that will not be collected from wild populations.

The Arizona plant list provided in Appendix A includes mesoriparian and hydroriparian trees that would not be appropriate for planting in an emergent marsh habitat. They have been included in this list because, as with all wetland habitats, the constructed treatment wetland will create a hydrologic gradient, though sometimes very short, at its margins. If considered early in the design of retaining berms to avoid potential engineering conflicts, planting on this gradient will create additional wildlife habitat (such as forage, cover, screening) and can enhance the project's appearance and value.

6.1.4 Animals

Animals in a wetland form an intricate food chain. Nesting waterfowl usually colonize new wetlands to feed on macroinvertebrates in the water column. Fish, on the other hand, may need to be introduced. The decision to put fish in should be carefully considered. If game fish are introduced, fisherman may interfere with the wetland's other habitat benefits. Consumption of fish from the effluent-dominated waters may also be a concern. Small fish such as mosquito fish (*Gambusia affinis*) and fathead minnows (*Pimephales promelas*) can provide more prey for birds. Nongame fish such as native suckers could be considered as prey for osprey (*Pandion haliaetus*) and bald eagles (*Haliaetus leancocephalus*). Nesting rookeries of double-crested cormorants and black-crowned night herons (*Nycticorax nycticorax*) have established in the Show Low created wetlands because fathead minnow populations provide abundant prey. Local biologists need to be consulted when considering any fish stocking.

6.2 Public Use and Access

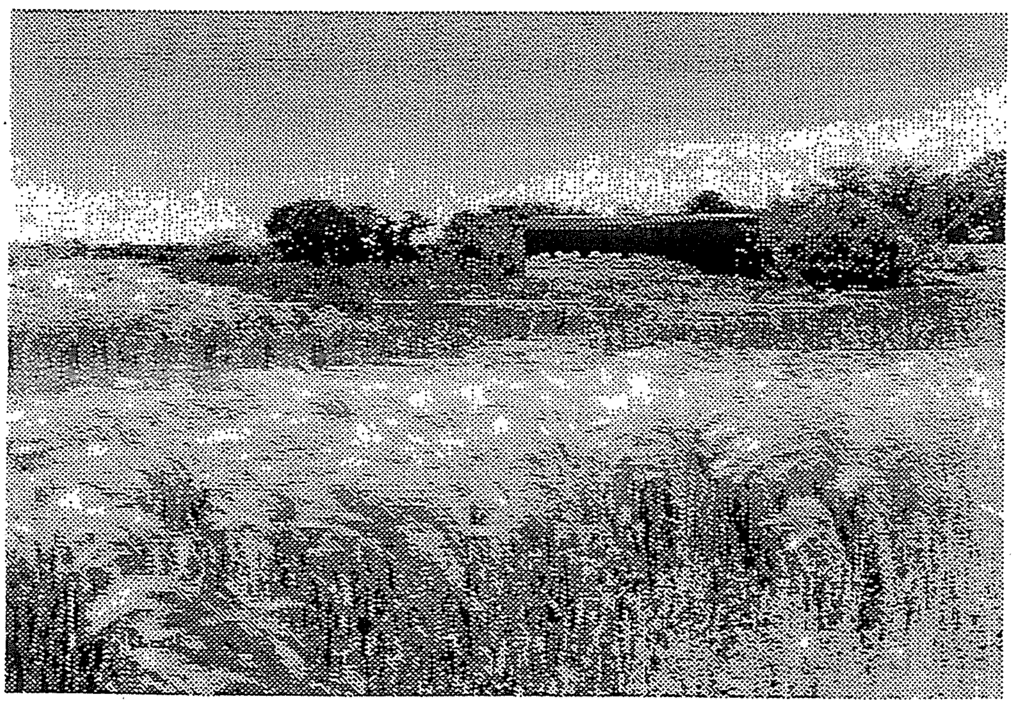
The decision to encourage public use should be made early in the planning process. Basic design can be altered in ways to accommodate public use and still maintain public safety and habitat values. An example might be screening to avoid disturbing wildlife or a boardwalk to allow access into the wetland. Making plans to accommodate public use early in a project's development can garner additional public support for the created wetland.

6.2.1 Nature Study

The use of wetlands for observing wildlife and studying wetland ecosystems is a growing public activity. Wetlands are some of the most vibrant natural areas that people can experience. They fairly teem with different life forms. This type of nonconsumptive use provides recreational opportunities without removing anything from the system.

Created wetlands can become outdoor classrooms for local schools. The very youngest classes can enjoy the sights and sounds of a wetland while the most advanced college classes can study both wildlife use and water treatment aspects. Trails, viewing platforms, displays, and viewing blinds facilitate educational use. An interpretative plan developed early in the planning process would be a great help in coordinating nature study.

Figure 6-1 shows the wildlife viewing blind at the Show Low constructed wetlands in northern Arizona. This is an example of a facility that improves access for nature study at a constructed wetland. The blind is designed to accommodate a class of up to 40 children. The viewing wall is a half circle with viewing ports at varying heights. A paved trail provides access for handicapped individuals who rely on wheelchairs.



Source: Mel Wilhelm

Figure 6-1. Viewing Blind at Pintail Lake, Show Low, Arizona. The blind permits visitors to view the wetland without disturbing wildlife.

Viewing blinds should be sited to provide optimum viewing and photographic opportunities. If several types of wetland habitat can be seen from the blind, more species of wildlife will be seen. View lanes of open water areas should be provided so visitors can see shy species at a distance without disturbing them. Perching trees at the proper distance can provide views of rare species such as bald eagles. Downed trees and rocks can be placed at proper distances from the blind to provide loafing sites for animals.

The aesthetics of a constructed wetland should not be underrated. The variety of textures, color, and form make them very scenic areas. The raw soils left after construction are soon covered by a dense green plant cover. Concern for scenic values in design can result in a beautiful wetland.

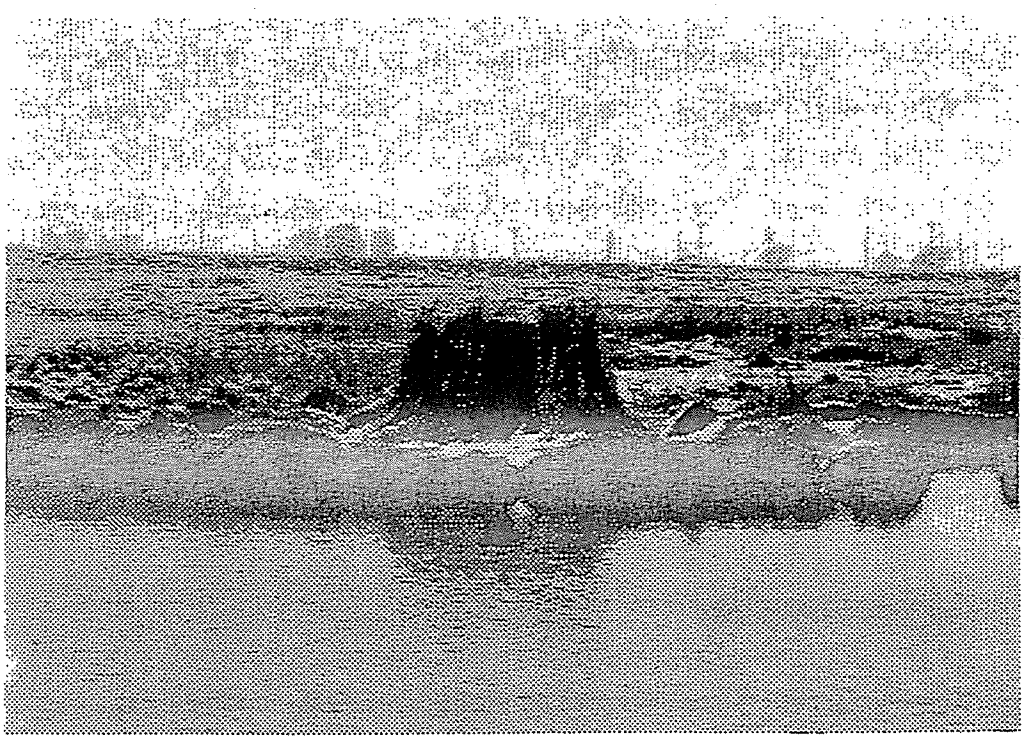
6.2.2 Fishing and Hunting

Fishing can be accommodated, but there may be drawbacks. Fisherman may disrupt ground nesting birds and displace normal feeding patterns. Sometimes, the public is reluctant to consume fish from effluent-dominated waters. The existing constructed wetlands in Arizona are not managed for game fish but rather focus on other ancillary benefits.

If fishing is desired, then deep water areas need to be provided. Oxygen levels can be depleted by decomposing vegetation, especially during winter months. A fisheries biologist needs to be part of the design team if game fish are to be part of the wetland fauna.

Hunting currently occurs in several of the constructed wetlands described in Section 4, including those at Show Low and Pinetop/Lakeside, Arizona, and Incline Village, Nevada (Figure 6-2). The waterfowl hunting season occurs in the fall after the breeding season ends and when bird watching activity usually diminishes. Undoubtedly, hunters and bird watchers are somewhat incompatible, and priorities for both groups should be considered during project planning. In addition to waterfowl, deer, elk, and antelope are attracted to wetlands for water and forage. The decisions regarding hunting are best worked out locally with AGF involvement.

Aquaculture is possible in a constructed wetland. Fish and shellfish are raised in other areas for profit. Water temperatures in constructed wetlands would probably favor warm-water fisheries. Bait fish could be raised for market if their habitat requirements are factored in the wetland design. However, submergent vegetation normally associated with wetlands can interfere with normal management procedures such as seining to manage populations. Also, intense aquaculture using animal feeds may result in unacceptably high concentrations of organic matter, solids, and nutrients in the wetland effluent.



Source: CH2M HILL

Figure 6-2. Duck Hunting Blind at Incline Village, Nevada. Hunters can be valuable partners in developing constructed wetlands.

6.3 Control of Nuisance Conditions

Historically, marshes have been perceived as a nuisance. The appreciation of wetlands as water-cleansing, productive ecosystems is a fairly recent development. There is potential for problems to develop in constructed wetlands, just as in natural wetlands. The following discusses some possible nuisance conditions and measures that can be taken to reduce their impact.

6.3.1 Mosquitoes

Mosquitoes are a common pest around wetlands, and problems already occur in some areas of Arizona. However, mosquitoes have not become a problem in the constructed wetlands around Show Low. Sampling done in 1991 of the Show Low wetlands collected 9,938 invertebrates of which only three were mosquito larvae. Sampling the same year at Incline Village, Nevada, found only five mosquito larvae out of a total sample size of 5,869 invertebrates (McAllister, 1993). In these two wetlands, the overwhelming numbers of predatory aquatic invertebrates and vertebrates are probably limiting mosquito reproduction. Where mosquitoes are a concern, stocking mosquito fish or other small fish can be an effective control method. Some endangered native fish could even be considered for this role. If adult mosquitoes are a potential problem to operators or neighbors, natural pest management by bats and birds can be encouraged by providing nesting and roosting facilities.

6.3.2 Dangerous Reptiles

Dangerous reptiles are a concern in wetlands in other parts of the country. However, Arizona is not inhabited by any native, poisonous, aquatic reptile such as water moccasins or alligators. The thick cover and prey base of constructed wetlands can attract a variety of reptiles already found in the vicinity, including rattlesnakes. Keeping walkways mowed is the best precaution for public safety.

6.3.3 Human Pathogens

Constructed treatment wetlands are generally not used for water contact recreation. Therefore, direct disease transmission is improbable. Presently, disinfection is required prior to discharge to wetlands as a further safeguard. The perception that wetlands are breeding grounds for human disease is gradually being replaced by confidence that these systems do not present any greater risk than other wastewater reuse systems, and that these risks are generally very slight. In fact, studies of two constructed wetlands in California found bacterial and viral indicators of pollution were removed at the 90 to 99 percent level (Gersberg et al., 1989). Normal safety procedures used in treatment facilities should be followed in wetland sampling.

6.3.4 Odors

Constructed wetland treatment systems have the same earthy smells as natural wetlands. Problem odors are indicative of something being wrong in the system. Constructed wetlands in Northern Arizona have shown no odor problems. Anaerobic conditions most often contribute to odor. Caution should be taken to avoid overloading wetland treatment systems with oxygen-demanding pollutants and to insure that sludge or improperly treated wastewater is not allowed into the wetland.

6.3.5 Wildlife Toxins and Pathogens

Two types of conditions that result in increased wildlife mortality can potentially develop in a constructed wetland: accumulation of toxic materials contained in the effluent, and chemical/biological conditions which produce botulism or avian cholera.

The quality of effluent is a prime factor in wetland design. Wetlands that are flow-through systems are less apt to accumulate metals or organochlorines to toxic levels. Closed constructed wetlands are of more concern. To date, no wetlands created to treat municipal wastewater and stormwater have been documented to have toxicity to fish and wildlife. Documented cases of wetland wildlife toxicity are from hazardous waste sites and in wetlands receiving agricultural runoff. Data collected to date on bioaccumulation of potentially toxic constituents in plant and animal tissues in treatment wetlands typically have not revealed levels that would cause concern. Research is continuing at a number of wetland pilot and full-scale facilities to further evaluate the potential for harmful levels of bioaccumulation.

Biological conditions that produce botulism and avian cholera are associated with low oxygen levels. They are not likely to develop in constructed wetlands designed for pollution control as long as loading of oxygen-demanding pollutants is not excessive. To date, no problems of this nature have been encountered in Arizona's constructed wetlands. Operating plans for constructed wetland treatment systems should avoid drastic changes in oxygen levels that cause die off of aquatic animals during hot weather. These swings in DO typically occur in response to excessive algal growth in poorly-vegetated constructed wetlands. As wetland vegetation develops in a new wetland, these types of problems become less likely.

