Chapter

1

Introduction to Land Application as a Treatment Process

Land treatment is defined as the application of partially treated wastewater or biosolids to the land at a controlled rate in a designed and engineered setting. The purpose of the activity is to obtain beneficial use of these materials, to improve environmental quality, and to achieve treatment and disposal goals in a cost-effective manner. In many cases the production and sale of crops can partially offset at least part of the cost of treatment. In arid climates the practice allows the use of wastewaters for irrigation and preserves higher-quality water sources for other purposes.

Disposal of wastes to the land has been an accepted and recognized cultural practice since time began. Stabilization and assimilation of body wastes in the soil are complete, and problems do not occur with low-density migratory populations of people or animals. The higher-density conditions that can cause problems have been documented since biblical times,[1] and these problems require a technique for management rather than random disposal. Controlled application of the wastes to the land emerged as a technology with the centralization of people in towns and cities. The earliest land application system documented in the literature was in Bunzlau, Germany,[2] where a sewage irrigation project was in operation for over 300 years, commencing in 1531. A system in the vicinity of Edinburgh, Scotland, began operation about 1650.[2] The value of the wastewater as a fertilizer for vegetables and other crop production was well recognized.

Land Application in North America

By the mid nineteenth century land application of wastes was considered to be the safest and most reliable method for waste disposal by the technical experts and regulatory officials of the time. The connection between contaminated water and disease was recognized, although the causative agents were not identified, so waste discharges to water supplies were avoided wherever possible. The first comprehensive reviews of wastewater disposal in the United States were by George Rafter of the U.S. Geological Survey. In a series of reports[3,4,5] from 1894 to 1899, he reviewed the status of wastewater treatment in the United States and Europe. Most of the 143 sewage treatment facilities in the United States and Canada as of 1899[3] were land treatment systems, as shown in Table 1.1.

Rafter drew the following conclusions from his studies (direct quotations):

- The most efficient purification method of sewage can be obtained by its application to land.
- On properly managed sewage farms the utilization of sewage is not prejudicial to health.

TABLE 1.1 Some Early Land Treatment Systems in the United States

Location	Date started	Area, acres
Boulder, Colo.	1890	—
Calumet City, Mich.	1888*	12
Woodland, Calif.	1889	240
Fresno, Calif.	1891*	4000
San Antonio, Tex.	1895	4000
Vineland, N.J.	1901*	14
Lubbock, Tex.	1915*	—
Bakersfield, Calif.	1912*	2400

*System still in operation.

- Sewage may be purified by broad irrigation in all seasons of the year at any place where the mean annual temperature of the coldest month is not lower than about 20 to 25°F.
- From the experience gained abroad it is clear that we may successfully cultivate almost any of the ordinary agricultural productions of the United States on sewage farms, due regard being had in every case to the special conditions for each particular crop.
- Sewage utilization should go hand in hand with purification. When operated with reference to all the necessary conditions, a proper degree of purification may be obtained as well as satisfactory utilization.
- The proper method of utilizing sewage is, for purposes of irrigation, by means which do not differ, except in matters of detail, from those of ordinary irrigation as practiced abroad for centuries.

Current status in the United States

The use of land treatment began to decline soon after Rafter published his reports, and by the 1960s the concepts were almost forgotten. By the time discussion again began in the early 1970s many of his conclusions were the subject of bitter debate and controversy. Jewell and Seabrook[2] traced the developmental history of land treatment and the long, but temporary, decline. Among the factors identified for the decline were pressures for alternative land uses, overloading due to incomplete technical understanding, and probably most important, the development of the germ theory for disease transmission, with the use of chlorine as a disinfectant which made it "safe" to discharge partially treated sewage to waterways.

By the early 1920s the focus had shifted to "modern methods of sewage treatment," and design criteria for trickling filters, activated sludge, and other technologies were all available. A considerable effort has been expended during the past 60 years to improve the efficiency of these "modern methods," but the basic design criteria remain about the same. By the late 1960s it was recognized that there was more to pollution than BOD and TSS, and it was decided that a strong federal role and funds would be needed to clean up the nation's waterways. Federal legislation, commencing with the Clean Water Act of

1972 (PL 92-500), proposed a "zero discharge " goal and encouraged a reuse and recovery philosophy. Land application of wastewater is the only economical way to achieve all of these goals, and so the concept was reborn. However, it was not accepted at the time by much of the engineering profession and the regulatory community, and so a very significant research and development effort was undertaken to reconfirm the conclusions that were obvious to Rafter and to develop criteria for reliable and cost-effective design, construction, and operation. As a result of these efforts, land treatment has been reestablished as an acceptable waste management technology and is now routinely considered by planners and engineers.

In Rafter's time sewage treatment systems were typically found only at the larger, more sophisticated metropolitan centers that could not discharge to an ocean. Except in special cases it is unlikely that land treatment would be the sole method of treatment for the very large metropolitan centers that exist today. The costs and the jurisdictional problems in developing a single very large system would be difficult to resolve. However, there are no technical constraints on the size of a land treatment system. As will be shown in the remaining chapters of this book, land treatment can be a viable and cost-effective choice for industries and commercial activities, small towns, moderately large cities, and for portions of large metropolitan areas.

The design approach for land treatment systems is essentially empirical, based on observation of successful performance followed by derivation of criteria and mathematical expressions predicting performance expectations. Use of the criteria in this book should produce reliable, cost-effective, and conservative designs for municipal and industrial wastes.

Purpose and Organization of This Book

Portions of this book were first published in 1984,[6] but that book has been out of print for at least 20 years. The U.S. Environmental Protection Agency[7,8] also published design manuals on land treatment of wastewaters in the early 1980s, but those have not been updated. The Water Environment Federation (WEF) published a *Manual of Practice*[9] in 1989 which contained chapters on land treatment of wastewater. A new generation of planners, designers, and regulators are now responsible for waste management decisions, so it is appropriate to again offer, in a single text, up-to-date and expanded criteria for design, construction, and operation of these land treatment concepts.

This book contains 17 chapters; basic technical information applicable to all concepts can be found in Chaps. 2 through 9. Chapters 10, 11, and 12 are each devoted to one of the major land treatment concepts: slow rate (SR), overland flow (OF), and rapid infiltration (RI). Chapter 13 provides information on land treatment of industrial wastewaters, and Chaps. 14 and 15 cover costs, energy, operation, and maintenance. Chapter 16 describes on-site, small-scale systems and wetlands systems, and Chap. 17 covers land application of biosolids.

References

1. *Deuteronomy,* Chap. 23, verses 12–14.
2. Jewell, W. J., and B. L. Seabrook, "A History of Land Application as a Treatment Alternative," U.S. Environmental Protection Agency, EPA OWPO, Washington, D.C., 1979.
3. Rafter, G. W., and M. N. Bayer, *Sewage Disposal in the United States,* U.S. GPO, Washington, D.C., 1894.
4. Rafter, G. W., "Sewage Irrigation," in *Water Supply and Irrigation Papers,* U.S. Geological Survey Report 3, U.S. GPO, Washington, D.C., 1897.
5. Rafter, G. W., "Sewage Irrigation," in *Water Supply and Irrigation Papers,* Part II, U.S. Geological Survey Report 22, U.S. GPO, Washington, D.C., 1899.
6. Reed, S. C., and R. W. Crites, *Handbook of Land Treatment Systems for Industrial and Municipal Wastes,* Noyes Publications, Park Ridge, N.J., 1984.
7. U.S. Environmental Protection Agency, "Land Treatment of Municipal Wastewater," EPA 625/1-81-013, U.S. Environmental Protection Agency CERI, Cincinnati, Ohio, 1981.
8. U.S. Environmental Protection Agency, "Land Treatment of Municipal Wastewater—Supplement on Rapid Infiltration and Overland Flow," U.S. Environmental Protection Agency CERI, EPA 625/1/81-013a, Cincinnati, Ohio, 1984.
9. Water Environment Federation, *Natural Systems for Wastewater Treatment. Manual of Practice.* WEF, Alexandria, Va., 1989.

Chapter

2

Basic Technology and Design Approach

Concepts

Land treatment is defined as the controlled application of wastes onto the land surface to achieve a specified level of treatment through natural physical, chemical, and biological processes within the plant-soil-water matrix. The basic wastewater concepts include slow rate (SR), rapid infiltration (RI), and overland flow (OF). These titles were selected to reflect the rate of water movement and the flow path within the process. In addition to these basic wastewater processes, there are criteria in later chapters for combined systems, wetlands and other alternative technologies, on-site and small-scale systems, and land application of biosolids.

Site characteristics

The desirable site characteristics for the three wastewater processes are given in Table 2.1. These are not limits to be adhered to rigorously, but rather typical ranges based on successful experience.

Design features

Typical design criteria for the three land treatment processes are compared in Table 2.2. The range of values given represents

TABLE 2.1 Site Characteristics for Land Treatment Processes

Parameter	Slow rate (SR)	Rapid infiltration (RI)	Overland flow (OF)
Grade	20%, cultivated site 40%, uncultivated	Not critical	2 to 8% for final slopes
Soil permeability	Moderate	Rapid	Slow to none
Groundwater depth	2–10 ft	3 ft during application 5–10 ft during drying	Not critical
Climate	Winter storage in cold climates	Not critical	Same as SR

TABLE 2.2 Typical Design Features for Land Treatment Processes

Parameter	Slow rate (SR)	Rapid infiltration (RI)	Overland flow (OF)
Application method	Sprinkler or surface	Usually surface	Sprinkler or surface
Annual loading, ft	2–20	20–400	10–70
Treatment area for 1 mgd, acres	60–700	7–60	15–110
Weekly application, in	0.5–4	4–96	2.5–16
Minimum preliminary treatment	Primary	Primary	Grit removal and comminution
Need for vegetation	Required	Grass sometimes used	Water-tolerant grasses

successful experience in a variety of locations in the United States. Chapters 10, 11, and 12 contain the procedures for developing site-specific criteria for planning, evaluation, and final system design.

Performance expectations

The expected effluent quality from the three basic land treatment processes is shown in Table 2.3 for the most common wastewater parameters. The fate of metals, trace elements, salts, and the more complex organic compounds is discussed in Chap. 3. The average values in Table 2.3 result from the treatment that will occur within the immediate plant-soil matrix with no credit for mixing, dispersion, or dilution with the groundwater or further travel in the subsoil. Phosphorus, for example, can be reduced at least another order of magnitude for RI systems with additional travel through the soil.

