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CHAPTER 3

Natural Systems for Treatment

INTRODUCTION

Natural treatment systems for wastewater management are differentiated from conventional systems based on the source(s) of energy that predominates in the two treatment categories (Figure 3-1). In conventional wastewater treatment systems, nonrenewable, fossil-fuel energies predominate in the treatment process. While conventional treatment relies largely on naturally occurring, biological pollutant transformations, these processes are typically enclosed in concrete, plastic, or steel basins and are powered by the addition of forced aeration, mechanical mixing, and/or a variety of chemicals. Because of the power intensity in conventional treatment systems, the physical space required for the biological transformations is reduced considerably compared to the area required for the same processes in the natural environment.

Natural treatment systems require the same amount of energy input for every kilogram of pollutant that is degraded as conventional biological treatment systems; however, the source of this energy is different in natural systems. Natural treatment systems rely (to a greater or lesser extent) on renewable, naturally occurring energies, including solar radiation; the kinetic energy of wind; the chemical-free energy of rainwater, surface water, and groundwater; and storage of potential energy in biomass and soils. Natural treatment systems are land intensive, while conventional treatment systems are energy intensive.

Figure 3-2 summarizes and contrasts the estimated construction and operation and maintenance costs for a conventional activated sludge treatment system capable of achieving advanced secondary effluent quality and a natural treatment system incorporating a facultative lagoon and a constructed wetland, both with a treatment capacity of 3786 m^3/d and with final disinfection. This example does not include the raw wastewater collection and pumping system necessary to deliver wastewater to either of these two systems.

In this highly simplified analysis, the conventional system requires about 2 ha of land area, $427/d of high-quality labor, energy, and chemical input, with a capital cost of about $4,112,000. The natural treatment system requires about 36 ha of land, $123/d of high-quality energies, and solar and wind energies that come with the land, with a capital cost of about $3,664,000. A detailed comparison of these options would need to analyze the total energies focused into this treatment process, including energy losses occurring during fossil-fuel use (coal and oil) to produce electricity and chemicals. Generally, however, this example provides a good illustration of how conventional and natural treatment processes are different in their individual mixes of energy and land area uses.

Conventional technologies have been an attractive alternative for wastewater treatment in many locations because they provide a compact, controllable method of pollution abatement where large amounts of fossil-fuel energies can be focused to deal with increasing wastewater flows and mass loads. Conventional treatment systems will continue to be used to deal with pollution control in many highly urbanized areas; however, some negative aspects of these energy-intensive systems are increasingly evident.

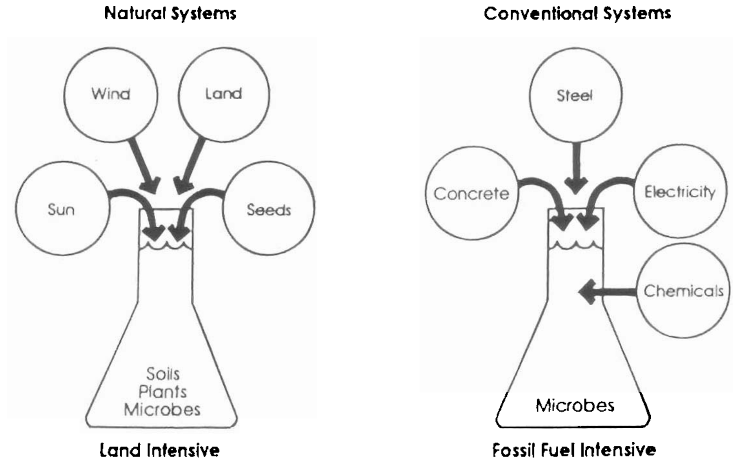


Figure 3-1 Comparison of the energy inputs to natural and conventional wastewater treatment technologies.

Three environmental consequences that are common to most conventional treatment systems include (1) depletion of nonrenewable resources, (2) ancillary environmental degradation associated with extraction and use of these nonrenewable resources, and (3) the fate of residual byproducts resulting from many conventional treatment technologies.

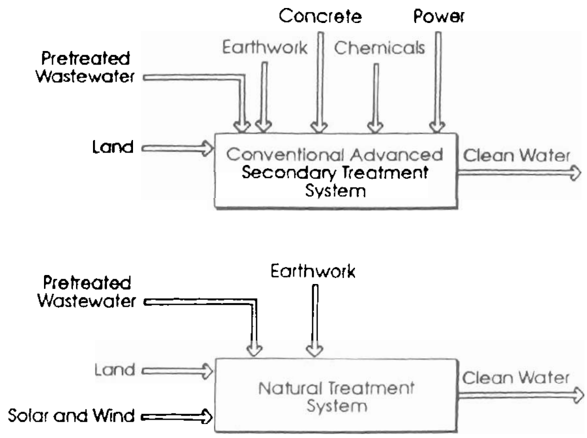
Fossil fuels are essentially nonrenewable resources and are being depleted over time. Any unessential use of fossil fuels will eventually eliminate their availability for more essential uses. For example, reaeration of wastewaters during secondary or advanced treatment can be accomplished by use of electricity to power mechanical aerators or alternatively by more land-intensive atmospheric diffusion. Use of fossil fuels (coal or oil) to generate electricity for aeration that could be provided naturally consumes a resource (electricity) that is irreplaceable for our electronic information society.

There is always an environmental effect associated with the extraction, refining, and transportation of fossil-fuel energies. Thus, use of electricity, plastics, concrete, and chemicals to reduce pollution at a conventional treatment facility results in some pollution elsewhere (Best, 1987). Many conventional treatment processes result in the formation of wastewater residuals or sludge, which in turn presents an environmental disposal problem. Thus, where natural treatment technologies are feasible, they offer the potential to reduce offsite and future environmental consequences associated with pollution control.

The goal of this chapter is to provide an overview of the natural treatment technologies that are currently in use. Treatment technologies included in the overall category of natural systems include onsite infiltration systems, slow-rate land application systems, rapid infiltration land treatment systems, overland flow treatment systems, wastewater stabilization pond systems, floating aquatic plant systems, and wetlands (Water Pollution Control Federation [WPCF], 1990b).

All of these natural treatment technologies are relatively land intensive; however, they have widely varying requirements for supplemental, fossil-fuel energy inputs; specific treatment capabilities; and different strengths and weaknesses for individual applications. Table 3-1 provides a comparison of design parameters and the cost of these natural wastewater treatment technologies.