SECTION 7.0

Operation and Monitoring of Wetland and Aquatic Plant Treatment Systems

7.1 Operations and Maintenance Manual

An Operation and Maintenance (O&M) Manual must be submitted by the engineer before a constructed wetland or FAP system can begin operation. This guidance manual contains many of the components that will facilitate the development of an O&M Manual. Components that need to be included in the O&M Manual follow:

- Facility description
- Operator and manager responsibilities
- Permit limits/treatment goals
- Process description
- Operator controls/maintenance
- Monitoring methods/schedule/quality assurance/records
- Operator safety and emergency response plan

Some of the components of an O&M Manual are discussed in Section 5.0 of this guidance manual and are part of the constructed wetland design. Other components of the O&M Manual are discussed in this chapter.

The O&M Manual should specify what parameters are measured and how often. The list in Table 7-1 includes the minimum parameters that are usually specified as a part of the Aquifer Protection Permit (APP) monitoring requirements. The APP permit also specifies the point of compliance for that particular system. Monitoring results are routinely reported to ADEQ.

Quality assurance/quality control (QA/QC) is included as a part of the O&M Manual. These measures detail the procedures an operator will follow if a parameter is being used to indicate possible problems. As an example, the QA/QC guidance might specify a specific action to take if nitrate levels approach within 20 percent of the permitted limit. Additional guidance concerning monitoring and operation of treatment wetlands and FAP systems is provided below.

7.2 Monitoring Recommendations

Monitoring a constructed wetland includes both general observations and detailed sampling of parameters. The actual monitoring program at a given site must be integrated with the design of the wetland, treatment goals, habitat goals, permit requirements and regulatory standards.

7.2.1 Rationale

Constructed wetlands and FAP systems are complex ecosystems that develop site-specific characteristics. Frequent monitoring and evaluation will reveal trends and aberrations that guide operation. A history of monitoring will simplify and refine management.

Constructed wetlands are managed by controlling water quantity, quality, depth, and flow rates. With flexible water control, the operator can manage the wetland with minimal effort and, most importantly, react to changing conditions or developing problems. These developing problems are detected by regular monitoring. For effective management, a greater effort is generally devoted to monitoring and less effort to operation.

In addition, ADEQ and EPA require regular monitoring of certain parameters to safeguard the environment and to give early warning of potential problems. Routine testing also ensures that state and federal legal requirements are met.

7.2.2 Flows and Water Levels

Data should be gathered on a daily, weekly, and monthly basis for water flows into a constructed wetland or FAP treatment system and for static water level within the ponded system (Table 7-1). This information documents the system's performance and safeguards it from overfilling, spills, and damage to dikes or islands. For example, the seasonal variability of flow rates needs to be correlated with evapotranspiration so wetland basins will have excess storage capacity to avoid spills. As evaporation rates decrease in the fall, wetlands may fill and reach maximum levels in early spring. Outflow rate should be monitored on a daily basis or continuously in treatment systems that discharge offsite. When combined with measurements of water quality described below, inflow and outflow rate measurements allow estimation of mass removals in treatment wetlands and FAP systems.

7.2.3 Water Quality

At a minimum, water quality parameters should be monitored in accordance with permit requirements. Additional sampling will help refine the management of a constructed wetland or FAP treatment system. For instance, internal sampling can reflect changes in water quality as it progresses through a wetland, and monthly samples reflect seasonal influences.

Table 7-1 lists the recommended minimum sampling necessary to monitor a constructed treatment wetland or FAP system. The following parameters should be sampled at least monthly at major inflows and outflows: BOD_5, TSS, pH, DO, water temperature, conductivity, NO_2+NO_3-N, ammonia nitrogen, TKN, total phosphorus, chloride, and sulfate. Acute and chronic toxicity and metals should be sampled at least semiannually.

Field parameters for pH, DO, temperature and conductivity can be monitored by the system operator, while other parameters will typically need to be analyzed by a certified laboratory.

Table 7-1. Monitoring Suggestions for Operation of Constructed Wetlands and FAP Systems

Parameters	Sample Locations	Minimum Sample Frequency
Inflow and Outflow Water Quality		
BOD_5, TSS, pH, DO, conductivity, temperature, NO_2+NO_3-N, NH_4-N, TKN, TP, Cl-, SO_4=	Inflow & Outflow	Monthly to Weekly
Selected metals, acute and chronic toxicity	Wetland	Semiannually
Flow	Inflow & Outflow	Daily
Rainfall	Adjacent to Wetland	Daily
Water Stage	Within Wetland	Daily
Biological Plant Cover, Macroinvertebrates, and Fish	Inflow, Center, Outflow	Annually to Quarterly

These water quality data should be organized in a computer database that can be updated easily to view trends. Frequent review of data trends can allow operational changes to be made before permit violations occur. This database will become more valuable with each year's data.

Precipitation should be monitored at or near the constructed wetland or FAP treatment system. These data will be needed to prepare an overall water budget. Even more important in Arizona's dry climate is the monitoring of evapotranspiration. Monthly evaporation rates for the hotter months greatly exceed average rainfall. Pan evaporation data corrected by a factor of 0.77 from the nearest weather station may suffice. In instances where monitoring of the water budget is important, such as where estimates of seepage is an important parameter, then pan evaporation data should be collected onsite. A chart showing monthly net evaporation (total evaporation minus precipitation) will benefit monitoring.

7.2.4 Mass Loading and Removals

The quality of water supplied to a constructed wetland or FAP system depends on pretreatment capacity. Although inflow water quality and quantity are consistent under normal conditions, major storms can overload pretreatment systems with limited storage, resulting in poorly treated effluent going into a wetland. For that reason, extra storage capability prior to or within the wetland or FAP treatment system is a good safeguard for adequate treatment. Wetlands that are sized larger for additional wildlife habitat have flexibility to handle unusual climatic events.

Overfilling a wetland basin can harm vegetation if emergent plants are overtopped. When this happens, water levels should be drawn down within two weeks (or at the maximum rate allowed by permit consideration) to avoid serious injury to perennial plants. This situation is more critical during warm or hot weather.

7.2.5 Vegetation

A constructed wetland can have a diversity of plant species or it can depend on just a few. The operator should understand the biological requirements of the plants and manage water levels to provide for their needs. Optimum conditions are not always required, as wetland plants native to Arizona may endure harsh conditions such as periodic drying and fire. The plants' environment is most critical during seed germination and establishment.

Sometimes operators make the common mistake of drowning wetland plants. Usually, initial growth is best with transplanted plants in wet but well-aerated soil. Leaving the majority of the growing plants exposed with occasional inundation will allow the plants to obtain oxygen and grow fastest.

Plant cover needs to be periodically assessed and documented. Dramatic shifts can occur as plant succession proceeds. The plant community reflects management and can indicate improvement or problems. For example, submergent plants such as pondweed require light penetration into the water column. The disappearance of these plants indicates problems with water clarity.

In FAP systems, plant growth can be measured by enclosing representative plants within mesh baskets and periodically weighing them to determine increases in wet weight. Harvesting in FAP systems must be timed to maintain optimum plant growth conditions.

7.2.6 Animals

The animals in a constructed wetland or FAP system are necessary links in an aquatic food chain. They include microscopic plankton that feed on plants grown in the wetland or supplied by the water inputs. Aquatic insects feed on the plankton, fish and amphibians feed on the insects, and birds and mammals feed on the fish. The extent of monitoring depends on resources. If toxic conditions are a concern because of influent quality, then sampling for bioaccumulation in the food chain can give early warning. Macroinvertebrate sampling within the wetland can provide a record of food abundance and diversity for fish and birds, and used as an indicator of stress due to excessively low DO concentrations. To garner public interest, data on higher life forms such as bird use are helpful. Routine bird counts can be conducted along specific survey routes around or through the wetlands on a biweekly or monthly basis. All birds seen within or utilizing the wetland within a standard count time should be identified and tallied.

7.2.7 Microbes

Microbes are typically the most important biological components that assimilate pollutants in a wetland or FAP treatment system. Because microbial populations vary too much for direct monitoring to be easily interpreted, their ecological functioning can best be assessed in most cases by measuring water quality changes through the system. Attention to operational controls discussed earlier such as dense vegetation stands for microbial colonization and avoidance of highly anaerobic condition in the water column will generally insure viable microbial populations.

Population estimates of indicator bacteria such as fecal and total coliforms have little value for assessing the potential for human pathogens in constructed wetlands. This is because these organisms are added to the wetland in very large numbers by wetland wildlife. While wetlands are very effective for reducing coliform populations, significant coliform counts are found in nearly all wetland outflow surface waters. Typical background fecal coliform populations vary up to 400 to 1,000 colonies/100 mL.

7.2.8 Sediments

Sediments under a wetland should be sampled prior to construction to determine baseline levels for any metals or other priority pollutants of concern in the wastewater. Following the establishment of a wetland, sediment sampling can be periodically repeated (annually) to see if undesirable materials are accumulating above biologically-safe threshold levels. Sediment sampling is generally limited to the rooting depth of wetland vegetation (less than 300 cm or 1 foot for most marsh species).

7.2.9 Groundwater

Prior to constructing a wetland or FAP treatment system, the anticipated seepage rate and potential for affecting a groundwater aquifer should have been investigated. Data previously collected on the soils profile, soils texture, and seepage testing should be made available to the operator. If groundwater impacts were deemed probable and an APP was issued, then the operator should be familiar with a description of the hydrogeologic conditions underlying the site, the monitoring requirements of the APP, construction of monitoring wells, ambient groundwater quality, and quality of wastewater applied at the site.

A detailed water budget using inflow and outflow measurements and evapotranspiration estimates is used to estimate seepage rates to the groundwater. A typical groundwater monitoring system includes wells located upgradient and downgradient from the wetland facilities. Upgradient wells are indicative of ambient groundwater conditions. Downgradient wells are indicative of any changes to water quality caused by seepage from the wetland. Water quality testing data are often subject to substantial variability between samples for some constituents, particularly nutrients and metals. Therefore, trends and variability from multiple samples need to be examined to interpret the implications of the water quality monitoring data relative to permit compliance. In some instances, additional monitoring frequency for certain constituents may be needed to increase the reliability of the data interpretations.

In most instances, unlined constructed wetlands that discharge to groundwater should be monitored by testing the aquifer with monitoring wells. Exceptions might be made where adequate monitoring can be conducted at inlet locations or within the wetland water body to demonstrate compliance with AWQSs. The typical groundwater monitoring scheme for the APP Program would include monitoring for hazardous constituents at a well or wells placed at the downgradient edge of the pollutant management boundary—essentially the edge of any berm or other feature that delimits the area on which wastewater may be placed. Monitoring for nonhazardous constituents (nitrate, nitrite, barium, fluoride, and pathogens) can be conducted farther from the project, in a location where the nearest current or future use of the aquifer is protected. The number of wells and frequency of monitoring will depend on the size and character of the discharge. Completely lined wetlands and wetlands for onsite systems where the disposal density requirements of Bulletin 12 are met should not, in most cases, require groundwater monitoring.

7.2.10 Sample Point Access

Monitoring requires frequent access to sampling points. If access is difficult, sampling may not be done as often as needed. Driving across vegetated dikes or wading through muck can also damage the site. Appropriate vehicle access, trails, marked sampling sites, catwalks, and boardwalks should be considered to facilitate monitoring.

7.3 Operational Control

Constructed wetland and FAP treatment systems are operated by controlling water application rates and quality. Water depths are regulated by in-pond structures such as stand pipes, flash boards, or weir gates (Figure 7-1). If the treatment system has been designed for flexible operation, it may provide various routes for water flow and include stored water that can be released on demand.

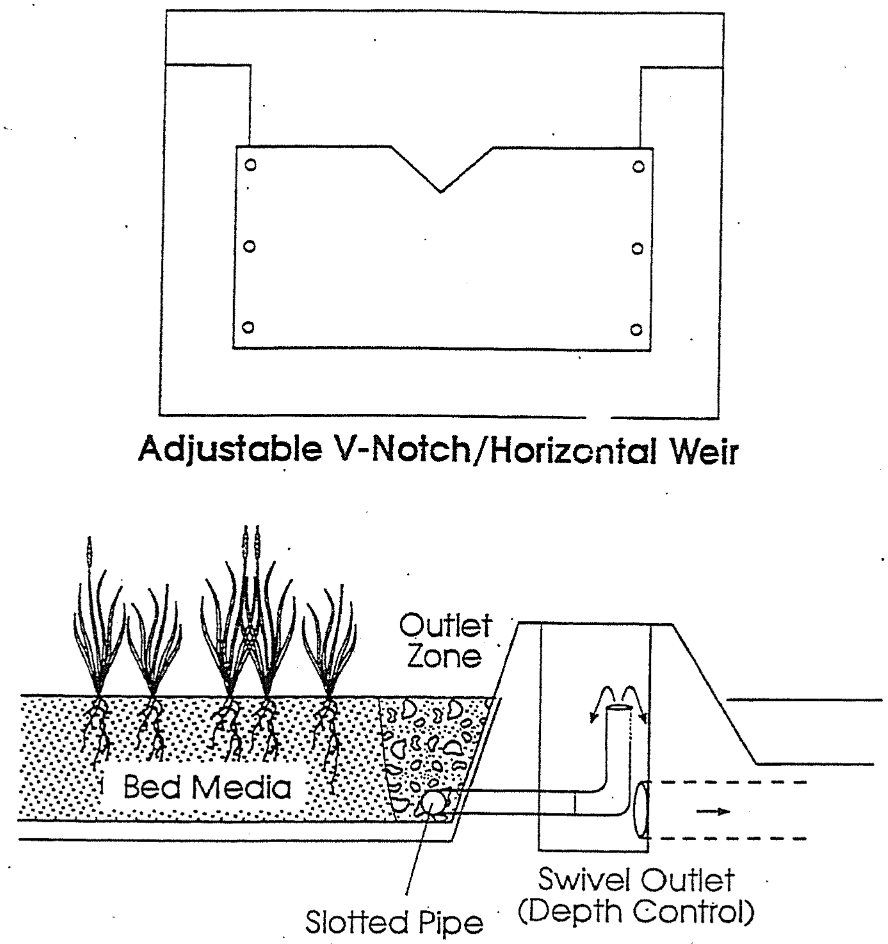


*Figure 7-1. **Water Level Control.** Water level in constructed wetlands can be controlled by a weir or swivel riser pipe. Depth of water is critical to plant growth and hydraulic residence time.*

7.3.1 Hydraulic Loading

Hydraulic loading multiplied by pollutant concentration is equivalent to mass loading. Mass removal in constructed wetlands and FAP systems is highly correlated to mass loading. An operator can regulate final effluent quality by changing hydraulic loading into the wetland. If data trends indicate that effluent concentrations are approaching permit limits, hydraulic loading must be decreased unless additional pretreatment is possible. Hydraulic loading may be decreased by discharging to other portions of the system with excess capacity or by storing influent wastewater.