TABLE 2.3 Expected Effluent Water Quality from Land Treatment Processes (mg/L Unless Otherwise Noted)

Parameter	Slow rate (SR)	Rapid infiltration (RI)	Overland flow (OF)
BOD_5	<2	5	10
TSS	<1	2	10
NH_3/NH_4 (as N)	<0.5	0.5	<4
Total N	3	10	5
Total P	<0.1	1	4
Fecal coli (number/100 mL)	0	10	200+

Slow Rate Process

Slow rate (SR) land treatment is the controlled application of wastewater to vegetated land surface at a rate typically measured in terms of a few inches of liquid per week (see Fig. 2.1). The design flow path depends on infiltration, percolation, and usually lateral flow within the boundaries of the treatment site. Treatment occurs at the soil surface and as the wastewater percolates through the plant root-soil matrix. Depending on the specific system design, some to most of the water may be used by the vegetation, some may reach the groundwater, and some may be recovered for other beneficial uses. Off-site runoff of any of the applied wastewater is specifically avoided by the system design. The hydraulic pathways of the applied water can include:

- Vegetation irrigation with incremental percolation for salt leaching
- Some vegetative uptake with percolation the major pathway
- Percolation to underdrains or wells for water recovery and reuse
- Percolation to groundwater and/or lateral subsurface flow to adjacent surface waters

Wastewater applications can be via ridge and furrow or border strip flood irrigation or with sprinklers using fixed nozzles or moving sprinkler systems. The selection of the application method is dependent on site conditions and process objectives and is discussed in detail in Chaps. 9 and 10. The surface vegetation is an essential component in all SR systems and criteria are given in Chap. 5; site selection criteria, design details, and management criteria are given in Chaps. 6, 10, and 15, respectively.

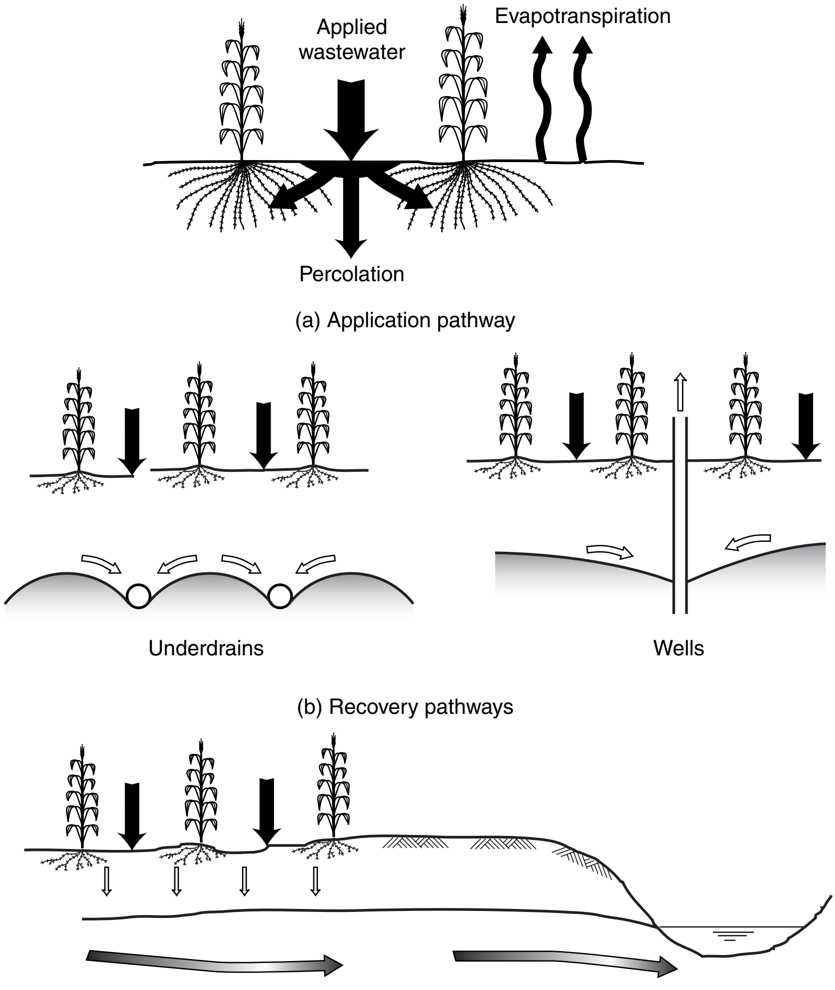


Figure 2.1 Hydraulic pathways for slow rate (SR) land treatment. (*After Ref. 12.*)

Slow rate land treatment can be operated to achieve a number of objectives including:

- Treatment of the applied wastewater
- Economic return from the use of water and nutrients to produce marketable crops
- Exchange of wastewater for potable water for irrigation purposes in arid climates to achieve overall water conservation

- Development and preservation of open space and greenbelts.

These goals are not mutually exclusive, but it is unlikely that all can be brought to an optimum level within the same system. In general, maximum cost-effectiveness for both municipal and industrial systems will be achieved by applying the maximum possible amount of wastewater to the smallest possible land area. That will in turn limit the choice of suitable vegetation and possibly the market value of the harvested crop. In the more humid parts of the United States optimization of treatment is usually the major objective for land treatment systems. Optimization of agricultural potential or water conservation goals are generally more important in the more arid western portions of the United States.

Optimization of a system for wastewater treatment usually results in the selection of perennial grasses because a longer application season, higher hydraulic loadings, and greater nitrogen removals are possible compared to other agricultural crops. Annual planting and cultivation can also be avoided with perennial grasses. However, corn and other crops with higher market values are also grown on systems where treatment is a major objective. Muskegon, Mich.,[11] is a noted example, with over 5000 acres of corn, alfafa, and soybeans under cultivation.

Forested systems also offer the advantage of a longer application season and higher hydraulic loadings than typical agricultural crops but may be less efficient than perennial grasses for nitrogen removal depending on the type of tree, stage of growth, and general site conditions. Early research at the Pennsylvania State University[2] established the basic criteria for full-scale forested systems. Subsequent work in Georgia, Michigan, and Washington State further refined the criteria for regional and species differences.[3] A large-scale slow rate forested system in Clayton County, Georgia, designed for 20 mgd, has been in continuous operation since 1981.[9] The largest operational land treatment system in the United States is the 8000-acre forested system in Dalton, Ga.

Rapid Infiltration Process

Rapid infiltration (RI) land treatment is the controlled application of wastewater to earthen basins in permeable soils at a rate typically measured in terms of feet of liquid per week. As shown in Table 2.2, the hydraulic loading rates for RI are usually at least an order of magnitude higher than for SR systems. Any surface vegetation that is present has a marginal role for treatment owing to the high hydraulic loadings. However, vegetation is sometimes critical for stabilization of surface soils and the maintenance of acceptable infiltration rates. In these cases, water-tolerant grasses are typically used. Treatment in the RI process is accomplished by biological, chemical, and physical interactions in the soil matrix, with the near surface layers being the most active zone.

The design flow path involves surface infiltration, subsurface percolation, and lateral flow away from the application site (see Fig. 2.2). A cyclic application, as described in Chap. 12, is the typical operational mode with a flooding period followed by days or weeks of drying. This allows aerobic restoration of the infiltration surface and drainage of the applied percolate. The geohydrological aspects of the RI site are more critical than for the other processes, and a proper definition of subsurface conditions and the local groundwater system is essential for design.

The purpose of a rapid infiltration system is wastewater treatment, so the system design and operating criteria are developed to achieve that goal. However, there are several alternatives with respect to the utilization or final disposal of the treated water:

- Groundwater recharge
- Recovery of treated water for subsequent reuse or discharge
- Recharge of adjacent surface streams
- Seasonal storage of treated water beneath the site with seasonal recovery for agriculture

The recovery and reuse of the treated RI effluent is particularly attractive in arid regions, and studies in Arizona, California, and Israel[1,5,12] have demonstrated that the recovery of the treated water is suitable for unrestricted irrigation on any type of crop. Groundwater recharge may also be attractive, but special attention is required for nitrogen if drinking water aquifers are involved. Unless special measures (described in Chap. 12) are employed, it is unlikely that drinking water levels for nitrate nitrogen (10 mg/L as N) can be routinely attained immediately beneath the application zone with typical municipal waste-

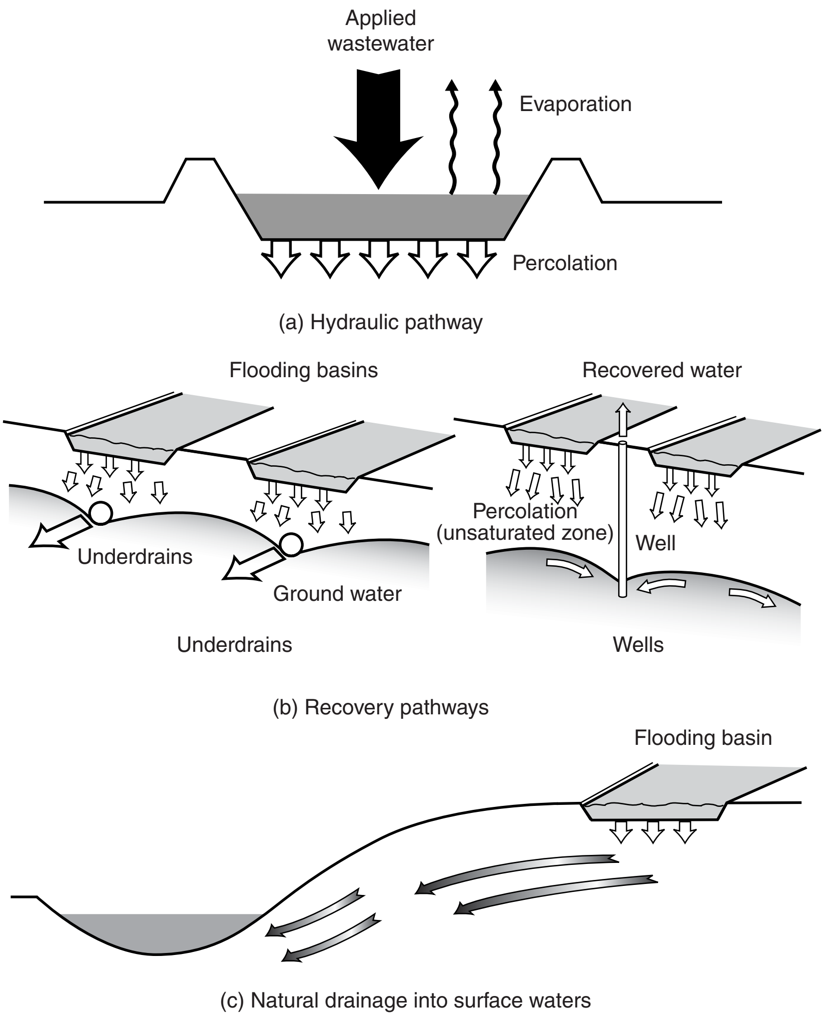


Figure 2.2 Hydraulic pathways for rapid infiltration (RI). (*After Ref. 12.*)

waters. If special measures are not employed, there must then be sufficient mixing and dispersion with the native groundwater prior to the downgradient extraction points. In the more humid regions neither recovery nor reuse is typically considered. In these cases groundwater impacts can often be avoided by locating the RI site adjacent to a surface water body. The quality of the subflow entering the surface water will generally exceed that which could be produced by an advanced wastewater treatment plant.