This chapter contrasts wetland treatment techniques with those of the other land-intensive, natural treatment technologies to help the reader choose the most suitable alternative or group of alternatives for a given treatment need. Detailed information concerning the planning



Cost Category	Conventional[a] WWTP	Natural[b] Treatment System
Construction Costs ($)		
Mobilization & Administration	$ 95,000	$ 91,000
Earthwork (Cleaning, Grubbing, and Excavation)	381,000	1,336,000
Wetland Planting	0	309,000
Other Sitework (Electrical, Controls and Piping)	728,000	1,720,000
Conventional Primary	639,900	0
Conventional Activated Sludge	698,000	0
Sludge Handling	687,000	0
Biological Nitrification	476,000	0
Chlorination and Outfall	208,000	208,000
	$4,112,000	$3,664,000
Operation and Maintenance Costs ($/Year)		
Personnel	$ 63,000	$ 24,000
Utilities	23,000	5,000
Chemicals (including Disinfection)	23,000	11,000
Equipment/Supplies	47,000	5,000
	$156,000	$45,000

[a] Conventional activated sludge with nitrification and disinfection; costs from EPA (1978, 1983) adjusted to 1994.

[b] Faculative lagoon and constructed surface flow wetland with disinfection from EPA (1983) and West Jackson County, MS.

Figure 3-2 Generalized comparison of a conventional activated sludge nitrification advanced secondary treatment plant and a natural treatment system composed of a facultative lagoon and a constructed wetland, both treating 3786 m^3/d of secondary effluent to 10 mg/L BOD and TSS and 2 mg/L NH_4^+.

and design of these other natural treatment systems can be found in WPCF (1990b), Reed et al. (1988), Metcalf and Eddy (1991) Water Environment Federation (WEF) (1992), U.S. EPA (1981, 1984a), and others.

UPLAND NATURAL TREATMENT SYSTEMS

Onsite infiltration systems, slow- and high-rate land application systems, and overland flow systems all rely on the use of relatively well-drained upland areas for treatment (Figure

Table 3-1 Comparison of Natural Wastewater Treatment Technologies

			Design Parameters			Capital Costs					
Natural System Type	Pretreatment Requirements	Treatment Goals	Hydraulic Loading (cm/d)	Specific Treatment Area (ha/1000 m^3/d)	Water Depth (m)	$1,000/ ha	$/$m^3$/d	O&M Costs $/$m^3$	Disposal To	Advantages	Disadvantages
Onsite infiltration	Primary settling in septic or Imhoff tank	BOD_5 and TSS reduction (approximately secondary)	0.5–4.0	2.5–20	N.A.		1000–3000	0.01–0.10	Groundwater	Zero discharge; low energy use	Requires permeable, unsaturated soils; limited to small systems (<200 m^3/d)
Slow-rate land application	Primary or secondary	BOD_5, TSS, and nutrient reductions	0.15–1.6	6–67	N.A.	60–150	800–2000	0.10–0.20	Groundwater	Zero discharge	Requires permeable, unsaturated soils; high energy cost
High-rate land application	Primary or secondary	BOD_5 and TSS reduction	1.6–25	0.4–6	<1	300–600	450–900	0.05–0.10	Groundwater	Zero discharge; low energy use	Requires highly permeable, unsaturated soils; potential nitrate contamination
Overland flow	Primary or secondary	BOD_5 and TSS reduction	1–10	1–10	<0.1	240–400	600–1000	0.08–0.15	Surface water	Aerobic treatment; moderate energy use	Crop maintenance; TSS breakthrough
Facultative ponds	Primary	BOD_5 and TSS reduction	0.7–3.4	3–14	1.2–2.5	80–160	500–1000	0.07–0.13	Surface water	Aerobic/ anaerobic treatment; low energy use	High algal TSS in outflow; little operational control
Floating aquatic plant systems	Primary or secondary	BOD_5, TSS, and nutrient reduction	2–15	0.7–5	0.4–1.8	270	500–1000	0.12–0.14	Surface water	Phosphorus removal through harvesting	Anaerobic treatment; plant harvesting and disposal; pests
Wetlands	Primary, secondary, or advanced	BOD_5, TSS, and nutrient reduction	0.4–20	0.5–20	<0.6	25–250	500–1000	0.03–0.09	Surface water	Low energy; aerobic/ anaerobic treatment; wildlife habitat	Maintenance of plant populations; hydraulics in subsurface-flow systems

Note: Data from Water Pollution Control Federation (1990b). N.A.—not available.

3-3). All of these technologies use an unsaturated soil layer to provide either direct filtration and assimilation of pollutants or a rooting medium for growth of upland plants which filter wastewater solids and absorb dissolved pollutants for eventual harvest and removal.

Onsite and land application systems provide wastewater treatment coupled with ultimate discharge to groundwater. These systems are called "zero discharge" systems because they typically do not discharge, or only seasonally discharge, to surface waters. Overland flow treatment uses lower permeability, upland soils planted with a grass cover crop. Only a small fraction of the wastewater infiltrates to the groundwater in overland flow treatment, so this technology normally includes a discharge to surface waters.

ONSITE INFILTRATION

Onsite infiltration systems are the most numerous wastewater treatment systems in the U.S. Onsite systems include residential septic tanks and their associated drain fields and