The water delivery system of a constructed wetland or FAP system should allow water to be put directly into as many ponds as possible and to let water flow through cells in parallel or in series from cell to cell. Intercell structures with flash boards hold water levels at a set height, and excess water flows over the boards into the next cell. The operator then changes boards to regulate water levels in each of a series of cells. Wetland cells and FAP ponds should be able to be isolated for management such as vegetation manipulation or seepage monitoring. Similar adjustments can be made with a weir gate.

A water delivery system's design can facilitate treatment. For example, open vegetated channels (grassed swales) treat water as it passes through them. Water flowing through a corridor can provide water for trees and create a riparian habitat for wildlife and people. Vegetated channels treat water through the same mechanisms as constructed wetlands. Storing effluent in a basin so it can be diverted into a wetland also treats water. In other words, the more water runs through and is detained in storage basins, open channels, and riparian corridors, the more treatment occurs.

If a wetland or FAP system is designed for discharge, a linear basin could allow different points of discharge. Depending on its quality, water could flow to different distances in the basins before final release.

7.3.2 Discharge Site Rotation

The route water takes through a wetland or FAP system is a prime consideration for management. As water progresses, the nutrient levels decline. The cells getting the effluent first receive the most nitrogen and phosphorus. By varying the point of discharge into individual cells, nutrient loads can enhance vegetation.

The ability to dry a wetland cell while the remainder of the wetland continues to function helps in vegetation management, facility maintenance, and wildlife management. Natural wetlands regularly go through drying cycles, and constructed wetlands also benefit. Once established for a year or more, perennial plants such as bulrush and cattail can survive up to a year of drying and even burning if removing old vegetation is desired. When water is returned to a dry cell, the depths should be shallow at first to avoid overtopping new sprouts.

7.3.3 Water Level Control

Water levels are key to vegetation establishment and management. Water levels can even control waterfowl use of abundant food resources. For example, stands of wild millet can be progressively flooded to optimize waterfowl food over a long period.

Water depths also influence the degree of oxygen availability in the water column. DO influences microbial action and the system's ability to treat water. Generally, water depths should be lowest during the hotter months when oxygen depletion is most critical. Water levels can be raised in the winter months with few deleterious effects. In areas of the state prone to prolonged freezing conditions, water levels should be raised prior to freeze-over, and then lowered to allow winter operation under the ice.

In areas where flooding could cause a spill, allowances need to be made to allow extra storage capacity. The most common flood conditions occur in late winter.

7.3.4 Vegetation Management

When a wetland is constructed, vegetation should be established as quickly as possible. Planting of marsh species is best accomplished during the local plant growing season. Trees and shrubs generally transplant best when they are dormant. Plants can be established by seeding, planting rootlets or bulbs, or taking soil with seeds from an existing wetland and spreading it in the new one. If left unseeded, wind-blown seeds and seeds brought in by animals will enter the wetland. Vegetation establishes faster when wetland plants are transplanted from a nearby existing wetland. Permits may be required for harvesting plants from natural wetlands. Plants such as bulrush can be dug and transplanted with success, using partial tubers buried in wet soil. Commercial sources for a wide variety of wetland plants are also available but additional time may be necessary for plant propagation. A list of Arizona wetland plant species is provided in Appendix A.

When seeding, optimum conditions should be provided. Seeds are usually broadcast on wet soil or shallow water areas around pond edges. Seeds need oxygen to germinate but enough water to keep from drying out. Lowering the water level of a pond will provide a wet perimeter, which is a good place to sow seed. After germination, as shoots get taller, water can be raised slowly as the plants grow. Care should be taken to not overtop the new shoots for optimum growth. Annual plants grown from seed such as wild millet and smartweed can provide food resources for migrating waterfowl. Mesophytic annuals can occupy dry basins or overflow areas when insufficient water is available for a fully developed wetland. When sufficient water is available, these ephemeral wetlands can be further developed.

Trees and shrubs can also add to the vegetative diversity of a constructed wetland. Willows prefer to grow along pond banks and on islands. Cottonwood trees add nesting and roost sites for wildlife in and around the wetlands. These plants are usually propagated by cuttings pushed into wet soil. The presence of trees will add a more diverse set of bird species in a created wetland. Planting trees in strategic locations can provide additional viewing opportunities for visitors.

Plant management in FAP treatment systems is typically more intensive than in constructed wetlands. The floating plant species are harvested on a regular basis to maintain strong growth and to remove nutrients and metals from the wastewater. An inherent problem with monocultures (single-species plant cultures) is that they are susceptible to diseases and insect pests. A variety of mites, weevils, and fungal pathogens are present in North America that attack water hyacinths. Regular harvesting or pesticides are typically necessary to control these pests. If plant growth and vigor are not monitored and maintained, effluent quality will degrade and possibly cause permit violations.

Another management issue associated with FAP systems is the potential growth limitation resulting from limited concentrations of certain required micronutrients. Floating plants depend on dissolved nutrients in the water column, and they compete with algae or physical processes for micronutrients such as iron. Constructed wetlands typically do not lack micronutrients because the plants are rooted in soil that generally provide trace elements. Water quality monitoring of growth nutrients is an important aspect of management of FAP systems, and nutrient additions may be necessary in some systems.

A final aspect of system management that is particularly important in FAP systems is frost protection. Water hyacinths are very sensitive to frost. Complete frost kill of water hyacinths results in sudden system failure, requiring a long period necessary to restore adequate plant cover. The system manager must be aware of the potential for frost and take steps to minimize impacts. Duckweed FAP systems are much less susceptible to frost, but may occasionally have reduced plant cover during cold periods. Because of the typical size of water hyacinth and duckweed ponds, there is little that a system manager can do to protect against any detrimental climatic events.

SECTION 8.0

Regulatory Guidance

8.1 Introduction

A number of regulatory requirements must be satisfied to construct a wetland or FAP wastewater treatment system. This section summarizes the most common permitting requirements. This summary is not comprehensive (for example, local zoning regulations and environmental standards are not included), and the applicant should check with all local, state, and federal agencies likely to have jurisdiction before proceeding with final project design. Table 8-1 provides a list of state and federal regulatory contacts that might be involved in a constructed wetland or FAP project in Arizona.

Regulatory requirements for wastewater treatment plants (WWTPs), and more specifically, constructed wetland and FAP treatment systems, can be divided into two general categories—first, those related to the purpose of WWTPs (wastewater treatment and disposal permits) and secondly, those related to incidental site development activities (site development permits).

Table 8-1
State and Federal Agencies with Possible Regulatory Jurisdiction Over Constructed Wetland Projects

State of Arizona

Arizona Department of Environmental Quality
3033 N. Central Avenue
Phoenix, AZ 85012
(602) 207-2300

Aquifer Protection Permits (APP) - (602) 207-4682 (or toll free: 800-234-5677, ext. 4682)

National Pollutant Discharge Elimination System (NPDES)
Point Sources: (602) 207-4494 (or toll free: 800-234-5677, ext. 4494)
Storm Water: (602) 207-4677 (or toll free: 800-234-5677, ext. 4677)

Wastewater Reuse Permits - (602) 207-4687 (or toll free: 800-234-5677, ext. 4687)

State Water Quality Certification
(Section 401 of the Clean Water Act) - (602) 207-4466 (or toll free: 800-234-5677, ext. 4466)

Federal Government

U.S. Environmental Protection Agency
Region IX
75 Hawthorne Street (W-5-1)
San Francisco, CA 94105

NPDES - (415) 744-2125

NPDES General Permit for Construction Stormwater Discharges - (415) 744-1906

Section 401 Water Quality Certification for Tribal Lands - (415) 744-2015

U.S. Army Corps of Engineers
Regulatory Branch
3636 N. Central Avenue, Suite 760
Phoenix, AZ 85012-2936

Section 404 Permits (Clean Water Act) - (602) 640-5385

Wastewater treatment and disposal permits include Aquifer Protection Permits (APPs), reuse permits, design review based upon Engineering Bulletins No. 11 and 12, and National Pollutant Discharge Elimination System (NPDES) point-source discharge permits for WWTP discharges to waters of the U.S.

Site development-related permits or review processes that can often be required include Clean Water Act (CWA) Section 404 permits, National Environmental Policy Act (NEPA) review, Endangered Species Act (ESA) compliance, Federal Aviation Administration (FAA) bird-strike considerations, and state and federal cultural resource regulations. All of these regulatory and permit requirements are discussed in greater detail below. Table 8-2 summarizes some key elements of the more common permitting requirements for constructed wetland and FAP treatment systems in Arizona.

8.2 Wastewater Treatment and Disposal Permits

Until approximately 1992, ADEQ regulated constructed wetlands and FAP systems built for wastewater treatment or disposal under the reuse permitting process. Reuse permitting viewed wetlands as the end-use of wastewater upon discharge from the WWTP, not as part of the treatment process. Therefore, permitting was primarily concerned with public exposure to pathogens. Now that constructed wetlands for wastewater treatment in Arizona are considered part of the wastewater treatment facility, ADEQ review occurs under the APP program, which regulates discharges to groundwater.

If the constructed wetland discharges to surface waters of the U.S., the discharge must also be permitted under NPDES point-source discharge regulations in Section 402 of the federal CWA. Arizona has not sought primacy to regulate discharges to surface waters under NPDES, and the program is administered by EPA with coordination by ADEQ.

Table 8-2. Common Environmental Permits or Review Procedures for Construction of Wetlands for Wastewater Treatment.

Regulation/Permit	Resource	Lead Agency	Jurisdictional Trigger	Typical Data Requirements
Wastewater Treatment and Disposal Permits				
Aquifer Protection Permits	Groundwater quality	Arizona Department of Environmental Quality (ADEQ)	Potential for an action to discharge pollutants to the groundwater	Either: 1) demonstration that general permit conditions have been met, or 2) information and data required by ADEQ for Individual Permit Applications
Clean Water Act NPDES Permit (Section 402 Clean Water Act)	Surface Water Quality	EPA	Point-source discharge to jurisdictional waters of the United States (for constructed wetlands for wastewater treatment, this would be any outlet structures discharging to jurisdictional waters)	Expected water quality at discharge point, monitoring protocols and procedures, etc.
ADEQ Engineering Bulletin #11	Wastewater Treatment Facilities	ADEQ	Required for ADEQ approval of a Wastewater treatment facility discharging more than 20,000 gallons per day	Site layout and design drawings
ADEQ Engineering Bulletin #12	Wastewater Treatment Facilities	ADEQ	Required for ADEQ approval of a wastewater treatment facility discharging less than 20,000 gallons per day	Site layout and design drawings
Wastewater Reuse Permit	Reclaimed Effluent	ADEQ	Applies to operators of wastewater treatment facilities and certain industrial facilities that plan to use reclaimed effluent for irrigation or reuse. A permit is required from ADEQ for the protection of human health, groundwater, and surface water	Engineering report and design drawings
Site Development Permits				
State Water Quality Certification (Clean Water Act Section 401)	Surface Water Quality	ADEQ	Section 404 or 402 permit	Site layout, design drawings, and other supporting water quality data
Clean Water Act Section 404 Permit	Surface Water Quality	Army Corps of Engineers/ EPA	Placement of fill material into jurisdictional waters of the United States	· Endangered Species Act clearance · Cultural Resources Clearance · Jurisdictional Delineation to determine if acreage of fill or adverse impact and if there are any jurisdictional wetlands · Project Description

Table 8-2. Common Environmental Permits or Review Procedures for Construction of Wetlands for Wastewater Treatment.

Regulation/Permit	Resource	Lead Agency	Jurisdictional Trigger	Typical Data Requirements
NPDES General Permit for Storm-water Discharges from Construction Activities	Surface water quality	EPA/ADEQ	Owners/operators of construction sites where five or more acres of land will be graded or disturbed must apply for coverage under EPA's General Permit for stormwater discharges associated with construction activities	Engineering report and site layout
National Environmental Policy Act (NEPA)	Looks at a broad range of resources including, water quality/quantity, endangered species, cultural resources, socio-economic resources—in short, anything that could affect the Human Environment	Varies depending upon jurisdictional nexus	NEPA compliance is required for any major federal action including funding, issuance of a permit or license, activities proposed for federal lands, etc.	Project specific; each agency implements the NEPA process with a slightly different emphasis and approach, and the scope and complexity of NEPA review can vary considerably from project to project.
Endangered Species Act	Rare Plants and Animals	United States Fish and Wildlife Service	· The presence of any threatened or endangered animal species or critical habitat on federal or non-federal lands · Potential adverse impact to threatened and endangered plants when impacts would be in violation of state law or if the activity requires issuance of a federal permit or license or occurs on federal lands	Biological evaluation to determine if the project has the potential to adversely affect a federally listed species.
Arizona Native Plant Law	Native plants	Arizona Department of Agriculture and Horticultures	Grading and clearing of private, federal, or state-owned lands	· Twenty to sixty day notice of clearing · If protected plants will be transplanted off of the project site, then permits from the State Department of Agriculture and Horticulture are needed
FAA Airport Requirements	Airplane strike hazard by birds	Federal Aviation Administration	Any habitats that are attractive to birds within a given radius of certain airport types are discouraged	Location of and distance to propeller and jet airports in project vicinity.

Table 8-2. Common Environmental Permits or Review Procedures for Construction of Wetlands for Wastewater Treatment.