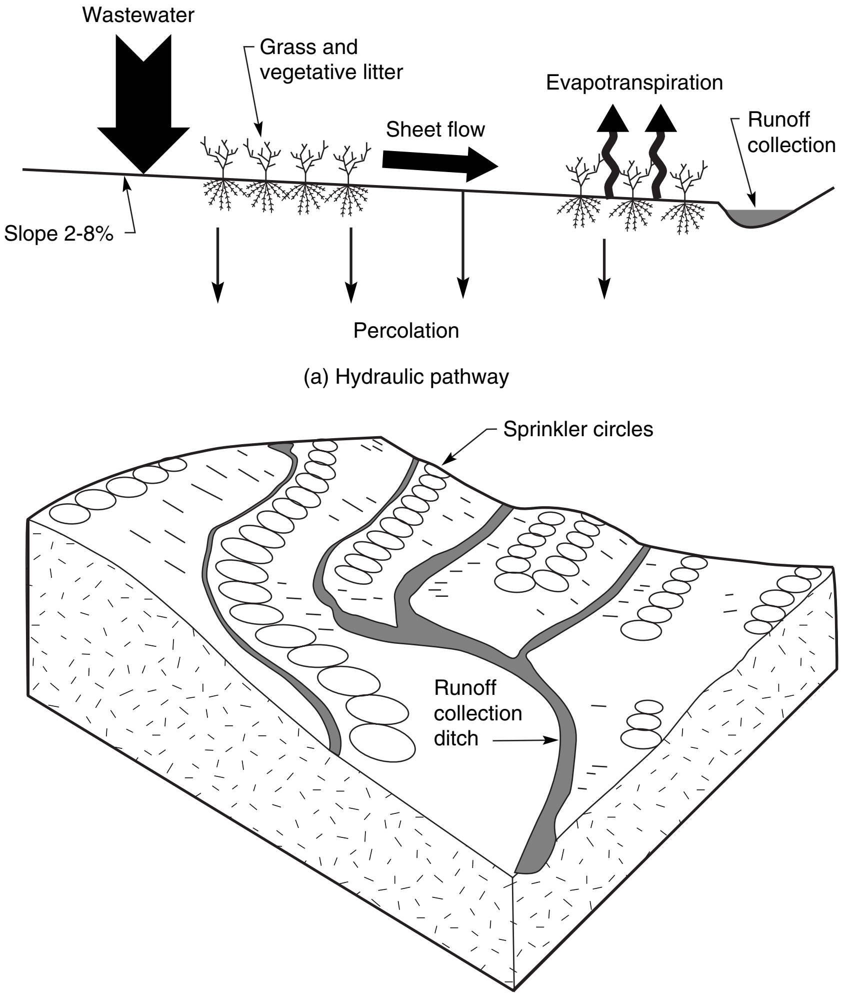
Overland Flow Process

Overland flow (OF) is the controlled application of wastewater to relatively impermeable soils on gentle grass covered slopes. The hydraulic loading is typically several inches of liquid per week and is usually higher than for most SR systems. Since costs tend to be directly related to hydraulic loading, OF systems are usually more cost-effective than SR systems for equivalent water quality requirements. Vegetation, consisting of perennial grasses, is an essential component in the OF system, for its contribution both to slope stability and erosion protection and to its function as a treatment component.

The design flow path is essentially sheet flow down the carefully prepared vegetated surface with runoff collected in ditches or drains at the toe of each slope (see Fig. 2.3). Treatment occurs as the applied wastewater interacts with the soil, the vegetation, and the biological surface growths. Many of the treatment responses are similar to those occurring in trickling filters and other attached growth processes. Wastewater is typically applied from gated pipe or nozzles at the top of the slope or from sprinklers located on the slope surface. Industrial wastewaters and those with higher solids content typically use the latter approach. A small portion of the applied water may be lost to deep percolation and a larger fraction to evapotranspiration, but the major portion is collected in the toe ditches and discharged, typically to an adjacent surface water. The SR and RI concepts may include percolate recovery and discharge but the OF process almost always includes a surface discharge, and the necessary permits are required. The purpose of overland flow is cost-effective wastewater treatment. The harvest and sale of the cover crop may provide some secondary benefit and help offset operational costs, but the primary objective is treatment of the wastewater. Chapter 11 presents detailed design procedures. One of the largest municipal overland flow systems in the United States was in Davis, Calif.,[10] designed for 5 mgd flow.

Limiting Design Parameter Concept

The design of all land treatment systems, wetlands, and similar processes is based on the limiting design parameter (LDP) con-



(a) Hydraulic pathway

(b) Pictorial view of sprinkler application

Figure 2.3 Hydraulic pathways for overland flow (OF). (*After Ref. 12.*)

cept. The LDP is the factor or the parameter, which controls the design and establishes the permissible size and loadings on a particular system. If a system is designed for the LDP, it will then function successfully for all other parameters of concern. Detailed discussions on the interactions in land treatment systems with the major wastewater constituents can be found in Chap. 3. Experience has shown that the LDP for systems that depend on significant infiltration, such as SR and RI, is either the hydraulic capacity of the soil or the ability to remove nitrogen to the specified level, when typical municipal wastewaters are applied. Whichever of these two parameters requires the largest treatment area controls design as the LDP, and the system should then satisfy all other performance requirements. Overland flow, as a discharging system, will have an LDP which depends on the site-specific discharge limits, and the parameter which requires the largest treatment area controls the design. Determining the LDP for treatment of industrial wastes can be more difficult because of the complex nature of some of these wastes; Chap. 13 and similar sources[4,7] can be consulted to identify the LDP for a particular industry.

References

1. Idelovitch, E., "Unrestricted Irrigation with Municipal Wastewater," in *Proceedings, National Conference on Environmental Engineering,* American Society of Civil Engineers, Atlanta, Ga., July 8–10, 1981.
2. Kardos, L. T., *Renovation of Secondary Effluent for Reuse as a Water Resource,* U.S. Environmental Protection Agency CERI, EPA 660/2-74-016, Cincinnati, Ohio, 1974.
3. McKim, H. L., *Wastewater Application in Forest Ecosystems,* Report 82-19, U.S. CRREL, Hanover, N.H., 1982.
4. Middlebrooks, E. J., *Industrial Pollution Control,* Vol. 1, *Agro Industries,* John Wiley & Sons, New York, 1979.
5. Olson, J. V., R. W. Crites, and P. E. Levine, "Groundwater Quality at a Rapid Infiltration Site," *Journal of Environmental Engineering Division,* **106**(5):885–889, American Society of Civil Engineers, 1980.
6. Overcash, M. E., and D. Pal, *Design of Land Treatment Systems for Industrial Water—Theory and Practice,* Ann Arbor Science, Ann Arbor, Mich., 1979.
7. Parr, J. F., P. B. Marsh, and J. M. Kim, *Land Treatment of Hazardous Wastes,* Noyes Publications, Park Ridge, N.J., 1983.
8. Reed, S. C., R. W. Crites, and E. J. Middlebrooks, *Natural Systems for Waste Management and Treatment,* 2d ed., McGraw-Hill, New York, 1995.
9. Reed, S. C., and R. K. Bastian, "Potable Water via Land Treatment and AWT," *Water Environment & Technology,* **3**(8):40–47, Water Environment Federation, Alexandria, Va., 1991.
10. Smith, R. G., and E. D. Schroeder, "Physical Design of Overland Flow Systems," *Journal WPCF,* **55**(3):255–260, Water Environment Federation, Alexandria, Va., 1983.
11. U.S. Environmental Protection Agency, "Muskegon County Wastewater Management System," EPA 905/2-80-004, U.S. Environmental Protection Agency Great Lakes Programs Office, Chicago, Ill., 1980.
12. U.S. Environmental Protection Agency, *Process Design Manual for Land Application of Municipal Wastewater,* U.S. Environmental Protection Agency CERI, Cincinnati, Ohio, 1981.

Chapter 3

Wastewater Parameters and System Interactions

The design approach for any land treatment system is based on the limiting design parameter (LDP) as introduced in Chap. 2. The LDP may be the ability of the soil profile to pass the desired amount of water, or the ability to remove a pollutant to desired levels, or the long-term accumulation of some substance in the soil. Land treatment differs from mechanical wastewater treatment processes in that removal of metals and similar substances is very effective, but these materials may then remain within the soil matrix and their long-term accumulation may limit the useful life of the site and/or its future use for agricultural purposes.