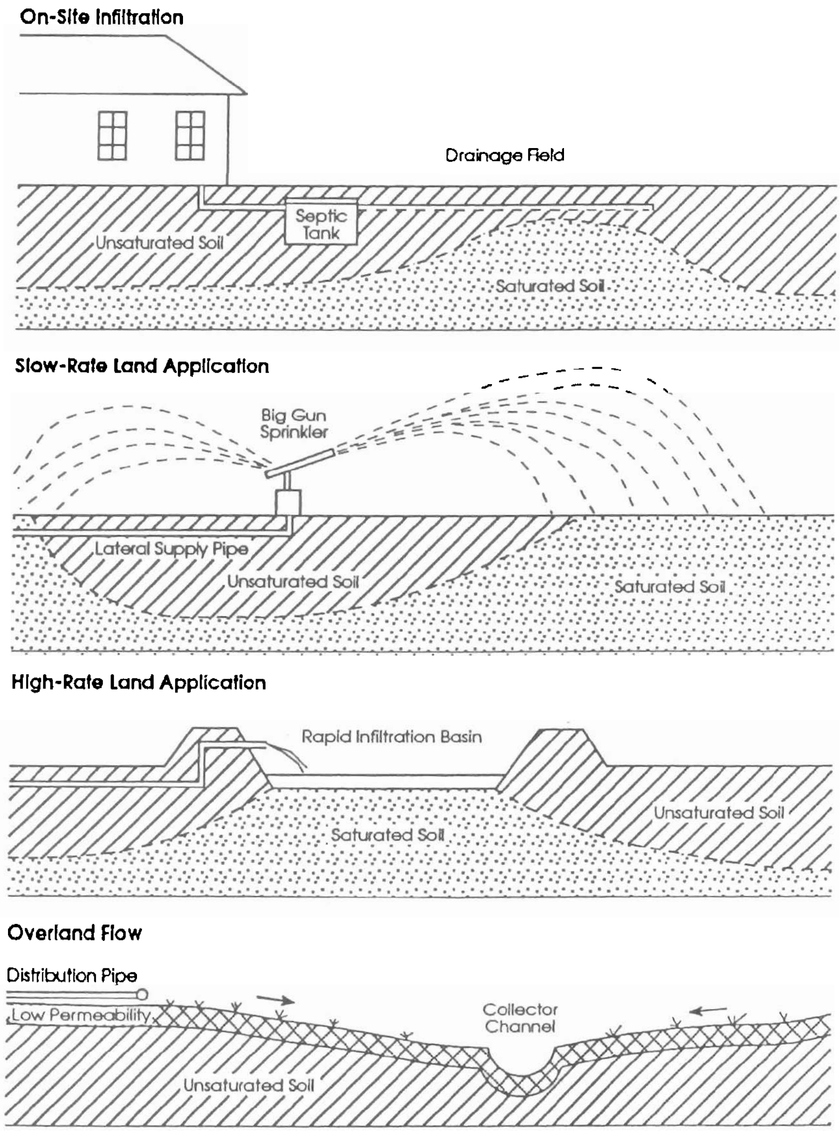


Figure 3-3 Diagrams of upland-based natural wastewater treatment technologies.

larger community systems consisting of a septic or Imhoff tank and a larger drainfield area. Typical flow rates to these systems are less than 200 m^3/d. Most single-family, onsite systems treat less than 1 m^3/d.

The septic tank provides a buried basin which is used for solids settling and anaerobic digestion of solids (Figure 3-4). Although only a small fraction of carbon and other wastewater constituents are removed by a septic tank, these constituents are partially transformed by anaerobic decomposition and converted to more stable particulate and dissolved forms before entering the leach lines.

The leach field consists of branched, perforated pipes surrounded by a highly porous media (typically coarse gravel) and buried in a permeable soil with a minimum of about 1.5 m of unsaturated zone above any existing shallow groundwater. The unsaturated zone can be constructed in areas with low permeability or high surficial groundwater by the use of a mound system using imported soil. The area necessary for a leach field is site specific and depends on existing soil and groundwater conditions. This area can be estimated by using Equation 3-1 from WPCF (1990b):

$$A = 1.5\ Q/k \tag{3-1}$$

where A = leach field area, m^2
Q = average wastewater flow, m^3/d
k = soil permeability, $m^3/m^2/d$

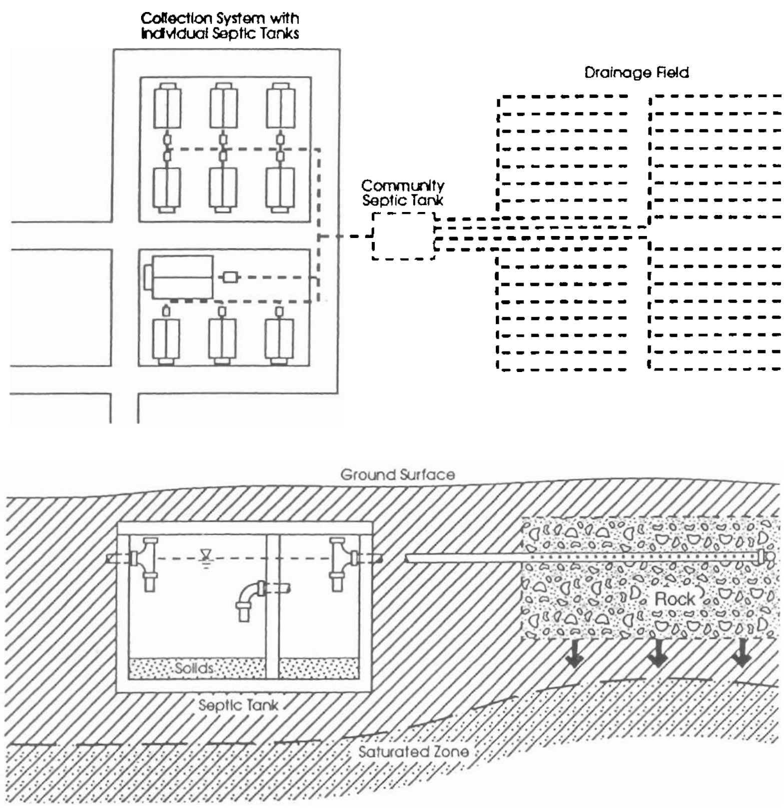


Figure 3-4 Schematic plan and section profiles of a small community onsite infiltration system.

Alternatively, WPCF (1990b) provides a range of hydraulic loading rates (cm/d) for onsite systems based on the texture of the upper 1 m of soil, ranging from 4 cm/d (2.5 ha/1000 m^3/d) for coarse to medium sand to 0.5 cm/d (20 ha/1000 m^3/d) for clays.

Hydraulic loading rate is directly related to the land area required for a given wastewater flow by the equation

$$A_s = 100/HLR \tag{3-2}$$

where A_s = specific treatment area for a given flow, $m^2/m^3/d$
HLR = hydraulic loading rate, cm/d

Onsite systems require relatively low capital investment and operational control. Typical capital cost is \$1000 to \$3000/m^3/d and operation cost is \$0.01 to \$0.1/m^3. However, onsite system design is more complicated and is subject to errors for larger systems because onsite systems typically operate continuously without resting and reestablishment of unsaturated soil conditions. Assumptions concerning the soil infiltrative capacity change radically when the application area is large compared to the wetted edge of the mound of applied wastewaters. Alternatively, slow- and high-rate land application system design accounts for this limitation by alternating application between different spray fields or infiltration basins.