Regulation/Permit	Resource	Lead Agency	Jurisdictional Trigger	Typical Data Requirements
National Historic Preservation Act (as amended)	Cultural Resources (including Traditional Cultural Properties)	Lead federal agency with oversight by the State Historic Preservation Officer and the National Advisory Council for Historic Preservation	Any federal action—Executive Order 11593: Protection and Enhancement of the Cultural Environment (1971) gave federal agencies direct responsibility for implementation of the National Historic Preservation Act and the National Environmental Policy Act	Class III cultural resource survey and appropriate data recovery plans if necessary
Native American Graves Protection and Repatriation Act of 1990 (NAGPRA)	Cultural Resources	Actions on federal or tribal lands	Mandates that human remains and associated funerary objects recovered from federal and tribal lands be turned over to Native American groups who can reasonably claim ancestral affiliation with such remains	Class III cultural resource survey to determine if human remains or funerary objects have the potential to occur on the subject property
State Law A.R.S. 41-865	Extends the federal protections of NAGPRA to all State and private Lands	State Historic Preservation Office	The presence of human remains and associated funerary objects	Class III cultural resource survey to determine if human remains or funerary objects have the potential to occur on the subject property
Arizona Antiquities Act	Cultural Resources on State Lands	State Historic Preservation Office	The presence of cultural resources	Class III cultural resource survey and appropriate data recovery plans if necessary

8.2.1 Aquifer Protection Permits

Arizona's APP Program governs facilities that may affect aquifers. Although constructed wetlands and FAP systems are not specifically named, similar related facilities include surface impoundments, ponds, lagoons, land treatment facilities, recharge or underground storage and recovery projects, NPDES facilities, and wastewater treatment facilities. In regulating discharges from landfills, WWTPs, mines, and industry, the APP Program covers all wetlands that are part of any wastewater treatment design. Depending on the quality and quantity of discharge, one of two APP permits, General or Individual, is required.

8.2.1.1 General Permit

A General Permit applies to all onsite wastewater systems discharging less than 2,000 gpd of materials conforming to Paragraph 1 of Subsection D, R18-9-801 through 809. Providing that depth to groundwater and disposal density meet established criteria, a General Permit can also cover systems discharging up to 20,000 gpd. General permits do not require application to ADEQ. Meeting the criteria outlined in the general permit is sufficient to satisfy APP requirements.

Site characteristics figure into the APP Program, with specific parameters delimited for site hydrology. To qualify for a General Permit, systems discharging between 2,000 and 20,000 gpd (8 to 80 m^3/d) of "typical sewage" must satisfy three criteria: (1) percolation rates must be between 1 minute and 1 hour per inch, (2) depth to groundwater must be compatible with the percolation rate (minimum of 1.5 m [5 feet] where percolation is slower than 10 minutes per inch), and (3) nitrogen content must not exceed ambient nitrate concentrations (for example, a maximum of about 0.45 kg/ha/d [0.4 lb/ac/d] where groundwater has 3 mg/L nitrate or less). Systems not meeting those standards, or discharging in excess of 20,000 gpd (80 m^3/d), require an Individual Permit.

8.2.1.2 Individual Permit

Issuance of an individual APP depends upon two technical demonstrations to be made by the permit applicant: Aquifer Water Quality Standards (AWQS) must be met at the point of compliance, and the facility must use Best Available Demonstrated Controlled Technology (BADCT).

Arizona AWQSs are equivalent to the Federal Primary maximum contaminant levels (MCLs) for drinking water and are listed in the Arizona Administrative Code under Article 4, R18-11-406. Groundwater contaminants of particular concern for wastewater discharge are typically nitrate, coliform bacteria, and trihalomethanes. AWQSs for nitrate nitrogen, coliform bacteria, and trihalomethanes are 10 mg/L, <1 colony-forming unit (CFU) per 100 mL, and <0.1 mg/L, respectively.

BADCT criteria are site-specific and determined through negotiation with ADEQ. Guidelines are contained in ADEQ's Wastewater Treatment BADCT Guidance Document. While the WWTP BADCT Guidance Document includes no specific reference to wetlands or FAP systems constructed for wastewater treatment, the standard water quality criteria remain applicable: total nitrogen–1 to 10 mg/L, turbidity–1 nephelometric turbidity unit (NTU), fecal coliforms–2.2/100 mL, trace metal–not to exceed MCL, and organic carcinogens or toxics be removed to the maximum extent practicable regardless of cost.

The following general information must be submitted with an APP application:

1. Topographic Map
2. Facility Site Plan
3. Facility Design
4. Past Discharge Activity Summary
5. BADCT Description
6. Demonstration of AWQS Compliance
7. Technical Capability Information
8. Financial Capabilities
9. Compliance History
10. Local Zoning

In addition to the information required above, ADEQ can require detailed hydrogeologic studies, analysis of ambient water quality, and the likely impact of discharges to groundwater quality. During the applicant's evaluation, they should propose a monitoring plan specifying compliance points, sampling frequency, protocols, alert levels, discharge limitations, and contingency plans.

Upon issuing an individual APP permit, the following terms and conditions will be prescribed by ADEQ:

1. Monitoring Requirements
2. Record Keeping and Reporting
3. Contingency Plan
4. Discharge Limitations
5. Compliance Schedule
6. Post-Closure Plan
7. Alert Levels
8. Other Terms Deemed Necessary

8.2.2 Disposal to Waters of the U.S.

The 1972 CWA (revised by amendments in 1977, 1981, and 1987) provides the basic framework for federal and state programs to control point and nonpoint sources of pollution. In Arizona, point sources of pollution to waters of the U.S. (except discharges of dredged or fill material regulated by ACOE) are regulated through permits issued by EPA under NPDES. Discharge from a wetland or FAP wastewater treatment facility into a water course that falls under Section 402 CWA jurisdiction will require an NPDES permit.

NPDES permits specify limits on the amount and types of pollutants that may be discharged, as well as data collection and reporting requirements. Permits ensure that specified water quality standards limit pollutant loads and require reporting and monitoring to ensure accountability. EPA evaluates compliance by screening self-monitoring reports submitted by the permitted facility.

A water quality standard defines the water quality goals of a water body or portion thereof by designating the uses of the water. Designated uses are defined under 40CFR 131.3(f) for each water body or segment whether or not they are being attained.

Water quality standards are adopted to protect public health or welfare, enhance the quality of water, and serve the purposes of the CWA. Wherever attainable, water quality standards provide for the protection and propagation of fish, shellfish, and wildlife and for recreation in and on the water. The standards consider the use and value of state waters for public water supplies, propagation of fish and wildlife, recreation, agricultural and industrial purposes, and navigation. Designated water uses in Arizona include the following:

- Aquatic and wildlife (cold-water fishery)
- Aquatic and wildlife (ephemeral)
- Aquatic and wildlife (effluent-dominated water)
- Aquatic and wildlife (warm-water fishery)
- Agricultural livestock watering
- Agricultural irrigation
- Domestic water source
- Full body contact
- Partial body contact
- Fish consumption

ADEQ has established numeric water quality standards for all designated tributary waters of the state, which are summarized in Appendix A of Title 18, Chapter 11 of the Arizona Administrative Code. The list of designated uses for navigable waters in Arizona are listed in Appendix B of Title 18, Chapter 11 of the Arizona Administrative Code.

Regulated pollutants can be conventional such as BOD_5, fecal coliform bacteria, pH, and oil and grease; nonconventional such as chemical oxygen demand (COD), nutrients such as phosphorus and nitrogen, ammonia, chloride, color, and iron; and toxic such as pesticide residues and metals. Pollutant monitoring required by an NPDES permit can vary in the type and frequency of analyses between permits. A minimal discharge monitoring plan could include monthly grab samples of influent and effluent discharge rates, BOD_5, TSS, pH, DO, temperature, and ammonia. Nutrient parameters such as total phosphorus and nitrogen may also be required on the same monitoring frequency. More detailed monitoring requirements could include more frequent effluent testing (for example, weekly) combined with periodic measurements of EPA priority pollutants including pesticide residues and metals in effluent water and receiving water sediments.

EPA recognizes that hydrology in the arid West may create conditions where the full range of designated uses and criteria are not always appropriate. WWTP discharges may support effluent-dominated aquatic and riparian ecosystems that may be lost if the discharge were removed. EPA Region 9 has established four methods to modify designated uses to preserve or create instream flows that support ecosystems in arid areas while complying with water quality standards and permit requirements and encouraging the development of water reclamation. All four approaches require substantial interaction with resource management agencies such as the USFWS, as well as ADEQ and EPA:

- The Total Maximum Daily Load (TMDL) analysis allows the discharger to demonstrate that water quality-based effluent limits of particular pollutants should be modified based on the total pollutant loading capacity of a water body.

- The Alternative Water Quality Criteria method enables the state to determine that water quality criteria for a water body should be different from the currently applicable criteria, if appropriate based upon site-specific physical, chemical, or biological characteristics.

- The Net Ecological Benefit Comparison Use Attainability Analyses may be applicable if the discharger can show that the ecological benefits of continuing an effluent discharge exceed the ecological benefits of removing the discharge from the water body.

- An Economic Feasibility Use Attainability Analysis may be applicable if it can be demonstrated that attaining the designated use will cause "widespread and substantial social and economic impact" to the defined community.

8.2.3 Wastewater Treatment

As previously discussed, ADEQ Engineering Bulletins provide design criteria intended to assure that wastewater installations meet ADEQ standards. Bulletin No. 11 covers those systems receiving more than 20,000 gpd, which require an individual APP permit. Bulletin No. 12 outlines approved technologies for onsite sewage systems receiving less than 20,000 gpd, which may qualify for a General Permit. Both bulletins recognize the processes by which constructed wetlands treat wastewater. They seemingly endorse wetlands-style treatment by accepting those mechanisms in more traditional systems, and they explicitly provide for innovative technologies.

8.2.3.1 ADEQ Bulletin No. 11

Bulletin No. 11 provides engineering guidelines to ensure the proper functioning of various natural treatment systems for municipal and domestic wastewater treatment. Approved conventional treatment systems (such as trickling filters, filtration systems, evapotranspiration beds, and wastewater lagoons and ponds) use the same biological processes found in wetlands-style treatment.

Bulletin No. 11, Chapter VII, Section P identifies construction of a marsh as an acceptable form of reuse. Biochemical parameters include a fecal coliform count not to exceed a geometric mean of 1,000/100 mL (with not more than 10 percent of the samples during a 30-day period to exceed 200/100 mL, based on a minimum of five samples during such period). pH is to range between 6.5 and 8.6, and DO must be a minimum of 4 mg/L.

Providing that bacteriological standards are met, policies governing creation of a wetland for its own inherent value are relatively non-restrictive.

Bulletin No. 11 does not establish guidelines for discharge to constructed wetlands that are primarily intended for wastewater treatment with secondary benefits arising from the use of these systems by wildlife. The purpose of this document (Constructed Wetlands Guidance Manual) is to provide the additional technical information necessary to review WWTP permit applications that include constructed wetlands in the overall treatment strategy.

The relationship of this guidance manual to Bulletin 11 can be characterized as a supplement describing an alternative technology. The general provisions of Bulletin No. 11 still apply at any WWTP with a constructed wetland system. The design information in this manual is meant primarily to replace unit processes described in Chapter VII, Section K, regarding wastewater lagoons and ponds. However, other unit processes such as sedimentation/clarification (Section D) and physical chemical treatment (Section I) are also analogous.

8.2.3.2 ADEQ Bulletin No. 12

The introduction to Bulletin No. 12 states that "The policy of the Department is to encourage, rather than obstruct, new methods and equipment for onsite disposal systems. For this reason, guidance documentation is included in the engineering bulletin to furnish the basis for the criteria. If it is proposed to deviate from the criteria, the exact nature of the proposed differences shall be noted in a Design Report."

Bulletin No. 12 describes onsite alternatives to septic tank and drainfield disposal systems. Acceptable "alternatives" in Bulletin No. 12 whose mechanisms bear some resemblance to constructed wetlands treatment include evapotranspiration beds, individual aerobic treatment systems, intermittent sand filters, mound systems, and a gravel-less trench system.

Constructed wetlands have performance records comparable to those of accepted alternatives. The first General Requirement of Bulletin No. 12 is that: "Alternative onsite disposal systems are intended and will be approved for individual lots only where conventional septic tank systems are not suitable and cannot be approved." Use of a septic tank with a minimum of two compartments for preliminary solids removal is necessary prior to a constructed wetland. Constructed SSF wetlands are viewed as a beneficial augmenting step in the septic tank system providing additional treatment between the septic tank and the soil absorption system.

8.2.4 Jurisdictional Status of Constructed Wetlands

An impediment to the wider use of constructed wetlands is the perception that, once created, a constructed wetland for wastewater treatment will be classified as waters of the U.S. If designated as such, influent to the constructed wetlands would be subject to applicable surface water quality standards and require a NPDES permit for input points in the system. However, the CWA specifically excludes WWTPs and treatment wetlands from its definition of waters of the U.S., and the same exclusion is written into Arizona's State Surface Water Rules at R18-9-103.1. While WWTPs and treatment wetlands constructed in non-jurisdictional, upland areas are excluded from the definition of wetlands jurisdiction, the construction of a wetland for wastewater treatment or as a point of disposal for treated effluent within jurisdictional areas (Figure 8-1) can result in the assertion of jurisdiction over the constructed wetlands by regulatory authorities.