An understanding of the basic interactions between the wastewater parameters of concern and the soil treatment system is essential for the determination of the LDP for a particular design. These interactions are generally the same for all of the land treatment processes and are therefore discussed together in this introductory chapter. The major pollutants of concern can be grouped in nine major categories:

- Biochemical oxygen demand (BOD_5)
- Total suspended solids (TSS)
- Pathogenic organisms
- Oil and grease
- Metals

- Nitrogen
- Phosphorus
- Inorganic trace elements and salts
- Persistent organics

Biochemical Oxygen Demand

All land treatment concepts are very efficient at removal of biodegradable organics, typically characterized as biochemical oxygen demand (BOD_5). Removal mechanisms include filtration, adsorption, and biological reduction and oxidation. Most of the responses in slow rate (SR) and rapid infiltration (RI) occur at the ground surface or in the near surface soils where microbial activity is most intense. Part of the reason for the intermittent or cyclic wastewater applications on these systems is to allow the restoration of aerobic conditions in the soil profile, and infiltration capacity at the soil surface. Essentially all of the responses in overland flow (OF) occur at the soil surface or in the mat of plant litter and microbial material. Settling of most particulate matter occurs rapidly in OF systems as the applied wastewater flows in a thin film down the slope. Algae removal is an exception, since the detention time on the slope is not usually sufficient to permit complete removal by physical settling.[46] The biological growths and slimes which develop on the OF slope are primarily responsible for ultimate pollutant removal. These growths are similar to those found in other fixed film processes (i.e., trickling filters, RBCs, etc.), and the presence of adjacent aerobic and anaerobic zones or microsites within the slime layer is to be expected. In a properly managed system, with acceptable loadings, the aerobic zones dominate. However, there are still numerous anaerobic sites which contribute to the breakdown of the more refractory organics and to nitrogen removal via denitrification. The application of high-strength or high-solids-content wastewaters usually requires sprinklers for more uniform distribution on the upper third of the slope. Table 3.1 presents typical BOD_5 removal data for land treatment systems receiving municipal effluent. Since the basic treatment mechanism is biological, all three systems have a continually renewable capacity for BOD_5 removal as long as the loading rate and cycle allows for preservation and/or restoration of aerobic conditions in the system. Pilot studies[4] in 1998 with soil columns indicate that BOD_5 removal to low "background" levels was independent of the level of pretreatment, independent of soil type, and essentially independent of infiltration rate. These responses confirm the results presented in Table 3.1 and also confirm the fact that high levels of preapplication treatment are not necessary for effective BOD_5 removal in land treatment systems.

Organic loading

A comparison of the values in Table 3.1 indicates that land treatment systems have a very high capacity for treatment of the degradable organics characterized as BOD_5. The RI systems produce an effluent close to that of the SR systems with an organic loading which is typically an order of magnitude higher. Similar data from industrial operations indicate that the RI operations listed in Table 3.1 are not being stressed by the BOD_5 loadings cited.

A study at five SR systems applying potato processing wastewater in Idaho utilized chemical oxygen demand (COD) loadings ranging from 40 to 280 lb/(acre·day) with removals up to

TABLE 3.1 BOD_5 Removal at Typical Land Treatment Systems[18,21,29]

Process/location	Hydraulic loading, ft/year*,†	BOD_5, mg/L Applied	BOD_5, mg/L Effluent	Sample depth, ft‡
Slow Rate				
Hanover, N.H.	4–25	40–92	0.9–1.7	5
San Angelo, Tex.	10	89	0.7	
Rapid Infiltration				
Lake George, N.Y.	140	38	1.2	10
Phoenix, Ariz.	360	15	1.0	30
Hollister, Calif.	50	220	8.0	25
Overland Flow				
Hanover, N.H.	25	72	9	
Easley, S.C.	27	200	23	
Davis, Calif.	41	112	10	

*ft/year × 0.305 = m/year
†ft/year × 325,851 = gal/(acre·year) × 0.00935 = m^3/(ha·year)
‡ft × 0.305 = m

98 percent after 5 ft of percolation in the soil.[39] Pilot-scale OF with high-strength snack food processing wastewaters was successful at BOD_5 loading rates ranging from 50 to 100 lb/(acre·day).[33] Pilot RI studies in Montana with partially treated kraft process paper mill wastes with BOD_5 concentrations up to 600 mg/L at hydraulic loadings of about 0.2 ft/day were also successful.[44] More information on organic loading rates with industrial wastewater is presented in Chap. 13.

Some of the industrial systems discussed above successfully operate with applied BOD_5 concentrations of 1000 mg/L or more. It should be obvious that land treatment with municipal wastewater, at 200 to 300 mg/L BOD_5, should be no problem. It can therefore be concluded that neither BOD_5 nor COD is likely to be the limiting factor for design of municipal land treatment systems. Typical organic loadings in current use are summarized in Table 3.2.

Total Suspended Solids

Slow rate and rapid infiltration systems are very effective for removal of suspended solids. Filtration in the soil profile is the principal removal mechanism. Overland flow systems depend on sedimentation and entrapment in the vegetative litter or on the biological slimes and are typically less efficient than SR or RI. However, OF systems can provide better than secondary effluent quality for total suspended solids (TSS) when either screened raw sewage or primary effluent is applied. Table 3.3 summarizes TSS removal at a number of land treatment systems receiving municipal wastewaters.

As indicated previously,[40] suspended solids removal in OF systems receiving facultative lagoon effluents is not always effective, owing to the variability of algal species present and the short detention time on the slope. The seasonal variation in

TABLE 3.2 Typical Organic Loading Rates for Land Treatment Systems[5,36]

Process	Organic loading, lb BOD_5/(acre·day)*
Slow rate (SR)	45–450
Rapid infiltration (RI)	130–890
Overland flow (OF)	35–100

*lb BOD_5/(acre·day) × 1.121 = kg/(ha·day)

TABLE 3.3 Suspended Solids Removal at Land Treatment Systems[29,36,42,46]

Process/location	Total suspended solids, mg/L Applied	Effluent
Slow Rate (SR)		
Hanover, N.H.	60	<1
Typical value	120	<1
Rapid Infiltration (RI)		
Phoenix, Ariz.	20–100	<1
Hollister, Calif.	274	10
Typical value	120	2
Overland Flow (OF)		
Ada, Okla. (raw sewage)	160	8
Hanover, N.H. (primary)	59	7
Easley, S.C. (raw sewage)	186	8
Utica, Miss. (facultative lagoon)	30	8
Davis, Calif. (facultative lagoon)		
Summer	121	80
Fall	86	24
Winter	65	13

performance of the Davis, Calif., system, shown in Table 3.3, clearly illustrates this problem. See Chap. 11 for additional information on this issue.

Municipal systems

Most of the suspended solids in municipal effluents are degradable organics in concentrations ranging from 30 to about 350 mg/L depending on the degree of treatment provided prior to land application. These suspended solids are a component in the total organic loading discussed previously. As a result, the amount of suspended solids in typical municipal wastewaters should not be the limiting factor for land treatment design. Experience with full-scale operating systems indicates the best performance with the least possible degree of preapplication treatment. The solids from screened raw sewage or primary treatment are more easily separated and oxidized than the more refractory solids in secondary effluents or algal-laden lagoon effluents.

Industrial systems

Problems have occurred in OF systems (also SR systems utilizing flood irrigation) due to the unequal deposition of solids on the treatment slope. These systems have usually employed gravity discharge from gated pipe at the top of the slope; this arrangement can result in the deposition of most of the suspended matter within the first 10 to 15 ft (3 to 4.5 m) beyond the discharge point. Gated pipe or other low-pressure devices, at the top of the slope, are the most cost-effective distribution systems and are recommended for municipal effluents. High-strength high-solids industrial effluents should use high-pressure sprinklers to ensure a more uniform distribution on the slope and avoidance of objectionable anaerobic conditions.

The accumulation of the more refractory solids on the soil surface in SR and RI systems has resulted in clogging problems and a reduction in the expected infiltration rates. These solids might, in some cases, be algal cells, as were observed at an RI system in Phoenix, Ariz., or other slowly degradable solids from industrial operations.

An SR system in Pennsylvania[32] receiving wastewater from a hardboard production facility was successfully operated with a solids loading of about 550 lb/(acre·day). The waste stream consisting of hexosans, pentosans, and hemicellulose products had a BOD_5 ranging from 6000 to 18,000 mg/L. The LDP for design of this site was solids loading rather than hydraulics or some other wastewater constituent. The loading rate was gradually increased to 900 lb solids/(acre·day) when toxic effects were noticed. A continuous year-round loading rate of 500 lb solids/(acre·day) was successfully established. The Reed canary-grass-covered site proved capable of accepting temporary shock loads up to 700 lb solids/(acre·day) for brief periods during the summer months. Commercial fertilizers were applied to the site twice per year, since the wastewater was deficient in all nutrients.

The 550 lb solids/(acre·day) [616 kg/(ha·day)] represented an organic loading of about 500 lb BOD_5/(acre·day) [560 kg/(ha·day)]. This is equivalent to at least 100 tons of organic solids per acre per year. In contrast, a typical municipal wastewater with 200 mg/L TSS, applied at a typical hydraulic loading rate (≈10 ft/year) would have a solids loading less 3 tons per acre per year.

Pathogenic Organisms

The pathogens of concern in land treatment systems are parasites, bacteria, and virus. The pathways, or vectors, of concern are to groundwater, contamination of crops, translocation or ingestion by grazing animals, and off-site transmission via aerosols or runoff. The removal of pathogens in land treatment systems is accomplished by adsorption, desiccation, radiation, filtration, predation, and exposure to other adverse conditions. The SR process is the most effective, removing about five logs (10^5) of fecal coliforms within a depth of a few feet. The RI process typically can remove two to three logs of fecal coliforms within several feet of travel, and the OF process can remove about 90 percent of the applied fecal coliforms.[36]

Parasites

Parasites may be present in all municipal wastewaters. *Ascaris, Entamoeba histolytica, helminths,* and other parasitic types have been recovered from wastewaters and biosolids. Under optimum conditions the eggs of these parasites, particularly *Ascaris,* can survive for many years in the soil. Because of their weight, parasite cysts and eggs will settle out in preliminary treatment or in storage ponds, so most will be found in sludges and biosolids.

There is no evidence available indicating transmission of parasitic disease from application of wastewater in properly operated land treatment systems. Transmission of parasites via sprinkler aerosols should not be a problem owing to the weight of the cysts and eggs. Schistosomiasis, which is a very serious parasitic problem in many parts of the world due to direct contact by humans with polluted water, is not a problem in the continental United States because the host snails are not present. The World Health Organization (WHO) considers parasite exposure by field workers to be the most significant risk for irrigation with wastewater. They recommend a pond for the short-term retention of untreated wastewater as a simple solution for the problem.