SLOW-RATE LAND APPLICATION

Slow-rate land application of wastewaters uses irrigation of vegetated systems for wastewater polishing and ultimate disposal (Figure 3-5). Irrigation rates are generally low and intermittent, allowing reestablishment of aerobic soil conditions at regular intervals. These aerobic conditions are essential for growth of dry land vegetation which in turn is essential for nutrient removal, filtering of wastewater solids, and maintenance of permeable soil texture. Slow-rate systems are used to treat and dispose of both municipal and industrial wastewaters. More than 800 slow-rate land application systems currently exist in the U.S.

The slow-rate land application technology has a wide variety of process modifications and design criteria depending on project goals. In some cases, water disposal is the primary goal, and the maximum wastewater volume compatible with site characteristics and groundwater criteria is applied to a given land area. These systems frequently use cover crops for partial nutrient removal through harvesting and byproduct recovery. Commonly used cover crops include pasture grasses, corn, legumes, and pine trees. The hydraulic loading rate to this type of land application system is limited by either long-term sustainable soil permeability or by the concentration of the most limiting wastewater constituent at the point of compliance with groundwater standards. The design hydraulic loading rate can be increased by adding soil underdrains; however, underdrains significantly increase system cost and convert this zero discharge technology into an alternative with an intermittent or continuous surface discharge.

In other cases, slow-rate land application is used to irrigate golf courses and other human contact, landscaped areas following a high level of pretreatment. These systems use only enough water to satisfy the requirements of the cultivated plants and generally store or discharge excess wastewaters during periods of rainy weather. In areas with water shortages, treated wastewater becomes a valuable commodity to be conserved and is used sparingly for irrigation of crops or landscaped areas.

Slow-rate land application systems are typically designed with hydraulic loading rates between 0.15 and 1.6 cm/d (6 to 67 ha/1000 m^3/d). Detailed guidelines for calculating land areas for slow-rate land application systems are given by the U.S. EPA (1981), Reed et al. (1988), Metcalf and Eddy (1991), and WEF (1992). Wastewater is generally pumped to multiple irrigated areas and spread using sprinklers, center-pivot irrigators, or ridge and furrow irrigation techniques. Individual irrigation areas may receive water from less than

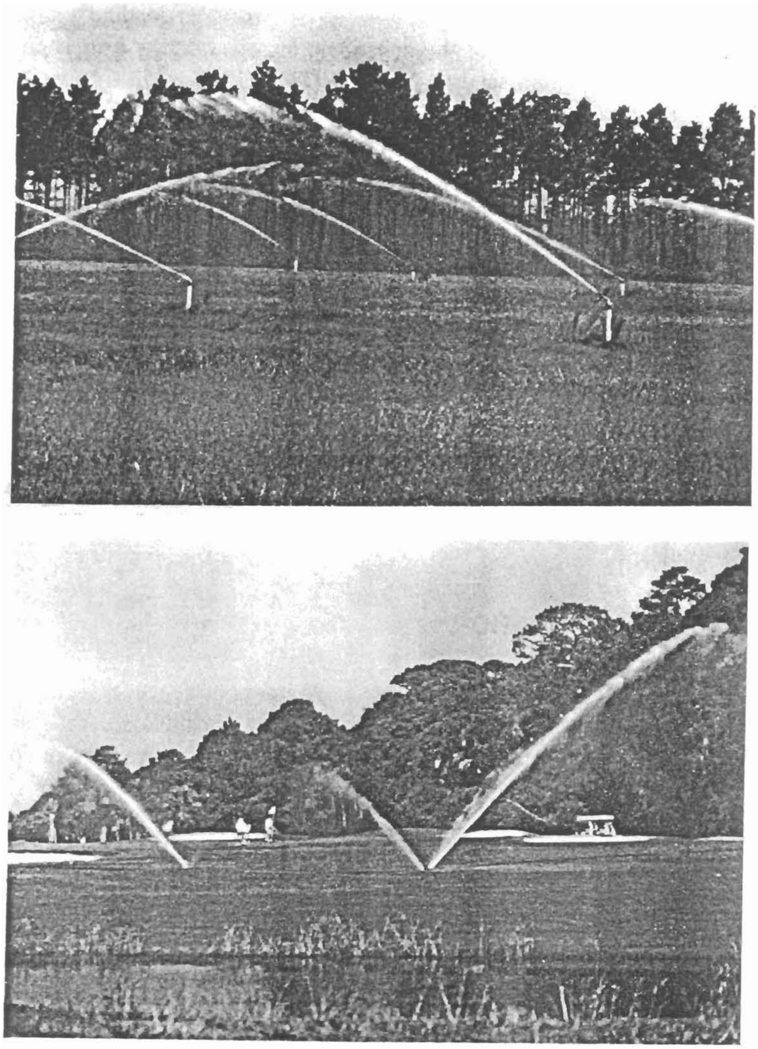


Figure 3-5 Two slow-rate land application systems.

once to three times per week. Irrigation is generally ceased if there is surface runoff observed from the application area.

The most common problems encountered with slow-rate land application systems are related to overestimation of the long-term soil infiltration capacity during periods of sustained irrigation. These problems are associated with the difficulty of establishing percolation rates during initial site investigations and with changes in soil structure that may occur during construction or operation of these systems. These types of problems are most commonly experienced in areas with clayey soils and in soils with higher seasonal groundwater levels that lack sufficient unsaturated capacity year round or develop low permeability strata through chemical and physical soil changes.

Because of the high land area requirements for slow-rate land application systems and because of the investment in piping and pumping necessary for wastewater distribution, these systems are generally the most costly of the natural system alternatives. Typical capital costs for system installation are about \$60,000 to \$150,000/ha (\$800 to \$2000/m^3/d), and operation and maintenance costs typically range from \$0.1 to \$0.2/m^3.

HIGH-RATE LAND APPLICATION (RAPID INFILTRATION)

High-rate land application systems use highly permeable soils for groundwater discharge (Figure 3-6). High-rate land application systems are generally designed as relatively small or narrow, shallow basins or ponds with berm heights less than 1.5 m. High-rate systems are typically loaded at hydraulic loading rates between 1.6 and 25 cm/d over the bottom area of the basins (0.4 to 6 ha/1000 m^3/d). Berm and buffer areas are additional.