8.3 Planning and Development Permits

A number of environmental permit requirements may be importan? selection of a site for a WWTP and for constructed wetland or FAP treatment portions of the WWTP. Planning and development permit requirements are dependent on jurisdictional responsibilities such as land ownership, funding source, and

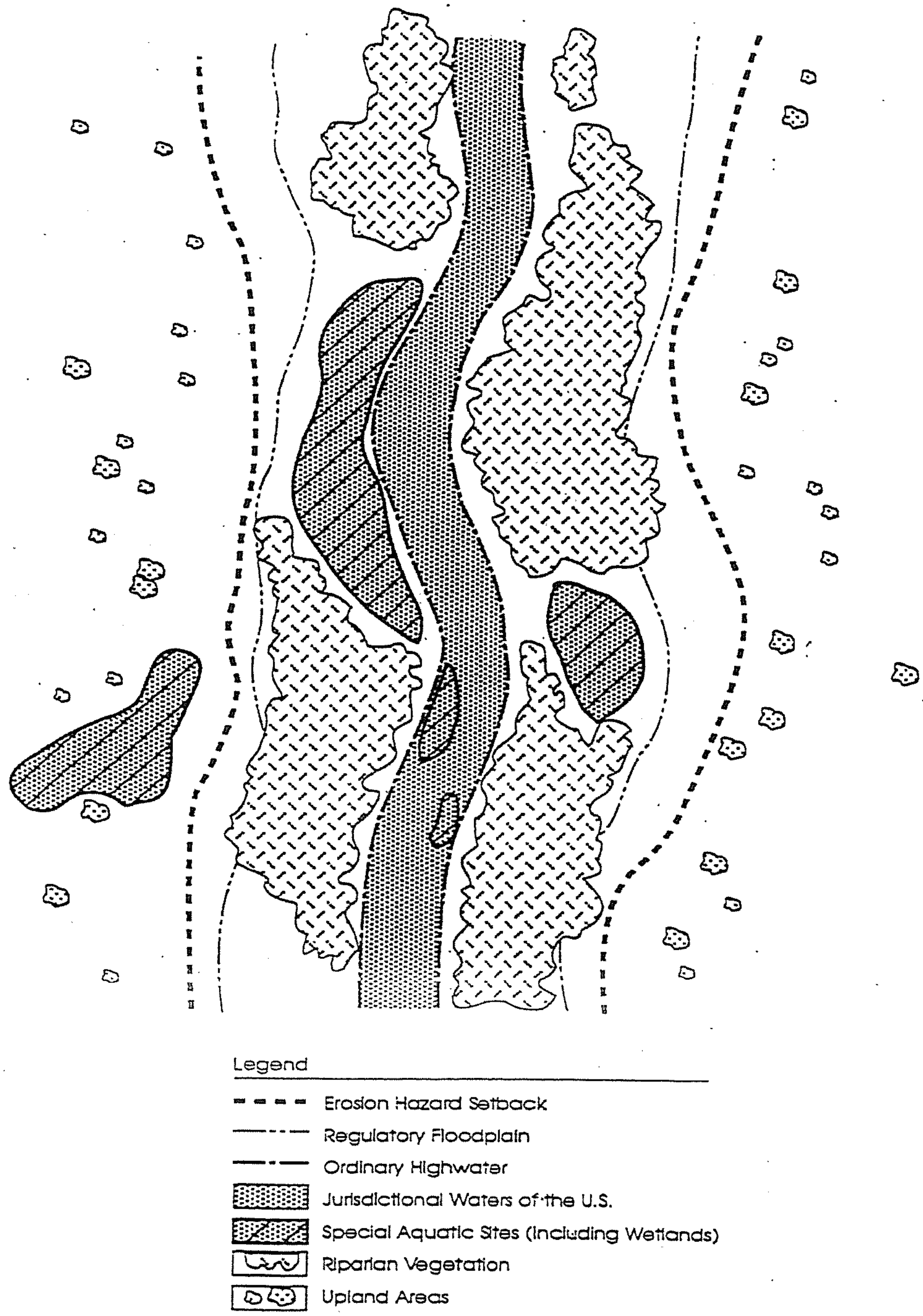


Figure 8-1. Schematic of Areas that Fall under Jurisdictional Boundaries. State and federal regulations can affect site selection for a constructed wetland.

potential impacts to targeted environmental resources (for instance, jurisdictional waters and endangered species). For example, if a project is located on federal lands or is federally funded, evaluation of project impacts to the human environment requires review under NEPA. Regulatory programs that potentially affect site selection and design are discussed below and summarized in Table 8-1.

8.3.1 Clean Water Act (CWA)

In addition to regulating discharge of treated effluent under NPDES, the CWA affects site selection, design, and development through avoidance of impacts to U.S. waters under Section 404; control of stormwater discharges under Section 402; and the requirement for State Water Quality Certification under CWA Section 401. Each of these elements is discussed in greater detail below.

8.3.1.1 Discharge to Navigable Waters

Section 401 of the CWA requires that applicants for a federal license or permit to conduct activities that may discharge into navigable waters provide certification from the state or appropriate interstate permitting agency that the discharge complies with applicable CWA standards. On tribal lands in Arizona, EPA has the authority to issue water quality certification. For all other lands within Arizona, this authority rests with ADEQ.

ADEQ evaluates the following when granting state certification of the federal permit:

- Are waters designated "unique waters?"
- Will the project cause degradation or violation of numeric or narrative water quality standards?

- Are there practicable alternatives to the project that will have less impact?
- Does the project avoid, minimize, or rehabilitate impact to water quality and the ecosystem?
- Does the project impair, maintain, or restore biological, physical, and chemical integrity of waters of U.S.?
- Should the project area be subject to cumulative impact analysis?
- Is the project consistent with regional, county, state, or other comprehensive plans?
- Are Best Management Practices for the activity being followed?

8.3.1.2 Stormwater Discharges

Section 8.2.2 covered NPDES permits for discharge of treated effluent to jurisdictional waters. Section 402 of the CWA also regulates the discharge of stormwater containing pollutants generated from non-point sources such as urban runoff and sediment from construction. These non-point pollutant sources are regulated at their point of discharge to jurisdictional waters.

Permits required to construct a wastewater treatment plant that includes wetlands would include the general permit required for construction activities that exceed 5 acres of surface disturbance at one time. This general permit requires preparing a pollution prevention plan (PPP) that provides for control of stormwater discharges, primarily sediment, during construction activities.

8.3.1.3 Dredge and Fill Permits

Section 404 of the CWA requires that all discharges of dredged or fill material into waters of the U.S. including "adjacent wetlands" must be permitted. EPA administers the CWA with the exception of the Section 404 permit program which is administered by ACOE.

Waters of the U.S. include wetlands and tributaries adjacent to navigable waters of the U.S.[1] and other waters where the degradation or destruction of the waters could affect interstate or foreign commerce. The definition of waters of the U.S. is broad; ACOE's jurisdiction includes the typically dry arroyos or washes found throughout Arizona, even if they have been isolated from navigable waters. All waters of the U.S. come under the jurisdiction of Section 404 of the CWA.

Determining the lateral jurisdictional boundaries of waters of the U.S. is based upon identifying the ordinary high water mark. In desert washes, the high water mark has one or more of three indicators: the sandy wash bottom. debris line, and vegetation establishment. Determining the jurisdictional status and the lateral boundaries of wetlands are based upon the criteria provided in ACOE's manual (ACOE, 1987).

Two broad categories of permits are available through the CWA 404 program: individual and general. Under its general permit program, ACOE has identified nationwide permits that cover a diverse array of fill activities within jurisdictional waters of the U.S. To qualify for one of the available nationwide permits requires certain conditions that vary but always include compliance with the Endangered Species Act and National Historic Preservation Act (cultural resource clearance).

If the project does not qualify for a nationwide permit or if ACOE uses its discretionary authority to deny a nationwide permit for a project that otherwise meets requirements, a project will be required to obtain an individual permit.

[1] Navigable waters of the U.S. are waters subject to the ebb and flow of the tide shoreward to the mean high water mark or waters previously used, presently used, or likely to be used in the future to transport interstate or foreign commerce.

During its review of the project, ACOE reviews a document, typically an environmental assessment (EA) for smaller projects, that satisfies the requirements of NEPA.

A project that proposes placement of fill or dredged material into a jurisdictional wetland is typically much more complicated to permit. Congress authorized ACOE and EPA to develop rules for administering the 404 permit process (the 404(b)(1) Guidelines). These guidelines require the evaluation of alternatives to determine if a less environmentally damaging alternative is available. Ultimately, site selection to avoid jurisdictional waters or wetlands will greatly simplify the permitting process.

8.3.2 National Environmental Policy Act (NEPA)

The NEPA requires evaluating the environmental effects of a proposed federal action, the "no-action" alternative, and other practical alternatives identified during project scoping. A federal action can include such things as issuance of an individual 404 permit (nationwide permits have already undergone NEPA review), a special-use permit for use of federal lands, a federal land exchange, or the use of federal monies for project development.

NEPA provides for three levels of analysis, depending on whether or not an undertaking could significantly affect the environment. These three levels include: categorical exclusion, preparation of an EA/finding of no significant impact (FONSI), and preparation of an environmental impact statement (EIS).

An action may be excluded from a detailed analysis of impacts (a categorical exclusion) if it meets predefined criteria that the lead agency has determined not to have significant environmental consequences. At the next higher level of review, the lead agency reviews an EA to determine whether or not the proposed federal undertaking would significantly affect the environment. If the answer is no, then the agency issues a FONSI. Within the FONSI, the agency may address measures to reduce potentially significant impacts. The level of analysis completed for an EA is extremely variable and depends upon the complexity of the project and potential for environmental impacts. If the EA determines that a proposed federal action may result in significant impacts, then an EIS must be prepared. The EIS is a more detailed evaluation of the proposed action and alternatives and has a much greater level of public participation, including formal notification requirements in the Federal Register. If it is expected that an EIS would ultimately be required, the lead federal agency can skip the EA and proceed directly to the EIS.

8.3.3 Endangered Species Act (ESA)

The ESA was established by Congress to conserve and restore populations of plants and animals in danger of extinction and the ecosystems upon which threatened and endangered species depend. Section 9 of the ESA includes a prohibition against "take," which is defined in the act as "harass, harm, pursue, hunt, shoot, wound, kill, trap, capture, or collect, or attempt to engage in any such conduct." The act provides different levels of protection for plants and animals. On non-federal and federal lands, animals are afforded the full protection of Section 9 prohibitions against take. For non-federal actions on private lands, the ESA protects plants by making it unlawful (a federal offense) to remove, cut, dig up, damage, or destroy any endangered plants in knowing violation of state regulations or in the course of violation of any state criminal trespass law.

The ESA also includes: the Section 7 consultation process, and Section 10a permits, by which a project proponent, federal or otherwise, may proceed with an action that may affect a federally listed species. Section 7 requires a federal agency to consult with the USFWS if any action regulated, funded, or authorized by the agency is likely to harm a listed species or adversely modify its critical habitat. Section 7 permits generally result in some form of mitigation to offset the adverse effects of the proposed federal action. Section 10a of the ESA provides a mechanism for non-federal entities to obtain permits for take by preparing a Habitat Conservation Plan for a single parcel or a region.

8.3.4 Arizona Native Plant Law

The Arizona Native Plant Law was established to protect specified native plants from excessive collection and use. The law does not prevent the destruction of protected native plants or clearing of land if (1) the land is in private ownership, (2) plants are not transported from the property and offered for sale, and (3) the owner or owner's agent notifies the commission at least 30 days prior to intended destruction in writing. The 30-day time period is required for parcels from 1 to 40 acres. Parcels less than 1 acre require a 20-day notice and parcels greater than 40 acres require a 60-day notice.

Several levels of permit for collection and relocation of plants have been established. These levels of permitting are based upon the perceived level of risk to the plant. Relocation of protected plants does not require a permit if the plant is moved to a contiguous portion of the same property (Mender, pers. comm.). Relocation of protected plants to off-site locations requires a permit and tag for each plant.

8.3.5 FAA Jurisdiction of Wildlife Attractions Near Airports

The Federal Aviation Administration (FAA) is concerned with air traffic safety and the potential for any facility to increase the hazard of birdstrikes with aircraft during takeoff or landings at airports. FAA Order 5200.5A, Waste Disposal Sites on or near Airports, dated January 31, 1990, provides guidance concerning the establishment, elimination, or monitoring of waste disposal sites near airports. The definition of waste disposal includes sanitary landfills, garbage dumps, sewer outfalls, and other similarly licensed or titled facilities used for operations to process, bury, store or otherwise dispose of waste, trash, and refuse. In September 1992, the FAA issued a draft circular which would expand the definition of facilities considered attractive to wildlife and hazardous to aircraft operations to include wastewater treatment facilities, wetlands, stormwater retention and detention facilities, and agricultural crops. The draft circular states that "if such land uses attract or sustain wildlife near airport operations, the potential for a collision between aircraft and wildlife may be significantly increased." Facilities located as far away as five miles from the airport that might induce bird movements across the approach and departure paths of aircraft can be deemed hazardous to airport operations. To obtain a formal determination from FAA concerning compliance with these guidelines requires the submittal of FAA Form 7460-1 with supporting materials on the proposed wetlands facility.

It should be noted that the FAA neither approves nor disapproves locations of waste disposal sites; the role of the FAA is to ensure that airport owners and operators meet their contractual obligations to the federal government regarding compatible land uses in the vicinity of airports. Therefore, the only enforcement action available to the FAA for noncompliance with these guidelines is to withhold federal funding for airport improvements.

8.3.6 Cultural Resources Regulations

The types of legislation governing the treatment of cultural resources for any specific project depends on two factors: the ownership of the land and the types of permits required for the construction and operation of the facility. If the facility is either wholly or partly on federal land, impacts to cultural resources would need to be evaluated and mitigated pursuant to the applicable federal legislation, particularly the National Historic Preservation Act and the Archaeological Resource Protection Act. The Arizona Antiquities Act provides for the treatment of cultural resources on state land, and various local regulations (such as the Pima County grading ordinance and City of Tucson Administrative Directive 1.07-7) contain provisions for the management of cultural resources on private lands within their jurisdiction.

Regardless of land ownership, the granting of nearly any federal permit requires compliance with the federal cultural resource legislation cited above. For example, the granting of a CWA Section 404 permit by ACOE requires documentation of compliance with Section 106 of the National Historic

Preservation Act. Such compliance would include a preliminary archaeological survey of the project area and might also require additional evaluation and mitigation of the project's impacts on cultural resources. In general, state and local environmental permits do not specifically require compliance with cultural resource legislation on land not controlled by state or local agencies.

The suite of cultural resources regulations potentially affecting development of wetlands constructed for wastewater treatment are summarized below.