Crop contamination

The major concerns for crop contamination are directed toward retention and persistence of the pathogens on the surfaces of the plant until consumed by humans or animals, or the internal infection of the plant via the roots. The persistence of polio virus on the surfaces of lettuce and radishes, for up to 36 days, has been demonstrated. About 99 percent of the detectable viruses were gone in the first 5 to 6 days. The general policy in the United States is not to grow vegetables to be consumed raw on land treatment systems without high levels of preliminary treatment, including filtration. Internal contamination of plants with virus has been demonstrated with transport from the roots to the leaves. However, these results were obtained with soils inoculated with high concentrations of virus, and then the roots were damaged or cut. No contamination was found when roots were undamaged or when soils were not inoculated with the high virus concentrations.

Criteria for irrigation of pasture with primary effluent in Germany require a period of 14 days before animals are allowed to graze. Bell[9] demonstrated that fecal coliforms from sprinkling of wastewater on the surfaces of alfalfa hay were killed by 10 h of bright sunlight. He also experimented with Reed canarygrass and found 50 h of sunlight were required. The longer period is probably due to the sheath on the grass leaf which is not present on alfalfa. He recommended a 1-week rest period prior to grazing to ensure sufficient sunlight, for Reed canary, orchard, and bromegrasses used for forage or hay. Since fecal coliforms have survival characteristics similar to those of salmonella, he suggests these results should be applicable to both organisms.

Runoff contamination

Runoff from a land treatment site might be a potential pathway for pathogen transport. Proper system design should eliminate runoff from adjacent lands entering the site and runoff of applied wastewater from the site. Overland flow is an exception in the latter case, since treated effluent and stormwater runoff are discharged from the site. The quality of rainfall runoff from an overland flow system is equal to or better in quality than the normal renovated wastewater runoff. However, an issue of concern in some cases is those systems with mass discharge limits. Significant discharge of rainfall runoff may result in excedance of the mass limits even if the discharge concentrations are acceptable. This condition must be considered during OF design and discussed with the appropriate regulatory agency. Runoff is not a factor of concern for rapid infiltration systems. If proper erosion control measures are utilized at SR systems, then runoff quality, if any occurs, should be no different than expected from normal agricultural practices.

Groundwater contamination

The risk of groundwater contamination by pathogens involves the movement of bacteria or virus to aquifers that are then used for drinking purposes without further treatment. The risk is not an issue for OF systems but has the highest potential for RI systems owing to the high hydraulic loading and the coarse texture and relatively high permeability of the receiving soils.

Bacterial removal can be quite high in the finer-textured agricultural soils commonly used for SR systems. Results from a 5-year study[23] in Hanover, N.H., applying both primary and secondary effluent to two different soils indicated essentially complete removal of fecal coliforms within a 5-foot soil profile. The soils involved were a fine-textured silt loam and a coarser-textured loamy sand. The concentrations of fecal coliforms in the applied wastewaters ranged from 10^5 for primary effluent to 10^3 for secondary effluents. In similar research in Canada,[9] undisinfected effluent was applied to grass-covered loamy sand. Most of the coliforms were retained in the top 3 in (75 mm) of soil, and none penetrated below 27 in (0.68 m). Die-off occurred in two phases: an initial rapid phase within 48 h of application when 90 percent of the bacteria died, followed by a slower decline during a 2-week period when the remaining 10 percent were eliminated.

Removal of virus, which is dependent on adsorption reactions, is also quite effective in these finer-textured agricultural soils. Most of the concern, and the research work on virus transmission in soils have focused on RI systems. Table 3.4 is a summary of results from several studies. The RI basins in the Phoenix system consisted of about 30 in of loamy sand underlain by coarse sand and gravel layers. During the study period indigenous virus were always found in the applied wastewater but none were recovered in the sampling wells.

At Santee, Calif., secondary effluent was applied to percolation beds in a shallow stratum of sand and gravel. The percolate moved laterally to an interceptor trench approximately 1500 ft from the beds. Enteric virus was isolated from the applied effluent but none were ever found at the 200-ft and 400-ft percolate sampling points.

TABLE 3.4 Virus Transmission through Soil at RI Land Application Sites[36]

Location	Sampling depth or distance, ft	Virus concentration (pfu/L)*	
		Applied	At sample point
Phoenix, Ariz.			
(Jan. to Dec. 1974)	10–30	8	0
		27	0
		24	0
		2	0
		75	0
		11	0
Gainesville, Fla.			
(Apr. to Sept. 1974)	23	0.14	0.005
		0.14	0
		0.14	0
		0.14	0
		0.14	0
		0.14	0
		0.14	0
		0.14	0
Santee, Calif.			
(1966)	200	Concentrated type 3 polio virus	0

*Pfu = plaque-forming units.

Lance[28] and others have examined the problem of virus desorption in the laboratory. Using soil columns, it was shown that applications of distilled water or rainwater could cause adsorbed virus to move deeper into the soil profile under certain conditions. However, viruses were not desorbed if the free water in the column drained prior to application of the distilled water. This suggests that the critical period would be the first day or two after wastewater application. Rainfall after that period should not then cause further movement of virus in the soil profile. Even if some movement does occur, the soil profile in nature does not necessarily have a shallow finite bottom like a laboratory soil column. A desorbed virus should have further opportunities for readsorption in the natural case. Lance's[28] work with polio virus in soil columns containing calcareous sand indicated that most viral particles are retained near the soil surface. Increasing the hydraulic loading from 2 to 4 ft/day (0.6 to 1.2 m/day) caused a virus breakthrough (about 1 percent of the applied load) at the bottom of the 8-foot column. However, 99 percent of the viral particles were still removed at hydraulic loadings as high as 39 ft/day. Lance suggested that the velocity of water movement through the soil may be the single most important factor affecting the depth of virus penetration in soils. Column studies[4] in 1998 have confirmed the earlier work by Lance. In this recent study, high virus-removal efficiencies (>99 percent) were observed in 1 m of soil at low infiltration rates. Assuming a first-order decay relationship, if 99 percent removal of virus occurred in 1 m of soil, then 99.999 percent would be removed in 3 m of soil. This same study routinely observed a four-log (99.99 percent) removal of *Cryptosporidium* after passing through 1 m of soil even at the highest infiltration rates.

Aerosols

The potential for aerosol transport of pathogens from land treatment sites was a controversial health issue. The lay public, and many professionals, tends to misunderstand what aerosols are and confuse them with the water droplets which emerge from sprinkler nozzles. Aerosols are almost colloidal in size, ranging from 20 μm in diameter or smaller. It is prudent to design any land treatment systems so that the larger water droplets emerging from the sprinklers are contained within the site. The public acceptance of a project will certainly be enhanced if it is understood that neither their persons nor their property will become "wet" from the sprinkler droplets.

Bacterial aerosols are present in all public situations and will tend to increase with the number of people and their proximity. Sporting events, theaters, public transportation, public toilets, etc., are all potential locations for airborne infection. Data in Table 3.5 summarize bacterial concentrations in aerosols at various locations, all of which involve the use or treatment of wastewaters. The cooling water for the power plant that is cited uses some disinfected effluent as makeup water. The aerosol concentration at this cooling tower is roughly the same as measured just outside the sprinkler impact zone at the California (Pleasanton) operation where undisinfected effluent is used. It does not appear that bacterial aerosols at or near land treatment sites are any worse than other sources. In fact, the opposite seems true; the aerated pond in Israel and the activated sludge systems have higher aerosol concentrations than the land treatment systems listed in the table. Aerosol studies in metropolitan areas have indicated a bacterial concentration of 4 particles per cubic foot of air in downtown Louisville, Ky., during daylight hours, and an annual average of 57 particles/ft^3 in Odessa, Russia. The aerosols from the land treatment systems listed in Table 3.5 fall within this range.

An epidemiological study at an activated sludge plant in the Chicago area[12] documented bacteria and virus in aerosols on the plant site. However, the bacterial and viral content of the air, the soil, and the surface waters in the surrounding area was not different from background levels and no significant illness rates due to the activated sludge plant were revealed within a 3-mile radius. A similar effort was undertaken at an activated sludge plant in Oregon with a school playground approximately 30 ft (10 m) from the aeration tanks. Positive counts for aerosol bacteria were noted in the schoolyard but no adverse health responses in the children. It can be inferred from these studies, since the concentrations of bacteria and virus in land treatment

TABLE 3.5 Aerosol Bacteria at Various Sources[36]

Location	Downwind distance, ft	Total aerobic bacteria, particles/ft^3*	Total coliform bacteria, particles/ft^3*
Activated sludge tank, Chicago, Ill.	30–100	396	0.2
Activated sludge tank, Sweden	0	2832	
Power plant cooling tower, California	0	83	
Aerated pond, Israel	100	—	8
Sprinklers,† Ohio	100	14	0.1
Sprinklers,‡ Israel	100	—	3.3
Sprinklers,‡ Arizona	150	23	0.2
Sprinklers,‡ Pleasanton, Calif.	30–100	73	0.2

*Aerosol counts are per cubic foot of air sampled.
†Disinfected effluent applied.
‡Undisinfected effluent applied.

aerosols are similar to those from activated sludge, and since there were no adverse health effects from the latter, that there should not be any adverse health effects from aerosols from land treatment operations.

The aerosol measurements[12] at the Pleasanton, Calif., land treatment system demonstrated that salmonella and viruses survived longer than the traditional coliform indicators. However, the downwind concentration of viruses was very low at 0.0004 pfu/ft^3. The source for these measurements was undisinfected effluent from high-pressure impact sprinklers, and the sampling point was 160 ft (48 m) from the sprinkler nozzle. The concentration cited is equal to one virus particle in every 250 ft^3 of air. Assuming a normal breathing intake of about 0.07 ft^3/min, it would take 59 h of continuous exposure by a system operator to inhale that much air. In normal practice an operator at Pleasanton might spend up to 1 h/day within 160 ft of the sprinklers. This is equivalent to the time an activated sludge operator spends servicing the aeration tanks. At this rate the operator at Pleasanton would be exposed to less than four virus particles per year and the risk to the adjacent population would appear to be nonexistent.