Because of groundwater mounding that occurs beneath high-rate land application basins, a sustainable infiltration rate is a function of the ratio between the length of the basin edges and the bottom surface area. Smaller basin areas and higher length-to-width ratios increase this infiltration rate. Multiple basins are typically used to allow dry down and resting. A careful rotational schedule can eliminate problems occurring due to overlapping groundwater mounds beneath basins. During resting periods, basin permeability may be renovated by rototilling or harrowing. Alternatively, a water-tolerant ground cover crop can be planted in the basins to maintain soil texture and aeration.

At typical hydraulic loading rates, high-rate land application systems provide limited wastewater quality renovation. While a significant fraction of the particulate organic matter and nutrients present in the pretreated wastewater are removed, soluble fractions are generally not diminished. One of the potential problems that occurs with rapid infiltration systems is the oxidation of reduced nitrogen compounds in the aerobic soil zone with the potential for elevated nitrate nitrogen concentrations in receiving groundwaters. The other potential problem with high-rate land application is over optimism concerning long-term soil infiltration rates. A successful design requires careful measurement of infiltration capacity and conservative hydraulic loading rates.

Because of the potentially low land area requirements for high-rate land application systems and the relative ease of periodically applying wastewater to the basins, when technically and regulatorily feasible, this technology is less costly (on a flow basis) than slow-rate land application and most other natural treatment alternatives. Capital costs range from \$300,000 to \$600,000/ha or about \$450 to \$900/m^3/d. Operational and maintenance costs range from \$0.05 to \$0.10/m^3 (WPCF, 1990b).

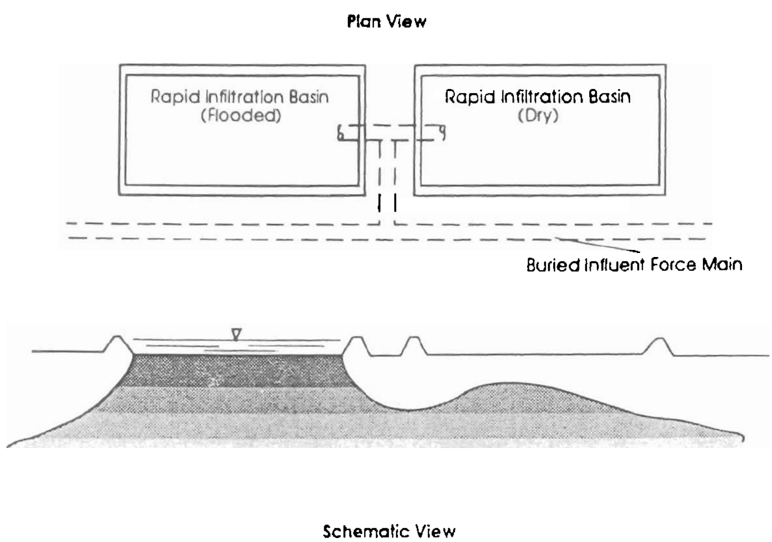


Figure 3-6 Diagram of a typical rapid infiltration system for municipal wastewater disposal.

OVERLAND FLOW SYSTEMS

Unlike other upland alternatives, overland flow treatment systems rely on low permeability soils to restrict infiltration and consequently have a surface discharge.

The conceptual basis of overland flow for treatment is illustrated in Figure 3-7. Pretreated (primary or secondary) wastewater is applied intermittently to the top of sloped, vegetated terraces by gated pipes or by spray nozzles and allowed to flow by gravity down the slopes to a series of collection channels. As water flows through the dense vegetation on the slope, particulate pollutants settle, and dissolved constituents are sorbed by plants and soils. Typically, wastewater application continues for 8 to 12 h out of every 24 h. During resting periods with no application, the organic fraction of the settled particulates is microbially oxidized, and sorbed nutrients are incorporated in biomass (primarily inorganic nitrogen and phosphorus), microbially transformed (nitrification of ammonia nitrogen to nitrate nitrogen), or bound in the soil layer.

Typically, overland flow slopes from 1 to 6 percent are graded by laser technology and are between 30 and 60 m in length. The width of slopes varies to provide the necessary wetted area to accomplish treatment goals. Typical average hydraulic application rates to overland flow systems range from 1 to 10 cm/d (1 to 10 ha/1000 m^3/d).

Overland flow systems are prone to operational problems in two areas: (1) maintenance of a viable cover crop and (2) violation of suspended solids criteria. Both of these problems can occur because of the difficulty of sustaining an even sheetflow on these slopes.

Ponding is likely to occur on overland flow terraces with low slopes, resulting in soil oxygen depletion and eventual death of desired cover crops. Alternatively, on higher slope terraces, erosion is likely to occur and result in high discharge concentrations of mineral sediments. A second factor that can contribute to suspended solids violations in overland flow systems is the relative inability of these systems to remove algal solids. When preceded by facultative or aerated lagoons with high algal production, overland flow systems have had difficulty consistently meeting total suspended solids limits.

Due to lower potential hydraulic loading rates and higher costs for plant maintenance and surface-discharge monitoring, overland flow systems are generally more expensive than high-rate land application systems. Typical costs for overland flow terrace construction are about $240,000 to $400,000/ha or $600 to $1000/m³/d (WPCF, 1990b). Operation and maintenance costs range from $0.08 to $0.15/m³.

AQUATIC AND WETLAND SYSTEMS

INTRODUCTION

Aquatic and wetland treatment systems are fundamentally different from upland systems because they are continuously flooded and typically develop an anaerobic sediment and soil

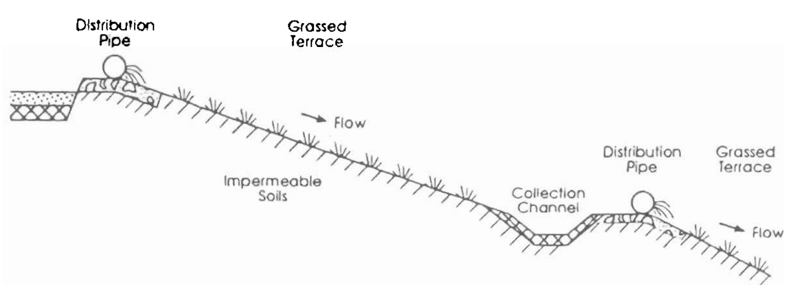


Figure 3-7 Diagram of a typical overland flow wastewater treatment system.

layer. This anaerobic condition excludes the growth of plant species that rely on abundant soil oxygen and results in the simultaneous occurrence of aerobic and anaerobic assimilation processes in a single, layered, natural treatment system. This section briefly describes and contrasts three types of natural, flooded, treatment systems: facultative ponds, floating aquatic plant-based systems, and wetland systems.