8.3.6.1 National Historic Preservation Act of 1966

This act provided the administrative and legislative power to carry out the spirit and intentions of the Historic Sites Act of 1935 and expanded its policies to include protection and preservation of significant properties. The act built on the existing Registry of National Historic Landmarks by establishing the National Register of Historic Places to record "districts, sites, buildings, structures, and objects significant in American history, architecture, archaeology, and culture" on the national, state, regional, and local levels.

This legislation greatly encouraged preservation activities on state and local levels. It established a program of matching grants to states and the National Trust for preservation efforts. It also created the Advisory Council for Historic Preservation to coordinate and publicize federal, state, and local preservation activities and advise the President, Congress, and federal agencies on historic preservation. Section 106, which requires Federal agencies to consult with the Advisory Council before undertaking activities affecting properties listed on the National Register, provides a mechanism for involving states in decision-making related to cultural resources.

8.3.6.2 Native American Graves Protection and Repatriation Act of 1990

This federal legislation mandates that human remains and associated funerary objects recovered from federal and tribal lands be turned over to Native American groups who can reasonably claim ancestral affiliation with such remains. The act also requires any and all institutions that are in possession of Native American human remains and funerary objects to prepare a detailed inventory of the items and provide this inventory to any tribe requesting such documentation. The act also provides for felony prosecution of any individual or institution participating in the trafficking of human remains or burial objects recovered from federal lands, either through permitted or illicit activities. Human remains and associated funerary objects are protected by ARS 41-865 for state and privately held lands.

8.3.6.3 Executive Order 11593: Protection and Enhancement of the Cultural Environment of 1971

This order gives federal agencies direct responsibility for the National Historic Preservation Act of 1966 and NEPA of 1969, ordering that federal agencies survey and nominate sites, buildings, districts, and objects under their jurisdiction that may be eligible for the National Register.

8.3.6.4 State Law A.R.S. 41-865

This Arizona state law extends the federal Native American Graves Protection and Repatriation Act (NAGPRA) to include the protection of all human remains and funerary objects recovered from land under state or private ownership in Arizona. This law requires that the landowner cease all operations when human remains are encountered and provide a written report of the discovery to the Arizona State Museum. The Museum Coordinator is then responsible for notifying appropriate Native American groups and coordinating the treatment of the remains. This legislation also renders illegal any attempts to sell or otherwise financially benefit from the sale or trafficking of human remains or associated objects recovered from lands within Arizona.

8.3.6.5 Arizona Antiquities Act

Essentially, this act applies most of the mandates of the federal legislation described above to state-owned lands within Arizona. The act makes defacing rock art sites and collecting archaeological specimens without a permit a misdemeanor. Excavation of sites on state land without proper permits results in a felony. This act also provides guidelines for discovery, treatment, and reporting of archaeological remains by institutions or individuals who possess permits to conduct such investigations.

SECTION 9.0

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APPENDIX A

Selected Arizona Wetland and Riparian Plants

Table A. Selected Arizona Wetland and Riparian Plants.[a]

Common Name and Species	Growth Form/ Habit	Hydrologic Regime	Soil/Substrate	Geographic Range	Elevation	Frequency of Occurrence	Comments
Alder *(Alnus oblongifolia)*	TR/SH	HY	SI/CO	CP/CH	5000-7500	FR	Often forms tall closed-canopy riparian woodland but also forms thickets along less stable water courses checking erosion; A. tenuifolia occurs at higher elevations (7500-9500') in Arizona
Annual rush *(Juncus bufonius)*	AN	HY/ME	CL/SA-T	BR	<3000	FR	The only annual rush, often very abundant over large areas
Arizona walnut *(Juglans major)*	TR	HY/ME	SI/CO	CH	4000-6000	FR	Large deciduous tree forming shady groves along streams and on flood plains; suspected of releasing allelopathogens into the soil; seedlings available through the Arizona State Land Department
Arrow-grass *(Triglochin concinna)*	PE	HY	NP	CP	6000-7000	IN	Rushlike perennial of wet soil; T. maritima also occurs in Arizona
Arrow-head *(Sagittaria cuneata)*	EM/SU	HY/SE-AQ	CI/SA	CP/CH/BR	<7000	IN	Leafy perennial spreading by rhizomes in wet soil; leaves submerged when water is present; similar species of Arizona include S. graminea, S. latifolia, S. longiloba, and S. greggii
Arrow-weed *(Tessaria sericea)*	PE	HY	CL/SA-T	BR	<4000	FR	Similar to seep-willow (Baccharis salicifolia) in habit and belongs to the same family; flowers pale lavender; often placed within the genus Pluchea
Azolla *(Azolla filiculoides)*	FL	AQ	N/A	CH/BR	2000-4000	IN	Clones of small leaves often cover large surface areas; technically a fern but similar in habit to the flowering plant Lemna (duck-weed)
Betony *(Stachys coccinea)*	PE	HY/ME	SI/CO	CH/BR	<8000	FR	Very attractive perennial with dark green leaves and bright red flowers; easily propagated; available from local nurseries
Bulrush *(Scirpus acutus)*	EM/PE	SE/HY	NP	CP/CH/BR	2500-9000	FR	Spreads by thick rhizomes forming dense tule-like masses of dark green terete stems generally ca. 2m tall (up to 5m); easily propagated by rhizomes; similar species or commonly-used synonyms include S. californicus (< 3500') and S. validus (2500-9000'); S. pallidus (<9000), S. americanus (< 6000'), and S. olneyi (< 7000,) have three-edged stems

Table A. (Continued)

Common Name and Species	Growth Form/ Habit	Hydrologic Regime	Soil/Substrate	Geographic Range	Elevation	Frequency of Occurrence	Comments
Bulrush (*Scirpus paludosus*)	EM/PE	SE/HY	NP	CH/BR	<5000	IN	Habit similar to sedges, generally < 1m tall
Button-bush (*Cephalanthus occidentalis*)	SH	HY/ME	SI/SA	CH/BR	<5000	IN	Handsome shrub to 2.5m tall with large leaves; prefers wet soil along streams
Cattail (*Typha domingensis*)	EM/PE	SE/HY	NP	CP/CH/BR	<4000	FR	Easily established, fast growing perennial spreading by rhizomes forming extensive thickets (tules) in shallow (< ca. 1m) water or mud; very important waterfowl habitat; seeds are wind- disperses en masse; shoots above ground die back each year
Cattail (*Typha latifolia*)	EM/PE	SE/HY	NP	CH/BR	3500-7500	IN	Very similar to T. dominguensis but occurs generally at higher elevations within Arizona
Columbine (*Aquilegia chrysantha*)	PE	HY/ME	SI/SA	CP/CH/BR	>3000	FR	Large showy bright green leaves and yellow flowers; shade tolerant; rhizomes easily divided and transplanted; this is the most common and widespread species but several others occur in Arizona
Cottonwood (*Populus angustifolia*)	TR	HY/ME	NP	CP/CH	5000-7000	FR	More similar in appearance to some willows (Salix) than to P. fremontii; P. acuminata is a species morpholocally intermediate between P. angustifolia and P. fremontii
Cottonwood (*Populus fremontii*)	TR	HY	NP	CH/BR	<6000	FR	Common and abundant deciduous tree with a large canopy; fruit wind-dispersed en masse
Coyote willow (*Salix exigua*)	SH	HY	SI/CO	CP/CH/BR	<9500	FR	Deciduous shrub spreading by rhizomes forming extensive tule-like areas along perennial waterways; easily propagated from shoots of the previous year
Duckweed (*Lemna gibba*)	FL	AQ	N/A	CP/CH/BR	<7000	FR	Often covers large surfaces of still or slow moving water; easily transplanted by casting a few live individuals; grows rapidly; an important species for waterfowl; although other species of the genus occur in Arizona, this is the most common and easily recognized; L. minor is also common

Table A. (Continued)

Common Name and Species	Growth Form/ Habit	Hydrologic Regime	Soil/Substrate	Geographic Range	Elevation	Frequency of Occurrence	Comments
Flat-sedge *(Cyperus niger)*	PE	HY/ME	SI/SA	CP/CH/BR	3000-7000	FR	One of the more common of ca. 25 species of the genus that occur in Arizona; similar in habit to the true sedge (Carex) but not as important in terms of bank stabilization
Godding willow *(Salix gooddingii)*	SH/TR	HY	SI/CO	CH/BR	<7000	FR	Common and abundant, often large deciduous tree of Arizona's middle and lower elevations; easily propagated from stems ca. 1" in diameter
Heliotrope *(Heliotropium curassavicum)*	PE	HY/ME	CL/SA-VT	CH/BR	<5000	FR	A low dark green succulent with small white flowers; often abundant but not usually dense
Hierba-mansa *(Anemopsis californica)*	PE	SE/ME	SI/SA-T	CH/BR	2000-5000	IN	Often forms thick masses in wet saline soil; frequently-used folk medicine
Horned-pondweed *(Zannichellia palustris)*	SU	AQ	N/A	CP/CH/BR	<8000	IN	The thin bright green grass-like leaves often occur in abundance near the surface of ponds and slow-moving waterways
Hornwort *(Ceratophyllum demersum)*	SU	AQ	N/A	CP/CH/BR	2000-6500	IN	Forms large masses under the surface of motionless or slow-moving water; restricts swimming and boat travel
Horsetail *(Equisetum laevigatum)*	EM/PE	SE/HY	SI/SA	CP/CH	4000-8000	FR	Spreads by rhizomes in wet and moist soils, often covering extensive areas; E. hiemale is another common species which occurs in Arizona
Knot grass *(Paspalum distichum)*	PE	HY	SI/SA	CH/BR	<4000	FR	Forms extensive stoloniferous masses along stream banks and in other areas of moist soil
Knotweed *(Polygonum amphibium)*	EM/PE	SE	NP	CP	5000-9000	FR	Often forms large masses in shallow water; the inflorescences are tinged pink and conspicuous in full flower
Knotweed *(Polygonum bistortoides)*	PE	HY	NP	CH	8500-1100	FR	See P. fusiforme
Knotweed *(Polygonum coccineum)*	EM/PE	SE	NP	CP/CH/BR	2500-7000	IN	Similar to P. amphibium in habit but occurs also at lower elevations in Arizona
Knotweed *(Polygonum fusiforme)*	PE	HY	CL/SA	CH/BR	<4500	FR	One of several species of knotweed that often occur in abundance on wet soil; see also P. persicaria and P. bistortoides

Table A. (Continued)

Common Name and Species	Growth Form/ Habit	Hydrologic Regime	Soil/Substrate	Geographic Range	Elevation	Frequency of Occurrence	Comments
Knotweed (*Polygonum persicaria*)	PE	HY	NP	CP	5000-7000	FR	See P. fusifome
Lobelia (*Lobelia cardinalis*)	PE	HY	CL/SA	CP/CH/BR	3000-7500	FR	The most common and abundant of the Arizona lobelias; often a significant element of the flora along water courses; flowers bright red and showy; rhizomes and corms are easily transplanted
Locust (*Robinia neomexicana*)	SH/TR	HY/ME	NP	CP/CH	4000-8500	FR	Large shrub or small tree with very showy clusters of white to violet flowers; large prickles deter pedestrian mobility; spreads by rhizomes forming large thickets; very fast growing and rhizomes easily transplanted
Manna grass (*Glyceria borealis*)	PE	HY	CL/SA	CP	7500-9000	FR	A tall graceful grass; three additional species occur in Arizona
Monkey-flower (*Mimulus cardinalis*)	PE	SE/HY	SI/CO	CP/CH/BR	2000-8500	IN	An attractive perennial with bright orange-red flowers; prefers seeps; similar to M. eastwoodiae, a stoloniferous species
Monkey-flower (*Mimulus guttatus*)	PE	SE/HY	SI/SA	CP/CH/BR	<9500	FR	Ubiquitous in wet soil; spreading by rhizomes and stolons; large and showy when in or near perennial water; flowers yellow; several other species of yellow monkey-flower occur in Arizona
Naiad (*Najas maritima*)	SU	AQ	N/A	BR	<4000	IN	
Nettle (*Urtica gracilis*)	HY	HY	CL/SA	CP/CH/BR	<9000	IN	Fast-growing leafy perennial spreading by rhizomes; herbage with stinging hairs
Paint-brush (*Castilleja minor*)	AN	HY	SI/SA	CP/CH/BR	3000-7500	IN	A thin annual to ca. 1m tall; top of stem has conspicuous red bracts when flowering
Panic grass (*Dichanthelium oligosanthes*)	PE	HY/ME	CL/SA	CH/BR	3000-6000	FR	Spreads by stolons; prefers moist sandy banks
Pepperwort (*Marsilea vestita*)	FL	AQ	N/A	CP/CH/BR	1500-7000	IN	The attractive clover-like leaves of this aquatic fern often cover large surface areas on still or slow-moving water

Table A. (Continued)

Common Name and Species	Growth Form/ Habit	Hydrologic Regime	Soil/Substrate	Geographic Range	Elevation	Frequency of Occurrence	Comments
Pink-stars *(Centaurium calycosum)*	AN	HY	SI/SA-T	CH/BR	<6000	FR	A thin annual of alkali seeps with showy pink flowers
Pondweed *(Potamogeton crispus)*	SU	AQ	N/A	CH	3500-6000	IN	A species only recently discovered within Arizona which indicates that it is possibly a recent introduction; forms olive-green masses at and below the surface of still or slow-moving water no more than ca. 2m deep; the wavy margins of the leaves make them rather attractive
Pondweed *(Potamogeton foliosus)*	SU	AQ	NP	CP/CH/BR	<8500	FR	Forms green masses at and below the surface of still or slow-moving water gen. < ca. 1m deep; similar species that occur in Arizona are P. pectinatus (1000 -5000'), P. pusillus (>6000'), and the submergent form of P. diversifolius (5000-7500')
Pondweed *(Potamogeton nodosus)*	FL	AQ/SE	NP	CP/CH/BR	<8000	FR	The oval leaves lie flat on the surface covering large areas where the water is no more than ca. 1m deep; similar species that occur in Arizona include P. natans (>8000'), P. gramineus (>5000), and the floating form of P. diversifolius (5000-7500')
Reed *(Phragmites communis)*	PE	HY	SI/SA-T	CH/BR	<6000	IN	Spreading by thick rhizomes to form extensive tule communities
Rose *(Rosa woodsii)*	SH	HY/ME	SI/CO	CP/CH	4000-9000	FR	Prickly shrubs spreading by rhizomes, often forming extensive masses along streambanks and moist in rocky drainage bottoms; flowers pink, showy; fruit valuable food for wildlife; the species is often split into several species or varieties
Rush *(Juncus balticus)*	EM/PE	SE/HY	CL/SA	CP/CH/BR	3000-7000	FR	A common species usually forming extensive, dense stands of wiry dark green stems; a good soil stabilizer; one of numerous species that occur in Arizona; rhizomes are easily divided and transplanted
Rush *(Juncus xiphioides)*	EM/PE	SE/HY	SI/CO	CP/CH/BR	>3500	FR	A common rush with flat, iris-like leaves; the group is taxonomically confusing and numerous synonyms are found in the literature