U.S. Environmental Protection Agency (EPA) guidelines have recommended a fecal coliform count of 1000/100 mL for recreational applications, based on standards for general irrigation water and for bathing waters and body contact sports. With respect to the aerosol risk of spraying such waters, Shuval[38] has reported that when the coliform concentration at the nozzle was below 1000/100 mL, none were detected at downwind sampling stations.

Procedures have been developed for estimating the downwind concentrations of aerosol microorganisms from sprinkler application of wastewater.[43] The equation takes the form

$$C_d = C_n D_d e^{ax} + B \tag{3.1}$$

where C_d = concentration at distance d, number/ft^3

C_n = microorganisms released at source, number/s

D_d = atmospheric dispersion factor, s/ft^3

$a = d/v$ = (downwind distance) / (wind velocity), ft/(ft/s)

x = decay or die-off rate for microorganism of concern, s^{-1}

The microorganisms released at the source C_n is a function of the microorganism density in the wastewater, the wastewater flow rate, the aerosolization efficiency, and a survival factor:

$$C_n = WFEI \tag{3.2}$$

where C_n = microorganism release at source, number/s
W = microorganism density in the wastewater, number/L
F = flow rate, L/s (gal/min × 0.06308)
E = aerosolization efficiency (percent as a decimal)
I = survival factor (dimensionless)

The survival factor I ranges from about 0.27 for fecal coliforms to 80 for virus particles.[43] Research at a number of land treatment sites indicates that with moderate- to high-pressure sprinklers about 0.33 percent of the wastewater is converted to aerosol droplets,[43] so the aerosolization efficiency E is about 0.33 percent ($E = 0.0033$). The decay rate [x in Eq. (3.1)] is about 0.023 for fecal coliforms and should be assumed to be zero for virus. The atmospheric dispersion factor D_d in Eq. (3.1) depends on a number of related meteorological conditions. Typical values for a range of expected conditions are given in Table 3.6.

TABLE 3.6 Atmospheric Dispersion Factor for Aerosols at a Distance of 300 ft from Source[43]

Atmospheric conditions	Dispersion factor D_d, s/ft^3
Wind speed < 4 mi/h, strong sunlight	5×10^{-6}
Wind speed < 4 mi/h, cloudy daylight	11×10^{-6}
Wind speed 4–10 mi/h, strong sunlight	4×10^{-6}
Wind speed 4–10 mi/h, cloudy daylight	9×10^{-6}
Wind speed > 10 mi/h, strong sunlight	8×10^{-6}
Wind speed > 10 mi/h, cloudy daylight	17×10^{-6}
Wind speed > 7 mi/h, night	17×10^{-6}

Example 3.1: Aerosols

Condition Sprinkler (100-ft-diameter circle) discharging at 1100 gal/min, aerosolization efficiency = 0.0033, survival factor (fecal coliforms) = 0.27, decay rate (fecal coliforms) = −0.023. Fecal coliform concentration in wastewater = 10^5/L, sprinklers operating in daylight with strong sunlight and a windspeed of 5 mi/h, background concentration of coliforms in the atmosphere = 0.

Find The fecal coliform concentration 300 ft downwind of the sprinkler.

Solution

$$C_n = WFEI = (10^5)(1100)(0.0631)(0.0033)(0.27)$$

$$= 6184/\text{s (released at nozzle)}$$

$$D_d = 4 \times 10^{-6} \text{ (from Table 3.6)}$$

$$a = d/v = (300 \text{ ft})/(7.33 \text{ ft/s})$$

$$= 40.9 \text{ s}^{-1}$$

$$B = 0$$

$$C_d = Q(D_d)(e^{xa}) = (6184)(4 \times 10^{-6})[e^{(-0.023)(40.9)}]$$

= 0.002 fecal coliform per cubic foot of air at a distance 300 ft downwind of sprinkler (200 ft from edge of wetted circle)

Oil and Grease

Oil and grease, also known as fats, oil, and grease (FOG), should not be a factor for land treatment of typical municipal wastewaters unless there is a spill somewhere in the municipal collection system. There is still no need to design the land treatment component for such an emergency, since standard containment and cleanup procedures can be used when needed.

Oil and grease are more likely to be a routine component in industrial wastewaters. The most likely sources are petroleum and animal and vegetable oils. Food processing, rendering, soap manufacturing, and margarine and wax production are all sources of animal or vegetable oils. Wastewaters from seafood processing, for example, can have up to 12,000 mg/L free or emulsified oil and grease. The intentional discharge of petroleum products to sewers is not expected, but leaky devices and the washdown of equipment and facilities can result in significant loadings. Oil concentrations ranging from 23 to 130 mg/L have been observed in wastewaters from 12 different refineries. Petroleum by-products have been successfully treated in soil systems for many years. Vegetation on these systems is not necessary; the waste material is mixed with the surficial soils, and with the presence of sufficient moisture and organic material the acclimated soil microorganisms completely degrade the hydrocarbons. Bausmith and Neufeld[8] have successfully demonstrated the biodegradation of propylene glycol–based deicing fluids using essentially the same technique.

The interactions between the soil-plant ecosystem and petroleum products have received the most attention. The major purpose has been to better understand the effects of an oil spill and to develop criteria for restoration. Two pathways for oil removal in a natural system have been demonstrated. The volatile portion is lost to the atmosphere and the soil microorganisms eventually decompose the remainder. A later section in this chapter discusses volatile organics in greater detail. Decomposition of animal or vegetable oils will proceed at higher rates than that of petroleum products, since these materials are more readily degraded by soil organisms.

Kincannon[25] applied petroleum sludges to soils and monitored the rate of oil loss. The control plots received no nutrient (N, P, K) fertilizers, and an average loss of 0.52 lb/month per cubic foot of soil was observed. Some combination of volatilization and microbial activity was responsible. The addition of commercial fertilizers doubled the rate of oil loss, with most of the loss occurring in the warm months, indicating that microbial activity was the major pathway. On an annual basis the rate of oil loss was 33 tons/acre on the control plots and 67 tons/acre on the fertilized and cultivated plots. Overcash[30] indicates that microbial decomposition could remove up to 98 tons of soybean oil per acre per year.

The addition of oil to the soil-plant matrix significantly changes the carbon to nitrogen (C:N) ratio. The addition of extra nitrogen and other micronutrients is necessary for the microbial reactions to proceed at acceptable rates. Kincannon added about 1000 lb of nitrogen and 200 lb of P_2O_5 per acre to achieve the maximum oil loss rates described above. Overcash[30] cites work recommending 0.005% N and 0.002% P on a soil weight basis to achieve maximum degradation of some oils.

Oil can also have a negative effect on the germination of seed when applied to an agricultural land treatment system. If the oil has a significant volatile fraction, it should be applied well before or well after the planting and germination period. The impact on germination and yield of the vegetation is more significant than the impact on the soil system. An oil level of about 1 percent of soil weight seems to be the threshold for reduced yields, and at levels of 1.5 to 2 percent the reduction in yield often exceeds 50 percent. These effects occur with a fresh application of oil prior to the loss of the volatile hydrocarbons.

A soil depth of about 6 in (150 mm) should be assumed when determining acceptable oil or grease loading rates. The maximum single dose that can be applied should be determined; then the in situ decomposition rate will determine the interval between applications. If there is no surface vegetation, a loading equal to 2 to 4 percent of the soil weight in the top 6 in might be acceptable. If there is a crop, a single dose higher than 1 percent might significantly reduce yield. A warm weather (soil temperature 50 to 60°F) decomposition rate of 0.2 to 0.4 percent oil, of soil weight per month, has been recommended.[30] Short-term on-site tests are recommended for final system design with a particular oil. Table 3.7 summarizes the oil tolerance for a range of commonly used crops.

TABLE 3.7 Oil Tolerance for Selected Crops[30]

Crop type	Single oil application
Yams, carrots, rape, lawn grasses, sugar beets	< 0.5% of soil weight (< 5 tons oil/acre)
Rye grass, oats, barley, corn, wheat, beans, soybeans, tomato	< 1.5% of soil weight (< 15 tons oil/acre)
Red clover, peas, cotton, potato, sorghum	< 3% of soil weight (< 30 tons oil/acre)
Perennial grasses, coastal Bermuda grass, trees	> 3% of soil weight (> 30 tons oil/acre)

Example 3.2: Oil Degradation Rate

Conditions Industrial waste with 1 percent vegetable oil, soil degradation rate 0.15 percent of soil weight per month. Corn is the intended crop with an acceptable oil tolerance of 0.5 percent of soil weight. Soil density in surface layer 90 lb/ft^3.

Find Waste loading per acre, and degradation time.

Solution

$$\text{Weight of soil in top 6 in} = (90\ \text{lb/ft}^3)(0.5\ \text{ft})(43{,}560\ \text{ft}^2\text{/acre}) = 1{,}960{,}200\ \text{lb/acre}$$

$$\text{Acceptable oil loading} = (0.005)(1{,}960{,}200) = 9801\ \text{lb/acre}$$

$$\text{Waste application} = (9801\ \text{lb/acre})/(0.01)(2000\ \text{lb/ton}) = 490\ \text{ton/acre}$$

At 0.15% per month the oil would be degraded in (0.5% applied)/(0.15% degraded/month) = 3.3 months

Metals

The removal of metals in the soil is a complex process involving the mechanisms of adsorption, precipitation, ion exchange, and complexation. Adsorption of most trace elements occurs on the surfaces of clay minerals, metal oxides, and organic matter; as a result, fine-textured and organic soils have a greater adsorption capacity for trace elements than sandy soils have. The slow rate (SR) land treatment process is the most effective for metals removal because of the finer-textured soils and the greater opportunity for contact and adsorption. Rapid infiltration (RI) can also be quite effective, but a longer travel distance in the soil will be necessary owing to the higher hydraulic loadings and coarser-textured soils. Overland flow (OF) systems allow minimal contact with the soil and typically remove between 60 and 90 percent depending on the hydraulic loading and the particular metal.

In general, metals are present in typical municipal wastewaters in low concentrations. As shown in Table 3.8, the typical metals concentrations in raw sewage are below the requirements for drinking and irrigation waters.

Wastewater treatment by activated sludge and similar processes tends to concentrate these metals in the sludge or biosolids. The land application of these biosolids is discussed in detail in Chap. 17. The land application of the liquid effluents from these processes should not therefore be a problem.