FACULTATIVE PONDS

Pond systems are one of the oldest and most widely used wastewater treatment technologies. Pond systems can be passive lagoons dominated by renewable energies from the sun, wind, and biota, or they can be highly sophisticated systems with liners and substantial forced aeration, in which case they are similar to conventional suspended growth treatment systems. This section only describes the lower energy, facultative (stabilization) pond approach to treatment (Figure 3-8).

Facultative ponds are designed to maintain a natural aerated surface layer over a deeper anaerobic layer. Natural aeration occurs because of the combined action of atmospheric oxygen diffusion and the release of oxygen during algal photosynthesis in the water column. Oxygen concentration may be highly variable over daily and seasonal periods within a facultative pond system. Excessive anaerobic conditions in a facultative pond are controlled by limiting the biochemical oxygen demand (BOD) loading rate. Typical design loading rates vary from about 14 to 50 kg BOD_5/ha/d with a detention time between 80 and 180 days (WEF, 1992).

Pond performance is typically a function of the effective hydraulic retention time, which in turn is related to flow dynamics and short circuiting. Multiple cell ponds typically are more effective, and flow curtains or cell configuration can be used to increase the ratio between actual and theoretical residence times. A typical depth for facultative ponds is about 1.2 to 2.5 m. Typical hydraulic loading rates range from about 0.7 to 3.4 cm/d (3 to 14 ha/ m^3/d) (WEF, 1992).

Conservatively designed and carefully operated facultative ponds are effective at consistently achieving reductions of biochemical oxygen demand. However, because of their reliance on algal growth, ponds have a fundamental limitation on attaining low suspended solids

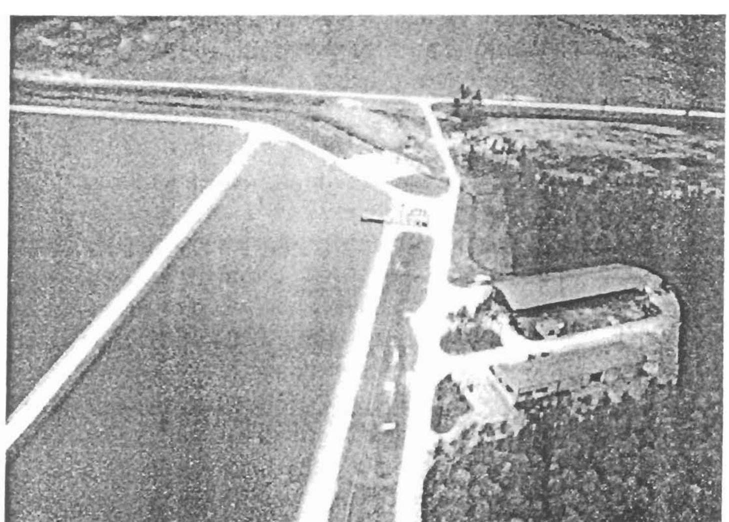


Figure 3-8 Photograph of a typical facultative pond wastewater treatment system.

outflow concentrations. These elevated levels of suspended solids (up to and exceeding 100 mg/L) contain a fraction of decomposable organics and nutrients, and, thus, facultative ponds do not produce tertiary quality water. Facultative ponds also have some potential for total nitrogen removal (Reed, 1985), but have little affect on total phosphorus concentrations.

Typical pond capital costs are about \$80,000 to \$160,000/ha, resulting in treatment costs of about \$500 to \$1000/m^3/d (WPCF, 1990b). Typical operation and maintenance costs range from \$0.07 to \$0.13/m^3.

FLOATING AQUATIC PLANT SYSTEMS

Pond systems can be purposely inoculated with floating aquatic plant species to provide wastewater treatment (Figure 3-9). Typical plant species that have been used in large-scale applications are water hyacinths (*Eicchornea crassipes*) and duckweed species (*Lemna, Spirodela,* and *Wolfiella*). Floating aquatic plant treatment systems are functionally different from facultative ponds because the photosynthetic component (floating aquatic plants as opposed to submerged planktonic algae) is releasing oxygen above the water surface, effectively reducing atmospheric oxygen diffusion. Consequently, floating aquatic plant systems are oxygen deficient, and aerobic processes are largely restricted to the plant root zone. The majority of the water column in floating aquatic plant systems is generally anaerobic, with the degree of oxygen depletion dependent on the organic loading rate.

Treatment occurs in floating aquatic plant systems through three primary mechanisms: (1) metabolism by a mixture of facultative microbes on the plant roots suspended in the water column and in the detritus at the pond bottom, (2) sedimentation of wastewater solids and of internally produced biomass (dead plants and microbes), and (3) incorporation of nutrients in living plants and subsequent harvest. Floating aquatic plant systems are typically effective at reducing concentrations of biochemical oxygen demand and total suspended

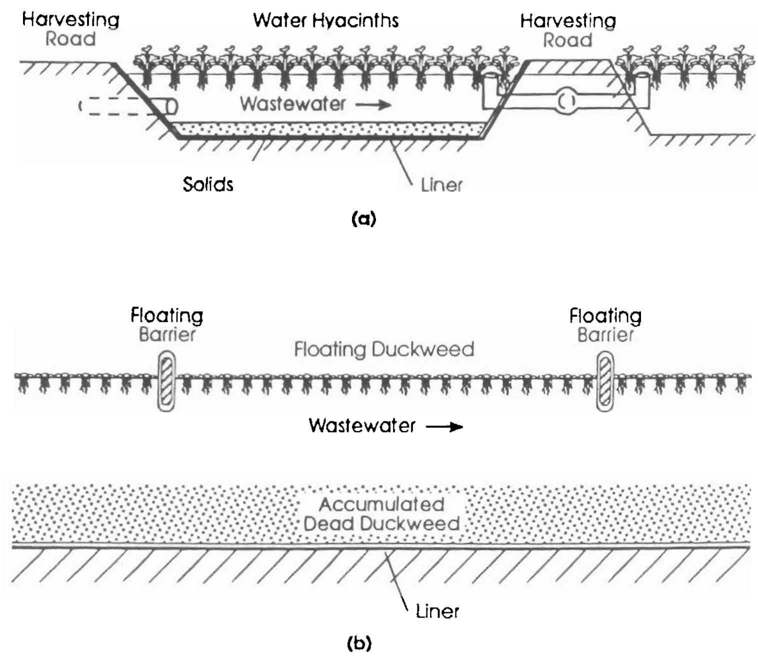


Figure 3-9 Diagram of typical floating aquatic plant treatment systems: (a) water hyacinth and (b) duckweed.

solids. Nitrate nitrogen may be effectively removed by denitrification. Total nitrogen and phosphorus removal can be consistently accomplished if the plants are harvested routinely.