Table A. (Continued)

Common Name and Species	Growth Form/ Habit	Hydrologic Regime	Soil/Substrate	Geographic Range	Elevation	Frequency of Occurrence	Comments
Salt grass *(Distichlis spicata)*	PE	HY/ME	CL/SA-VT	CP/CH/BR	<7000	FR	This common sod-forming grass often occurs singularly in saline soils
Sedge *(Carex praegracilis)*	PE	HY	SI/SA	CP/CH	>3000	FR	Forms grass-like masses in wet meadows and along shallow waterways; an excellent soil stabilizer
Sedge *(Carex senta)*	PE	HY	SI/SA	CP/CH/BR	>2000	FR	One of the most common and elegant of the sedges; its roots, rhizomes and stems are very dense and are therefore useful for bank stabilization; ca. 50 species of Carex occur in Arizona and many are similar in habit and habitat preference to C. senta.
Sedge *(Carex siccata)*	PE	HY	SI/SA	CP	>8000	FR	A common sedge of higher elevations
Seep-willow *(Baccharis salicifolia)*	SH	HY/ME	SI/CO	CH/BR	<5000	FR	Often forming dense thickets 2-3m tall; not a true willow but similar to coyote willow (Salix exidua) but evergreen and more drought-tolerant; releases myriads of wind-born seeds in fall; often referred to as B. glutinosa
Spike-rush *(Eleocharis macrostachya)*	EM/PE	SE/HY	CL/SA-T	CP/CH/BR	<8000	IN	Although several species of spikerush occur in Arizona, this species is the most frequent and abundant
Spike-rush *(Eleocharis rostellata)*	EM/PE	SE/HY	CL/SA-T	CP/CH/BR	<8000	IN	One of the most salt-tolerant of the spike-rushes
Sycamore *(Platanus wrightii)*	TR	HY	NP	CH/BR	2000-6000	FR	Large deciduous tree with white trunks; often forming closed canopy riparian woodlands
Toad-flax *(Linaria texana)*	AN	HY/ME	SI/SA	CH/BR	1500-5000	IN	Tall annual with dark blue flowers
Triodanis *(Triodanis perfoliata)*	AN	HY/ME	CL/SI	CP/CH/BR	<7500	IN	In wet soil of warmer climates grows tall (ca. 1m) with showy purple flowers
Velvet ash *(Fraxinus velutina)*	TR	HY/ME	SI/CO	CP/CH/BR	2000-7000	FR	A common and abundant deciduous tree along intermittent and perennial streams especially in the mid-elevations of Arizona; morphologically variable; seedlings available through the Arizona State Land Department

Table A. (Continued)

Common Name and Species	Growth Form/ Habit	Hydrologic Regime	Soil/Substrate	Geographic Range	Elevation	Frequency of Occurrence	Comments
Water bird (*Betula fontinalis*)	TR/SH	HY/ME	NP	CP	7000-8000	IN	Primarily a streamside tree with smooth, glossy, red-brown bark
Water buttercup (*Ranunculus aquatilus*)	SU	AQ	NP	CP/CH	4500-9000	FR	Forms delicate masses of thin leaves and stems in shallow slow-moving or still water; flowers white, emergent; R. circinatus is a similar Arizona species
Water lupine (*Lupinus latifolius*)	PE	HY	SI/SA	CH	5000-6000	IN	Leafy perennial often forming large masses to 1.5m tall along waterways; flowers large but not colorful; common only in the Prescott ar.., L. latifolius var. leucanthus is the from found in Arizona and it is often referred to as L. parishii
Water speedwell (*Veronica anagallis-aquatica*)	EM/PE	SE/HY	NP	CP/CH/BR	<7000	FR	Forms leafy, often extensive, patches along perennial stream banks; V. americana (< 9500') is a similar Arizona species
Water-milfoil (*Myriophyllum sibiricum*)	SU/FL	AQ	N/A	CP/CH	5000-9000	IN	Forms masses of feathery vegetation on and below the surface of still or slow- moving water; M. brasiliense is also known from Arizona
Water-pimpernel (*Samolus valerandi*)	PE	SE/HY	NP	CH/BR	<5000	IN	An attractive perennial for its thin green leaves; often locally abundant along perennial streams
Water-plantain (*Alisma plantago-aquatica*)	EM	SE	CL/SA	CP/CH	4000-8000	FR	Similar to A. subcordatum
Water-plantain (*Alisma subcordatum*)	EM	SE	CL/SA	CP/CH	5000-7000	FR	Fibrous roots, leaves mostly emersed, blades broadly ovate, leaves occasionally floating, flowering in summer
Water-weed (*Elodea canadensis*)	FL/SU	AQ	N/A	CP/CH	4000-8000	IN	Forms masses on and below the surface of still or slow-moving water
Willow (*Salix laevigata*)	TR	HY	SI/CO	CP/CH/BR	2000-7000	FR	Large deciduous shrub or tree; easily propagated from green shoots ca. 1" in diameter; similar Arizona species include S. lasiolepis (4000-7500') and S. bonplandiana (5000-6500')

[a]This table illustrates the diversity of native plants that can be used in wetlands constructed for wastewater treatment. This list includes species, such as cattail that have long been associated with wetland wastewater treatment systems and other plants whose efficiency for wastewater treatment have not been demonstrated. Included with this list are general information regarding the geographic distribution within the state, frequency of occurance, typical hydrologic regime, soil preference, and elevational range. The availability in nurseries of these and other wetland plants not listed can not be quaranteed. During the early planning phases of a constructed wetland project, after funding and construction schedules are known, it would be prudent to contract-grow in advance those plants that will not be collected from wild populations.

(Growth Form/Habit = SHrub, TRee, PErennial herb, ANnual, VIne, SUbmergent, EMmergent, FLoating; Typical Hydrologic Regime = AQuatic, SEmi-aquatic, HYdroriparian, MEsoriparian; Soil Preference = CLay, SIlt, SAnd, GRavel, COBble, No Preference (When known the salt tolerance of a given species is included as a modifier as follows: Not Tolerant, Moderately Tolerant, Very Tolerant.); Geographic Range = Basin & Range, Central Highlands, Colorado Plateau Elevation Range = reported in feet above MSL Frequency of Occurance (Natural Populations) = INfrequent, FRequent, Frequent & Abundant.)

APPENDIX B

Glossary

Glossary

absorption The movement of a dissolved chemical through a semipermeable membrane into a living organism.

acid A chemical substance that can release excess protons (hydrogen ions).

activated sludge A complex variety of microorganisms growing in sludge in aerated wastewater treatment basins. Following settling, a portion of this microbial and sludge mixture is recycled to the influent of the treatment system, where microbes continue to grow. The remaining activated sludge is removed (wasted) from the treatment system and disposed of by different processes.

adsorption The adherence of a gas, liquid, or dissolved chemical to the surface of solid.

advanced wastewater treatment (AWT) Treatment of wastewater beyond the secondary treatment level. In some areas AWT represents treatment to less than 5 milligrams per liter (mg/L) of 5-day biochemical oxygen demand (BOD_5), 5 mg/L of total suspended solids (TSS), 3 mg/L of total nitrogen (TN), and 1 mg/L of total phosphorus (TP).

adventitious roots Roots that grow from the stems of some plants as a response to flooding. Adventitious roots develop on these plants when the plant's normal roots are in oxygen-deficient, flooded soils, and the adventitious roots are in the overlying, oxygen rich water column.

aeration The addition of air to water, usually for the purpose of providing higher oxygen concentrations for chemical and microbial treatment processes.

aerobic Pertaining to the presence of elemental oxygen.

algae A group of autotrophic plants that are unicellular or multicellular and typically grow in water or humid environments.

alkalinity A measure of the capacity of water to neutralize acids because of the presence of one or more of the following bases in the water: carbonates, bicarbonates, hydroxides, borates, silicates, or phosphates.

allocthonous Pertaining to substances (usually organic carbon) produced outside of and flowing into an aquatic or wetland ecosystem.

ammonification Bacterial decomposition of organic nitrogen to ammonia.

anaerobic Pertaining to the absence of free oxygen.

anion A negatively charged ion.

annual Occurring over a 12-month period.

anoxic Pertaining to the absence of all oxygen (both free oxygen and chemically-bound oxygen).

aquaculture The propagation and maintenance of plants or animals by humans in aquatic and wetland environments.

aquatic Pertaining to flooded environments. Over a hydrologic gradient, the aquatic environment is the area waterward from emergent wetlands and is characterized by the growth of floating or submerged plant species.

arenchyma Porous tissues in vascular plants that have large air-filled spaces and thin cell walls. Arenchymous tissues allow gaseous diffusion between aboveground and belowground plant structures, thus permitting plants to grow in flooded conditions.

aspect ratio Ratio of wetland cell length to width.

autocthonous Pertaining to substances (usually organic carbon) produced internally in an aquatic or wetland ecosystem.

autotrophic The production of organic carbon from inorganic chemicals. Photosynthesis is an example of an autotrophic process.

bacteria Microscopic, unicellular organisms lacking chlorophyll. Most bacteria are heterotrophic (some are chemoautotrophs), and many species perform chemical transformations that are important in nutrient cycling and wastewater treatment.

benthic Pertaining to occurrence on or in the bottom sediments of wetland and aquatic ecosystems.

bioassay The use of plants or animals for testing water quality. Often refers to use of living organisms for testing toxicity of wastewaters.

biomass The total mass of living tissues (plant and animal).

BOD (biochemical oxygen demand) A measure of the oxygen consumed during degradation of organic and inorganic materials in water.

bog An acidic, freshwater wetland, dominated by mosses, which typically accumulates peat.

bottomland Floodplain wetlands typically dominated by wetland tree species.

brackish water Pertaining to surface or groundwaters containing a salt content greater than 0.5 parts per thousand.

bulk density A measurement of the mass of soil occupying a given volume.

buttress The lower emergent, somewhat conical portion of some trees that grow in response to flooded conditions. The buttress may or may not include distinct ridges that broaden and anchor the base of tree species such as cypress, black gum, and wetland oak species.

carbonate An inorganic chemical compound containing one carbon atom and three oxygen atoms ($-CO_3$).

carnivore A plant or animal that feeds primarily on living animals.

cation A positively charged ion.

channel A deeper portion of a water flowway that has faster current and water flow.

channelization The creation of a channel or channels resulting in faster water flow, a reduction in hydraulic residence time, and less contact between waters and solid surfaces within the water body.

chemosynthesis The use of chemically reduced energy for microbial growth.

chlorophyll A green organic compound produced by plants and used in photosynthesis.

cienega A Spanish term meaning a swamp or marsh typically formed by hillside springs.

clarifier A circular or rectangular sedimentation tank used to remove settled solids in water or wastewater.

constructed wetland A wetland that is purposely constructed by humans in a non-wetland area.

consumer An animal that derives nutrition from other living organisms. Primary consumers feed on plants, and secondary and higher consumers feed on other animals.

degraded wetland A wetland altered by human action in a way that impairs the wetland's physical or chemical properties, resulting in reduced functions such as habitat value or flood storage.

delineation The process of determining boundaries. Wetlands delineation uses regulatory definitions based on hydrologic, soil, and vegetative indicators to identify these boundaries.

denitrification The anaerobic microbial reduction of oxidized nitrate nitrogen to nitrogen gas.

detritivore An animal that feeds on dead plant material and the associated mass of living bacteria and fungi.

detritus Dead plant material that is in the process of microbial decomposition.

diffusion The transfer of mass through a gas or liquid from a region of high concentration to a region of lower concentration.

disinfection The killing of the majority of microorganisms, including pathogenic bacteria, fungi, and viruses, by using a chemical or physical disinfectant. Disinfection is functionally defined by limits, such as achieving an effluent with no more than 200 colonies of fecal coliform bacteria in 100 milliliter (mL).

dispersion Scattering and mixing within a water or gas volume.

disturbed wetland A wetland directly or indirectly altered by a perturbation, yet retaining some natural wetland characteristics; includes anthropogenic and natural perturbations.

diversity In ecology, diversity refers to the number of species of plants and animals within a defined area. Diversity is measured by a variety of indices that consider the number of species and, in some cases, the distribution of individuals among species.

diurnal Occurring on a daily basis or during the daylight period.

drained wetland A wetland in which the level or volume of ground or surface water has been reduced or eliminated by artificial means.

ecology The study of the interactions of organisms with their physical environment and with each other and of the results of such interactions.

ecosystem All organisms and the associated nonliving environmental factors with which they interact.

ecotone The boundary between adjacent ecosystem types. An ecotone can include environmental conditions that are common to both neighboring ecosystems and can have higher species diversity.

effluent A liquid or gas that flows out of a process or treatment system. Effluent can be synonymous with wastewater after any level of treatment.

emergent plant A rooted, vascular plant that grows in periodically or permanently flooded areas and has portions of the plant (stems and leaves) extending through and above the water plane.

enhanced wetland An existing wetland with certain functional values that have been increased or enhanced by human activity.

estuary An enclosed or open natural, transitional water body between a river and the ocean.

eutrophic Water with an excess of plant growth nutrients that typically result in algal blooms and extreme (high and low) dissolved oxygen concentrations.