Metal limits

The major concern with respect to metals is the potential for accumulation in the soil profile and then subsequent translo-

TABLE 3.8 Metals Concentrations in Wastewaters and Suggested Concentrations in Drinking and Irrigation Waters

Element	Raw sewage, mg/L	Drinking water, mg/L	Irrigation water, mg/L	
			20 years*	Continuous†
Cadmium	0.004–0.14	0.01	0.05	0.005
Chromium	0.02–0.70	0.05	20	5.0
Lead	0.05–1.27	0.05	20	5.0
Zinc	0.05–1.27	0.05	20	5.0

*For fine-textured soils only. Normal irrigation practice for 20 years.
†For any soil, normal irrigation practice, no time limit.

cation, via crops or animals, through the food chain to man. The metals of greatest concern are cadmium (Cd), lead (Pb), zinc (Zn), copper (Cu), and nickel (Ni). Most crops do not accumulate lead, but there is some concern with respect to ingestion by animals grazing on forages or soil to which biosolids have been applied. In general, zinc, copper, and nickel will be toxic to the crop before their concentration in plant tissues reaches a level that poses a significant risk to human or animal health. Cadmium is the greatest concern because the concentration of concern for human health is far below the level which could produce toxic effects in the plants. As discussed in Chap. 17, the World Health Organization (WHO) has published guidelines for annual and cumulative metal additions to agricultural crop land.[13] Adverse effects should not be expected at these loading rates. Table 3.9 summarizes these loading rates; although developed for biosolids applications, it is prudent to apply the same criteria for wastewater applications.

TABLE 3.9 WHO Recommended Annual and Cumulative Limits for Metals Applied to Agricultural Cropland[13]

Metal	Annual loading rate,* lb/acre‡	Cumulative loading rate,† lb/acre‡
Arsenic	1.78	36.58
Cadmium	1.70	34.80
Chromium	133	2677
Copper	67	1338
Lead	13	268
Mercury	0.76	15.2
Molybdenum	0.80	16.1
Nickel	18.7	375
Selenium	4.5	89
Zinc	125	2498

*Loading lb/acre per 365-day period.
†Cumulative loading over lifetime of site.
‡lb/acre × 1.1208 = kg/ha.

Example 3.3: Cadmium Loadings

Conditions Slow rate land treatment on agricultural site, wastewater application 8 ft/year. Cadmium concentration in applied wastewater 0.01 mg/L.

Find The useful life of the site for cumulative cadmium applications.

Solution

$$(8 \text{ ft/year})(43{,}560 \text{ ft}^2/\text{acre})(7.48 \text{ gal/ft}^3) = 2{,}606{,}630 \text{ gal/(acre·year)}$$

$$(0.01 \text{ mg/L})(8.34)(2.6066) = 0.22 \text{ lb/(acre·year) Cd}$$

$$0.22 \text{ lb/(acre·year)} < 1.70 \text{ lb/(acre·year) so annual loading O.K.}$$

$$\text{Cumulative time limit} = (34.8 \text{ lb/acre})/[0.22 \text{ lb/(acre·year)}] = 158 \text{ years}$$

Metals removal in soils and crops

It is not possible to predict the total renovative capacity of a land treatment site with simple ion exchange or soil adsorption theories. Although the metals are accumulated in the soil profile, the accumulation does not seem to be continuously available for crop uptake. Work by several investigators with sludges demonstrates that the metals uptake in a given year is more dependent on the concentration of metals in the sludge most recently applied than on the total accumulation of metals in the soil.

The capability of metal uptake varies with the type of crop grown. Swiss chard and other leafy vegetables take up more metals than other types of vegetation. Metals tend to accumulate in the liver and kidney tissue of animals grazing on a land treatment site or fed harvested products. A number of studies with domestic and indigenous animals do not show adverse effects. Tests done on a mixed group of 60 Hereford and Angus steers that graze directly on the pasture grasses at the Melbourne, Australia, land treatment site (untreated raw sewage applied) showed that "the concentrations of cadmium, zinc and nickel found in the liver and kidney tissues of this group are within the expected normal range of mammalian tissue."[1] Anthony[2] has reported on metals in bone, kidney, and liver tissue in mice and rabbits which were indigenous to the Pennsylvania State University land treatment site, and no adverse impacts were noted.

The average metal concentrations in the shallow groundwater beneath the Hollister, Calif., rapid infiltration site are shown in Table 3.10. After 33 years of operation the concentration of cadmium, chromium, and cobalt was not significantly different

TABLE 3.10 Trace Metals in Groundwater under Hollister, Calif., Rapid Infiltration Site[34]

Metal	Average concentration, mg/L
Cadmium	0.028
Chromium	0.014
Cobalt	0.010
Copper	0.038
Iron	0.36
Manganese	0.96
Nickel	0.09
Zinc	0.08

from normal off-site groundwater quality. The concentration of the other metals listed was somewhat higher than the off-site background levels.

The metal concentrations in the upper foot of soils in the RI basins at the Hollister, Calif., system are still below or near the low end of the range for typical agricultural soils, after 33 years of operation.

In overland flow, the major mechanisms responsible for trace element removal include sorption on clay colloids and organic matter at the soil surface and in the litter layer, precipitation as insoluble hydroxy compounds, and formation of organometallic complexes. The largest proportion of metals accumulate in the biomass on the soil surface and close to the initial point of application.

In summary, it is unlikely that metals will be the LDP for design of land application of municipal wastewaters. It is possible that metals could be the LDP for land treatment of industrial wastewaters, and it is probable that metals will be the LDP for the application of biosolids to the land as described in Chap. 17.

Nitrogen

The removal of nitrogen in land treatment systems is complex and dynamic owing to the many forms of nitrogen (N_2, organic N, NH_3, NH_4, NO_2, NO_3) and the relative ease of changing from one oxidation state to the next. The nitrogen present in typical municipal wastewater is usually present as organic nitrogen (about 40 percent) and ammonia/ammonium ions (about 60 percent).

Activated sludge and other high-rate biological processes can be designed to convert all of the ammonia ion to nitrate (nitrification). Typically only a portion of the ammonia nitrogen is nitrified, and the major fraction in most system effluents is still in the ammonium form (ammonia and ammonium are used interchangeably in this text).

It is important in the design of all three land treatment concepts to identify the total concentration of nitrogen in the wastewater to be treated as well as the specific forms (i.e., organic, ammonia, nitrate, etc.) expected. Experience with all three land treatment processes demonstrates that the less oxidized the nitrogen is when entering the land treatment system the more effective will be the retention and overall nitrogen removal.[36]

Soil responses

The soil plant system provides a number of interrelated responses to wastewater nitrogen. The organic N fraction usually associated with particulate matter is entrapped or filtered out of the applied liquid stream. The ammonia fraction can be lost by volatilization, taken up by the crop, or adsorbed by the clay minerals in the soil. The latter is a renewable process since the soil microbes oxidize the retained ammonium to nitrate and restore the adsorptive capacity of the soil. Nitrate can be taken up by the vegetation or converted to nitrogen gas via denitrification in anaerobic zones and lost to the atmosphere. The decomposition of the organic nitrogen contained in the particulate matter proceeds more slowly. This aspect is more critical for sludge and biosolids application systems where the solids fraction is a very significant part of the total application. As the organic solids decompose, the contained organic nitrogen is mineralized and released as ammonia. This is not a major concern for most wastewater land treatment systems with the exception of those systems receiving facultative lagoon effluent containing significant concentrations of algae. The nitrogen content of the algae must be considered in project design, because it can represent a significant ammonia load on the system.

Nitrification is very effective in all three of the basic land treatment concepts as long as the necessary aerobic status is maintained or periodically restored. Under favorable conditions (i.e., sufficient alkalinity, suitable temperatures, etc.) nitrification ranging from 5 to 50 mg/(L·day) is possible. Assuming that these reactions are occurring with the adsorbed ammonia ions in the top 4 in of a fine-textured soil means that up to 60 lb of ammonia nitrogen per acre can be converted to nitrate each day. At a typical wastewater concentration of 20 mg/L up to 1 ft of wastewater could be applied each day if the soil could be maintained in an aerobic condition.

The maintenance and/or restoration of the necessary aerobic conditions is the reason for the short application periods and cyclic operations typically used in land treatment systems. In RI systems, for example, the ammonia adsorption sites are saturated with ammonium during the early part of the application cycle. The aerobic conditions are restored as the system drains during the rest period, and the soil microbes convert the adsorbed ammonium to nitrate. At the next application cycle ammonium adsorption sites are again available and much of the nitrate is denitrified as anaerobic conditions develop. Denitrifying bacteria are common soil organisms, and the occurrence of anaerobic conditions, at least at microsites, can be expected at both SR and OF systems as well as RI.

Nitrification is a conversion process, not a removal process for nitrogen. Denitrification, volatilization, and crop uptake are the only true removal pathways available. Crop uptake is the major pathway considered in the design of most slow rate systems, but the contribution from denitrification and volatilization can be significant depending on site conditions and wastewater type. In RI, ammonia adsorption on the soil particles followed by nitrification typically occurs, but denitrification is the only important actual removal mechanism. For OF, crop uptake, volatilization, and denitrification can all contribute to nitrogen removal. Crop uptake of nitrogen is discussed in detail in Chap. 5 and in the process design chapters. Nitrogen removal data for typical SR, RI, and OF systems are shown in Table 3.11.

Nitrates

The health issue of concern for nitrogen is excess concentrations of nitrate in drinking waters for infants under 6 months of age. The U.S. primary drinking water standard for nitrate (as N) is set at 10 mg/L for this reason. The pathway of concern in SR and RI systems is conversion of wastewater nitrogen to nitrate and then

TABLE 3.11 Nitrogen Removal in Typical Land Treatment Systems[11,34,41]

Process and location	Applied wastewater, mg/L	Process effluent, mg/L
	SR	
Dickinson, N.Dak.	12	3.9
Hanover, N.H.	28	7.3
Roswell, N.M.	66	10.7
San Angelo, Tex.	35	6.1
	RI	
Calumet, Mich.	24	7
Ft. Devens, Mass.	50	20
Hollister, Calif.	40	3
Phoenix, Ariz.	27	10
	OF	
Ada, Okla.		
Raw wastewater	34	7
Primary effluent	19	5
Secondary effluent	16	8
Easley, S.C. (pond effluent)	7	2
Utica, Miss. (pond effluent)	20	7

percolation to drinking water aquifers. When potable aquifers are involved, the current guidance requires that all drinking water standards be met at the land treatment project boundary. As a result, nitrogen often becomes the LDP for SR systems because of its relatively high concentration as compared to other drinking water parameters. Chapter 10 presents complete design details for nitrogen removal in these systems. There are a number of safety factors inherent in the approach that ensures a conservative design. The procedure assumes that all of the applied nitrogen will appear as nitrate (i.e., complete nitrification) and within the same time period assumed for the application (no time lag or mineralization of ammonia), and there is no credit for mixing or dispersion with the in situ groundwater.