Pond depth in floating aquatic plant systems is typically from 0.4 to 1.2 m for water hyacinth and 1.2 to 1.8 m for duckweed treatment systems. These systems can be used to provide secondary treatment, in which case biochemical oxygen demand mass loading should be limited to less than 100 kg/ha/d. When floating aquatic plant systems are used for advanced wastewater treatment and nutrient removal, organic loadings should be kept below 35 kg/ha/d. Typical hydraulic loading rates are in the range of 2 to 15 cm/d (0.7 to 5 ha/1000 m^3/d). Floating aquatic plant systems cost about $270,000/ha to build (capital costs are $500 to $1000/$m^3$/d), and operation and maintenance costs are about $0.12 to $0.14/$m^3$ (WPCF, 1990b).

Floating aquatic plant systems have some potential weaknesses that have limited their widespread use. Since these systems depend on one or just a few plant species for colonization of the pond surface, they are susceptible to catastrophic events which can kill part or all of these populations during a short time period. For example, water hyacinths are easily killed by cold weather and are attacked by numerous plant pest species. Duckweed is less sensitive to cold weather and pests, but it can also be killed by winter conditions. When plant cover is lost in a floating aquatic plant system, treatment effectiveness may be seriously impaired for a period of weeks or months as new plants are established.

A second potential problem with floating aquatic plant systems results from harvesting biomass for nutrient removal and for maintenance of plant growth at an optimum rate. These plants are more than 95 percent water when harvested so drying is required, and once dried there is typically a significant residual solids disposal problem.

WETLAND SYSTEMS

Wetland treatment systems use rooted, water-tolerant plant species and shallow, flooded, or saturated soil conditions to provide various types of wastewater treatment. The three basic types of wetland treatment systems include natural wetlands, constructed surface flow (SF) wetlands, and constructed subsurface-flow (SSF) wetlands (Figure 3-10).

While there are many types of naturally occurring wetlands, only those types with plant species that are adapted to continuous flooding are suitable for receiving continuous flows of wastewaters. Also, due to their protected regulatory status, discharges to natural wetlands must receive a high level of pretreatment (minimum of secondary). Constructed wetlands mimic the optimal treatment conditions found in natural wetlands, but provide the flexibility of being constructible at almost any location. They can be used for treatment of primary and secondary wastewaters as well as waters from a variety of other sources including stormwaters, landfill leachate, industrial and agricultural wastewaters, and acid-mine drainage.

Surface-flow wetlands (natural and constructed) are densely vegetated by a variety of plant species and typically have water depths less than 0.4 m. Open water areas may be incorporated into the design to provide for optimization of hydraulics and for wildlife habitat enhancement. According to the WPCF (1990b), typical hydraulic loading rates are between 0.4 to 4.0 cm/d (2.5 to 25 ha/1000 m^3/d) in natural wetlands and 0.7 to 5.0 cm/d (2 to 14 ha/1000 m^3/d) in constructed surface-flow wetlands.

Subsurface-flow wetlands use a bed of soil or gravel as a substrate for growth of rooted wetland plants. Pretreated wastewater flows by gravity, horizontally through the bed substrate where it contacts a mixture of facultative microbes living in association with the substrate and plant roots. Bed depth in SSF flow wetlands is typically less than 0.6 m, and the bottom of the bed is sloped to minimize that water flow overland.

Typical plant species used in SSF wetlands include common reed (*Phragmites australis*), cattail (*Typha* spp.), and bulrush (*Scirpus* spp.). Some oxygen enters the bed substrate by

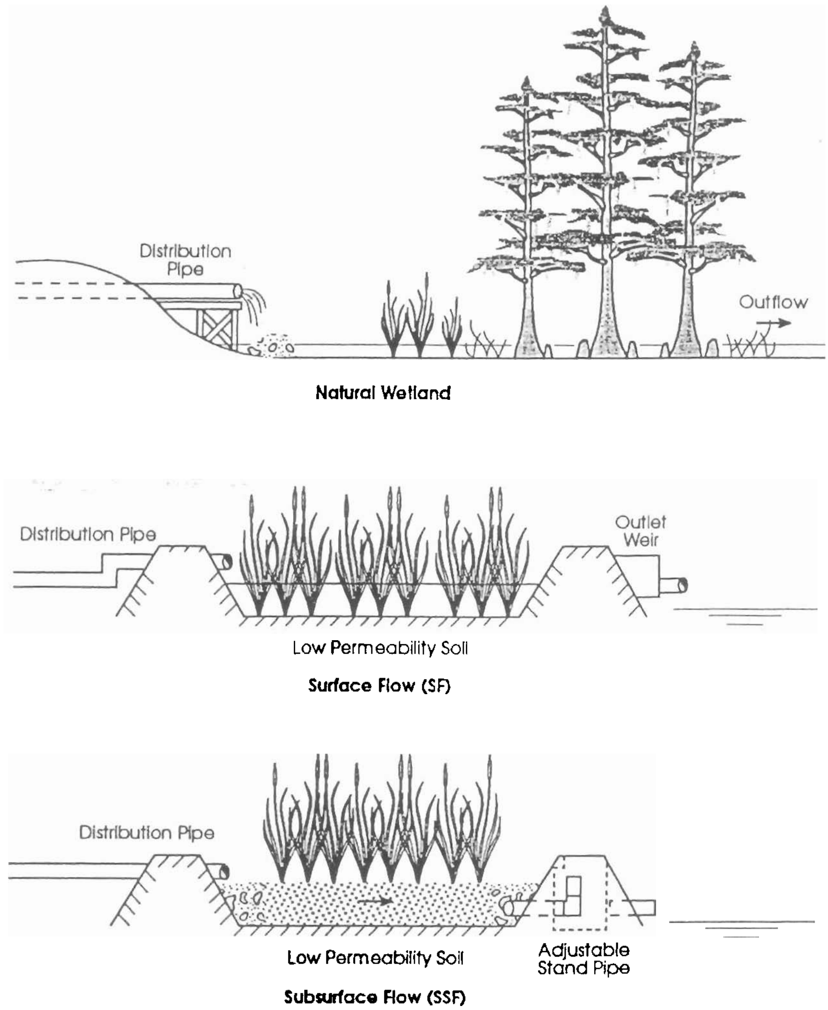


Figure 3-10 Diagram of three basic wetland treatment system types.