evaporation The process by which water in a lake, river, wetland, or other water body becomes a gas.

evapotranspiration The combined processes of evaporation from the water or soil surface and transpiration of water by plants.

exotic species A plant or animal species that has been intentionally or accidentally introduced and that does not naturally occur in a region.

facultative Having the ability to live under different conditions (for example, with or without free oxygen).

fecal Pertaining to feces.

fecal coliform Aerobic and facultative, Gram-negative, nonspore-forming, rod-shaped bacteria capable of growth at 44°C (112°F), and associated with fecal matter of warm-blooded animals.

fen A freshwater wetland occurring on low, poorly drained ground and dominated by herbaceous and shrubby vegetation. Soil is typically organic peat.

flash boards Removable boards used to control water levels.

floating aquatic plant A rooted or nonrooted vascular plant that is adapted to have some plant organs (generally the chlorophyll-bearing leaves) floating on the surface of the water in wetlands, lakes, and rivers.

floodplain Areas that are flooded periodically (usually annually) by the lateral overflow of rivers. In hydrology, the entire area that is flooded at a recurrence interval of 100 years.

food chain or web The interconnected group of plants and animals in an ecosystem. Foodchain specifically refers to the progression of trophic levels (for example, primary producer, primary consumer, secondary consumer, tertiary consumer, etc.).

fresh water Water with a total dissolved solids content less than 500 mg/L (0.5 parts per thousand salts).

fungi Microscopic or small nonchlorophyll-bearing, heterotrophic, plant-like organisms that lack roots, stems, or leaves, and typically grow in dark and moist environments.

geomorphology The land and submarine relief features of the earth.

grazer An organism that feeds on plants or animals attached to surfaces.

greenway A strip or belt of vegetated land often used for recreation, as a land use buffer, or to provide a corridor and habitat for wildlife.

groundwater Water that is located below the ground surface.

habitat The environment occupied by individuals of a particular species, population, or community.

heavy metals Metallic elements that are above 21 atomic weight on the periodic table.

herbaceous Plant parts that contain chlorophyll and are non-woody.

herbivore An animal that feeds primarily on plant tissues.

heterotrophic An organism that derives nutrition from organic carbon compounds.

hydraulic loading rate (HLR) A measure of the application of a volume of water to a land area with units of volume per area per time or simply reduced to applied water depth per time (for example, $m^3/(m^2/d)$ or cm/d).

hydraulic residence time (HRT) A measure of the average time that water occupies a given volume with units of time. The theoretical HRT is calculated as the volume divided by the flow (for example, $m^3/(m^2/d)$). The actual HRT is estimated based on tracer studies using conservative tracers such as lithium or dyes.

hydric soil A soil that is saturated, flooded, or ponded long enough during the growing season to develop anaerobic conditions. Hydric soils that occur in areas having indicators of hydrophytic vegetation and wetland hydrology are wetland soils.

hydrology A science dealing with the properties, distribution, and circulation of water on the land surface and in the soil, underlying rocks, and atmosphere.

hydrograph A record of the rise and fall of water levels during a given time period.

hydroperiod The period of wetland soil saturation or flooding. Hydroperiod is often expressed as a number of days or a percentage of time flooded during an annual period (for example, 25 days or 7 percent).

influent Water, wastewater, or other liquid flowing into a water body or treatment unit.

inorganic All chemicals that do not contain organic carbon.

invertebrate All animals that do not have backbones.

kinetics Pertaining to the rates at which changes occur in chemical, physical, and biological processes.

lacustrine The deepwater zone of a lake or reservoir.

lagoon Any large holding or detention pond, usually with earthen dikes, used to hold wastewater for sedimentation or biological oxidation.

leachate Liquid that has percolated through permeable solid waste and has extracted soluble dissolved or suspended materials from it.

lentic Pertaining to a lake or other non-flowing water body.

limnetic Relating to or inhabiting the open water portion of a freshwater body with a depth that light penetrates. The area of a wetland without emergent vegetation.

littoral The shoreward zone of a lake or wetland. The area where water is shallow enough to allow the dominance of emergent vegetation.

lotic Pertaining to flowing water bodies such as streams and rivers.

macrophyte Macroscopic (visible to the unassisted eye) vascular plants.

marsh A wetland dominated by herbaceous, emergent plants.

mass loading The total amount, on a mass or mass per area basis, of a constituent entering a system.

mesotrophic Water quality characterized by an intermediate balance of plant growth nutrients.

metabolism The chemical oxidation of organic compounds resulting in the release of energy for maintenance and growth of living organisms.

micronutrient A chemical substance that is required for biological growth in relatively low quantities and in small proportion to the major growth nutrients. Some typical micronutrients include molybdenum, copper, boron, cobalt, iron, and iodine.

microorganism An animal or plant that can only be viewed with the aid of a microscope.

mitigation The replacement of functional values lost when an ecosystem is altered. Mitigation can include replacement, restoration, and enhancement of functional values.

natural wetland A wetland ecosystem that occurs without the aid of humans.

nitrification Biological transformation (oxidation) of ammonia nitrogen to nitrite and nitrate forms.

nitrogen fixation A microbial process in which atmospheric nitrogen gas is incorporated into the synthesis of organic nitrogen.

nutrient A chemical substance that provides a raw material necessary for the growth of a plant or animal.

oligotrophic Water quality characterized by a deficiency of plant growth nutrients.

omnivore An animal that feeds on a mix of plant and animal foods.

organic Pertaining to chemical compounds that contain reduced carbon bonded with hydrogen, oxygen, and a variety of other elements. Organic compounds are typically volatile, combustible, or biodegradable and include proteins, carbohydrates, fats, and oils.

oxbow A bend in a river channel that over time becomes isolated from the river's main flow and contains water and wetland vegetation.

oxidation A chemical reaction in which the oxidation number (valence) of an element increases because of the loss of one or more electrons. Oxidation of an element is accompanied by the reduction of the other reactant and, in many cases, by the addition of oxygen to the compound.

oxygen sag The decrease in dissolved oxygen measured downstream of a relatively constant addition of an oxygen-consuming wastewater in a flowing water system.

palustrine All nontidal wetlands dominated by trees, shrubs, persistent emergents, emergent mosses, or lichens, and all such tidal wetlands in areas where salinity from ocean-derived salts is below 0.5 parts per thousand.

parasite An organism that lives within or on another organism and derives its sustenance from that organism without providing a useful return to its host.

peat Partially decomposed but relatively stable organic matter formed from dead plants in flooded environments.

peatland An area where the soil is predominantly peat.

periphyton The community of microscopic plants and animals that grows on the surface of emergent and submergent plants in water bodies.

perennial Persisting for more than one year. Perennial plant species persist as woody vegetation from year to year or resprout from their rootstock on an annual basis.

photic zone The area of a water body receiving sunlight.

photosynthesis The biological synthesis of organic matter from inorganic matter in the presence of sunlight and chlorophyll.

phytoplankton Microscopic algae that are suspended in the water column and are not attached to surfaces.

piezometric surface The surface elevation of pressurized groundwater within a well or in a spring.

plant community All of the plant species and individuals occurring in a shared habitat or environment.

plug flow Linear flow along the length of a wetland cell.

pocosin A southeastern coastal plain freshwater wetland typically occurring on poorly-drained, level lands between stream drainages. Pocosins are dominated by shrubs and trees adapted to periodic fires and have peat soils.

pretreatment (or preliminary treatment) The initial treatment of wastewater to remove substances that might harm downstream treatment processes or to prepare wastewater for subsequent treatment.

primary production The production of organic carbon compounds from inorganic nutrients. The energy source for this production is generally sunlight for chlorophyll-containing plants, but in some cases can be derived from reduced chemicals (chemoautotrophs).

primary treatment The first step in treatment of wastewaters. Primary treatment usually consists of screening and sedimentation of particulate solids.

protozoa Small, one-celled animals including amoebae, ciliates, and flagellates.

receiving water A water body into which wastewater or treated effluent is discharged.

reclaimed wastewater Wastewater that has received treatment sufficient to allow beneficial reuse.

redox potential The potential of a soil to oxidize or reduce chemical substances.

reduction A chemical reaction in which the oxidation state (valence) of a chemical is lowered by the addition of electrons. Reduction of a chemical is simultaneous with the oxidation of another chemical and frequently involves the loss of oxygen.

respiration The intake of oxygen and the release of carbon dioxide as a result of metabolism (biological oxidation of organic carbon).

restoration The return of an ecosystem from a disturbed or altered condition to a previously existing natural condition as a result of human action (for example, by fill removal).

rhizosphere The chemical sphere of influence of plant roots growing in flooded soils. Depending on the overall oxygen balance (availability and consumption), the rhizosphere can be oxidized, resulting in the presence of aerobic soil properties in an otherwise anaerobic soil environment.

riparian Pertaining to a stream or river. Plant communities occurring in association with any spring, lake, river, stream, creek, wash, arroyo, or other body of water or channel having banks and a bed through which waters flow at least periodically.

riverine wetlands Wetlands associated with rivers.

salinity A measure of the total salt content of water. Salinity is usually reported as parts per thousand (ppt). The salinity of normal seawater is about 35 ppt.

saturated soil Soil in which the pore space is filled with water.

secondary production The production of biomass by consumer organisms by feeding on primary producers or lower trophic level consumers.

secondary treatment Generally refers to wastewater treatment beyond initial sedimentation. Secondary treatment typically includes biological reduction in concentrations of particulate and dissolved concentrations of oxygen-demanding pollutants.

sediment Mineral and organic particulate material that has settled from suspension in a liquid.

seed bank The accumulation of viable plant seeds occurring in soils and available for germination under favorable environmental conditions.

sheet flow Water flow with a relatively thin and uniform depth.

short-circuit A faster, channelized water flow route that results in a lower actual hydraulic residence time than the theoretical hydraulic residence time.

shrub swamp Wetlands dominated by woody vegetation less than 6 meters (20 feet) tall. Plant species include shrubs, young trees, and trees that are small or stunted because of environmental conditions.

slough A slow-moving creek or stream characterized by herbaceous and woody wetland vegetation.

sludge The accumulated solids separated from liquids, such as water or wastewater, during the treatment process.

soil The upper layer of the earth that can be dug or plowed and in which plants grow.

stabilization pond A type of treatment pond in which biological oxidation of organic matter results by natural or artificially enhanced transfer of oxygen from the atmosphere to the water.

stage-area curve The relationship between the depth of water and the surface area of a wetland or lake.

stage-discharge curve The relationship between water depth and outflow from a body of water.

stemflow Rainfall intercepted by plant leaves and branches and traveling to the ground via stems and the trunk.

submerged plants Aquatic vascular plants or plants that grow below the water surface for all or a majority of their life cycles.

substrate Substances used by organisms for growth in a liquid medium. Surface area of solids or soils used by organisms to attach.

subsurface flow (SSF) Flow of water or wastewater through a porous medium such as soil, sand, or gravel.

succession The temporal changes of plant and animal populations and species in a given area following disturbance.

surface flow (SF) Flow of water or wastewater over the surface of the ground.

swamp A wetland dominated by woody plant species including trees and shrubs.

temperate zone The geographical area in the Northern Hemisphere between the Tropic of Cancer and the Arctic Circle and in the Southern Hemisphere between the Tropic of Capricorn and the Antarctic Circle. Temperate indicates that the climate is moderate and not extremely hot or cold.

terrestrial Living or growing on land that is not normally flooded or saturated.

tertiary treatment Wastewater treatment beyond secondary and often implying the removal of nutrients.

toxicity The adverse effect of a substance on the growth or reproduction of living organisms.

transition zone The area between habitats or ecosystems (see ecotone). Frequently, transition zone is used to refer to the area between uplands and wetlands. In other cases, wetlands are referred to as transitional areas between uplands and aquatic ecosystems.

transpiration The transport of water vapor from the soil to the atmosphere through actively growing plants.

trickling filter A filter with coarse substrate or media to provide secondary treatment of wastewater. Microorganisms attached to the filter media use and reduce concentrations of soluble and particulate organic substances in the wastewater.

trophic level A level of biological organization characterized by a consistent feeding strategy (for example, all primary consumers are in the same trophic level in an ecosystem).

tropical The geographical area between the Tropic of Cancer and the Tropic of Capricorn. An area characterized by little variation in day length and temperature. Most tropical areas have high annual average temperatures. Tropical areas may or may not have seasonably variable rainfall patterns.

TSS (total suspended solids) A measure of the filterable matter in a water sample.

upland Any area that is not an aquatic, wetland, or riparian habitat. An area that does not have the hydrologic regime necessary to support hydrophytic vegetation.

vegetation The accumulation of living plants within an area.

vertebrate An animal characterized by the presence of a spinal cord protected by vertebrae.

volatile Capable of being evaporated at relatively low temperatures.

watershed The entire surface drainage area that contributes runoff to a body of water.

water table The upper surface of the groundwater or saturated soil.

weir A device used to control and measure water or wastewater flow.

weir gate Water control device used to adjust water levels and measure flows simultaneously.

wetland An area that is inundated or saturated by surface or groundwater at a frequency, duration, and depth sufficient to support a predominance of emergent plant species adapted to growth in saturated soil conditions.

wetland function A physical, chemical, or biological process occurring in a wetland. Examples of wetland functions include primary production, water quality enhancement, groundwater recharge, organic export, wildlife production, and flood intensity reduction.

wetland mitigation bank A preserved, restored, constructed, or enhanced wetland that has been purposely set aside to provide compensation credits for losses of wetland functions caused by future human development activities as approved by regulatory agencies.

wetland structure The physical, chemical, and biological components of a wetland. Wetland structural components typically include wetland soils, macrophytes, surface water, detritus and microbes, and wetland animal populations.

wetland treatment system A wetland that has been engineered to receive water for the purpose of reducing concentrations of one or more pollutants.

wetland values Structural and functional attributes of wetlands that provide services to humans.

zonation The development of a visible progression of plant or animal communities in response to a gradient of water depth or some other environmental factor.

zooplankton Microscopic and small animals that live suspended in the water column.