direct atmospheric diffusion and some through the plant leaves and root system, resulting in a mixture of aerobic and anaerobic zones. The majority of the saturated bed is anaerobic under most wastewater design loadings. According to the WPCF (1990b), typical hydraulic loading rates in SSF wetlands range from 2 to 20 cm/d (0.5 to 5 ha/1000 m^3/d).

Wetlands have been found to be effective in treating biochemical oxygen demand, suspended solids, nitrogen, and phosphorus, as well as for reducing metals, organics, and pathogens. Effective wetland performance depends on adequate pretreatment, conservative constituent and hydraulic loading rates, collection of monitoring information to assess system performance, and knowledge of successful operation strategies.

The most common difficulties experienced by wetland treatment systems have been related to maintaining partially aerated soil conditions. When wetland systems are overloaded by oxygen-demanding constituents or are operated with excessive water depth, highly reduced conditions occur in the sediments, resulting in plant stress and reduced removal efficiencies for biochemical oxygen demand and ammonia nitrogen. A common problem encountered in SSF constructed wetlands is inadequate hydraulic gradient and resulting surface flows.

Natural wetlands, when available, are typically the least expensive natural treatment alternative, requiring minimal capital expenditures for pumps, pipes, and water distribution structures in addition to the cost of the land itself. However, pretreatment and operational monitoring costs are typically higher for discharges to natural wetlands.

Constructed SF wetlands require a capital expenditure typically between $10,000 to $100,000/ha (20th and 80th percentile), primarily as a result of the earthwork costs. Subsurface flow wetlands are typically more expensive on a per area basis than SF systems, with capital costs from $100,000 to $200,000/ha (Knight et al., 1993a). Operation and maintenance costs for natural and constructed wetlands are primarily related to system monitoring and are generally low ($0.03 to $0.09/m^3) (WPCF, 1990b).

SUMMARY OF NATURAL TREATMENT TECHNOLOGIES

Table 3-1 summarizes and contrasts the principal features of natural wastewater treatment technologies. Each technology has strengths and weaknesses that must be considered during project planning and implementation. All of the natural treatment system technologies have the advantage of reducing the use of fossil fuels during construction and operation compared to conventional treatment systems. Where land is available, energy costs are expected to increase over time, and permit criteria do not preclude their use; natural treatment systems will often provide the most cost-effective and practicable alternatives.

Onsite infiltration systems have been the technology of choice for single households and small communities when soil percolation rates and groundwater levels are not limiting. These systems are relatively inexpensive, easy to install, and require little or no operation and infrequent maintenance. In some areas where groundwater levels are a constraint to percolation, the SSF wetland technology has been combined with septic tanks, resulting in an onsite system with periodic surface discharges. This alternative has been found to be preferable to mounded or failing drainfields where central sewage collection and treatment is not feasible.

Small- to medium-sized towns and cities have a number of natural treatment system options to consider. Where technically feasible and approved by regulating agencies, high-rate land application systems are generally the most cost-effective choice. They have moderate capital costs and low operation and maintenance costs. If suitable natural wetlands are available and approved, then they also represent a relatively low cost alternative for disposal, usually following a minimum of advanced secondary treatment. Natural wetland systems must be sized conservatively to minimize alterations of the existing biota (see Chapter 22 for a detailed approach to natural wetland treatment system design).

Facultative ponds, overland flow systems, and unharvested floating aquatic plant systems also offer a viable approach for small towns located adjacent to a receiving water with adequate assimilative capacity to accept secondarily treated wastewater. Where receiving waters do not have adequate capacity to directly discharge from a lagoon, overland flow system, or floating aquatic plant system, a constructed wetland can be added for advanced wastewater treatment. If surface discharge is not permittable and soils are only moderately permeable, a slow-rate land application system offers a final alternative for natural treatment at a reasonable cost.

Medium- to large-sized cities may believe that natural systems cannot be used for dealing effectively with their large wastewater flows. Medium- to large-sized cities, such as Arcata, CA; Orlando, FL; Lakeland, FL; and Columbia, MO have combined conventional technologies with natural systems to achieve very stringent discharge requirements in a cost-effective manner and also provide ancillary benefits to their citizens and surrounding environment by discharging to natural systems. When conventional technologies are used to provide a consistent, high-quality reclaimed water through tertiary treatment, this water can be used for beneficial reuse for humans (crop and landscape irrigation) and the environment (construction of habitat wetlands). When high levels of nutrient removal are required, harvested floating aquatic plant systems and constructed wetlands provide natural treatment technologies that do not create chemical sludges.

One last general point to make about natural treatment systems concerns both the designer and the regulator of these technologies. Land-intensive systems typically have longer hydraulic residence times (from about 3 to 200 days) than conventional systems (less than 1 to 2 days) and therefore are effective at modulation of erratic inflow volume and quality. However, because of their long hydraulic and solid residence times and because natural systems are typically outdoors and are spread over larger land areas that are susceptible to storms, wind, fires, insects, floods, and earthquakes, these natural systems are relatively slower to respond to operational changes and more apt to respond to natural events outside of the control of the system operator or owner. To achieve project success, both the engineer and the regulator must be aware of these differences between natural and conventional treatment systems.

The engineer who wishes to design natural systems should use conservative design criteria founded upon operational data from successful systems, and the regulator should provide realistic permit criteria that allow for normal daily, weekly, monthly, seasonal, or annual effluent quality variations typical of natural systems. The remainder of this book presents the information necessary to plan, design, and operate a successful wetland treatment system. The other texts referenced earlier provide information for the other natural treatment system technologies.