Design factors

The nitrogen mass balance for RI systems would not usually include a component for crop uptake. The percolate nitrogen concentration is not a concern for OF systems since the percolate volume is generally considered to be negligible. As indicated previously, application of biosolids does include a mineralization factor to account for the previous organic nitrogen deposits. There are four potential situations where a mineralization factor might be included in the nitrogen balance for SR and OF systems:

Industrial wastewaters with high solids concentrations having significant organic nitrogen content

Grass-covered systems where the grass is cut but not removed

Pasture systems with intense animal grazing and animal manure left on the site

Sludge or manure added to the site as supplemental fertilizers

Organic nitrogen

Mineralization rates developed for wastewater biosolids are given in Table 3.12. The values are the percent of the organic nitrogen present that is mineralized (i.e., converted to inorganic forms such as ammonia and nitrate) in a given year. For example, 40 percent of the organic nitrogen in raw biosolids would be mineralized during the first year, 20 percent the second year, and so forth.

TABLE 3.12 Mineralization Rates for Organic Matter in Biosolids*

	Mineralization rate, %			
Time after biosolids application, years	Unstabilized primary	Aerobically digested	Anaerobically digested	Composted
0–1	40	30	30	10
1–2	20	15	10	5
2–3	10	8	5	†
3–4	5	4	†	

The fraction of the biosolids organic N initially applied, or remaining in the soil, that will be mineralized during the time intervals shown is provided as examples only and may be quite different for different biosolids, soils, and climates. Therefore, site-specific data, or the best judgment of individuals familiar with N dynamics in the soil-plant system involved, should always be used in preference to these suggested values.

†U.S. Environmental Protection Agency, *Process Design Manual for Land Application of Sewage Sludge and Domestic Septage,* EPA/625/R-95/001, Sept. 1995.

*Once the mineralization rate becomes less than 3 percent, no net gain of plant available nitrogen above that normally obtained from the mineralization of soil organic matter is expected. Therefore, additional credits for residual biosolids N do not need to be calculated.

The mineralization rate is related to the initial organic nitrogen content, which in turn is related to treatment level for the biosolids in question. Easily degraded industrial biosolids would be comparable to raw municipal biosolids. Industrial solids with a high percentage of refractory or stable humic substances might be similar to composted biosolids. Animal manures would be similar to digested sludges, and it would be conservative to assume that grass cuttings and other vegetative litter would decay at the same rates as digested sludges. Another consideration is necessary for animal manures to account for volatilization of the ammonia fraction. When the manure is deposited on the ground surface, essentially all of the ammonia content will be lost to the atmosphere, leaving the organic fraction to be mineralized. If data are not available, it can be assumed that the manure is similar in character to digested municipal biosolids, with about 50 percent of the nitrogen in the ammonia form and the remainder as organic nitrogen. Examples 3.4 and 3.5 illustrate the use of the factors in Table 3.12 for two possible situations.

Example 3.4: Nitrogen Cycling in Greenbelts

Conditions Slow rate land treatment site used as a greenbelt parkway. The grasses are cut but not removed from the site. At the wastewater loading rates used, the grasses will take up about 300 lb/(acre·year).

Find The nitrogen contribution from the on-site decay of the cut grass.

Solution The most conservative assumption is to use anaerobically digested sludge rates from Table 3.12 and to assume that all of the nitrogen is in the organic form.

1. In first year:

(300 lb/acre)(0.30)		= 90 lb/acre

2. In second year:

Second year cutting	= (300)(0.30)	= 90 lb/acre
Residue from first year	= (300−90)(0.10)	= 21
	Total, second year	= 111 lb/acre

3. In third year:

Third year cutting	= (300)(0.30)	= 90 lb/acre
Residue from second year	= (300 − 90)(0.10)	= 21
Residue from first year	= (300 − 111)(0.05)	= 9
	Total, third year	= 120 lb/acre

4. In fourth year:

Fourth year cutting		=90 lb/acre
Residue from third year		=21

Residue from second year		=9
Residue from first year	= (300−120)(0.03)	= 5
	Total fourth year	= 125 lb/acre

5. In fifth year:

Fifth year cutting		= 90 lb/acre
Residue from fourth year		= 21
Residue from third year		= 9
Residue from second year		= 5
Residue from first year	= (300−125)(0.03)	= 5
	Total fifth year	= 130 lb/acre

6. As shown by the sequence above, the amount of nitrogen contributed becomes relatively stable after the third or fourth year and increases only slightly thereafter. In this example, it can be assumed that about 125 lb/acre of nitrogen is returned to the soil each year from the cut grass. For this case, that would be about 40 percent of the nitrogen originally taken up by the grass, so the net removal is still very significant. The 40 percent returned is also significant and would be included in the nitrogen mass balance in a conservative design.

Example 3.5: Nitrogen Cycling from Manures on Grazed Pastures

Conditions Pasture receives wastewater effluents; pasture grasses take up about 300 lb/(acre·year) of nitrogen. Assume all of the grass is consumed by the grazing animals, and that all of the manure is deposited on the site.

Find The nitrogen contribution from decay of the animal manures on the site.

Solution Assume that animal manures are similar to anaerobically digested sludges with about 50 percent of the nitrogen in the ammonia form. Further assume that all of that ammonia is volatilized.

1. Annual available organic nitrogen = (300 lb/acre)(0.50) = 150 lb/acre
2. Using digested mineralization rates from Table 3.12:

First year contribution	= (150)(0.30)	= 45 lb/acre
Second year contribution	= 45 + (150 − 45)(0.10)	= 55 lb/acre
Third year contribution	= 45 + 10 + (150 − 55)(0.05)	= 60 lb/acre

And so forth

3. In this example, the animal manure will return about 60 lb/acre of nitrogen each year after equilibrium is reached. That is only 20 percent of the wastewater nitrogen originally applied. If the manure or biosolids were immediately plowed into the soil, the 50 percent credit for volatilization would not apply and the returned nitrogen would be the same as in Example 3.4.

These two examples illustrate the critical importance of knowing what form the nitrogen is in when it is applied to the land treatment site. This is particularly important if elaborate pretreatment is provided, since the nitrogen may not then be in the simple and easily managed combination of organic nitrogen and ammonia that is present in untreated municipal wastewater and primary effluents. Any nitrogen losses which occur during this preapplication treatment or storage should be considered. Facultative lagoons or storage ponds can remove up to 85 percent of the contained nitrogen under ideal conditions.[36] Such losses are especially significant when nitrogen is the LDP for design, because any reduction in nitrogen prior to land application will proportionally reduce the size and therefore the cost of the land treatment site.

Phosphorus

The presence of phosphorus in drinking water supplies does not have any known health significance, but phosphorus is considered to be the limiting factor for eutrophication of fresh surface waters so its removal from wastewaters is a concern for many. Phosphorus is present in municipal wastewater as orthophosphate, polyphosphate, and organic phosphates. The orthophosphates are immediately available for biological reactions in soil ecosystems. The necessary hydrolysis of the polyphosphates proceeds very slowly in typical soils, so these forms are not as readily available. Industrial wastewaters may contain a significant fraction of organic phosphorus, but typical municipal wastewaters do not.

Removal mechanisms

Phosphorus removal in land treatment systems can occur through plant uptake, biological, chemical, and/or physical processes. The nitrogen removal described in the previous section is almost entirely dependent on biological processes, so the removal capacity can be maintained continuously or restored by proper system design and management. In contrast, phosphorus removal in the soil depends to a significant degree on chemical reactions which are not necessarily renewable. As a result, the retention capacity for phosphorus will be gradually reduced over time, but not exhausted. At a typical SR system, for example, it has been estimated that a 1-ft depth of soil may become saturated with phosphorus every 10 years. The removal of phosphorus will be almost complete during the removal period. Percolate phosphorus should not be a problem until the entire design soil profile is utilized, and the percolate then emerges or is otherwise discharged to surface waters.

It is unlikely that phosphorus in municipal wastewaters would be the LDP for process design of the land treatment system. Some regulatory agencies have specified phosphorus as the LDP for land application of biosolids. This is a very conservative approach, taken to ensure that the nitrogen or metals in biosolids cannot exceed limits. However, this approach when used on agricultural sites intended for crop production results in a nitrogen deficiency for optimum crop production, and supplemental commercial nitrogen fertilizers are typically required. On some SR sites phosphorus may limit the design life of the site. An example might be a site with coarse-textured sandy soils with underdrains at a shallow depth which discharge to a sensitive surface water. In this case the useful life of the site might range from 20 to 60 years depending on the soil type, underdrain depth, wastewater characteristics, and loading rates.

The phosphorus removals which have been observed at typical SR and RI systems are summarized in Table 3.13. Crop uptake contributes to phosphorus removal at SR systems, but the major removal pathway in both SR and RI systems is in the soil. The phosphorus is removed by adsorption-precipitation reactions when clay, oxides of iron and aluminum, and calcareous substances are present. The phosphorus removal increases with increasing clay content and with increasing contact time in the soil. The percolate phosphorus values listed in Table 3.13 for SR systems are close to the background levels for natural groundwater at these locations.

Rapid infiltration

There is no crop uptake in RI systems, and the soil characteristics and high hydraulic loading rates typically used require greater travel distances in the soil for effective phosphorus removal. Data from several of the RI systems in Table 3.13 indicate a percolate phosphorus concentration approaching background levels after several hundred feet of travel in the subsoils. Most of these systems (Vineland, Lake George, Calumet, Ft. Devens) had been in operation for several decades prior to collection of the percolate samples.

TABLE 3.13 Typical Percolate Phosphorus Concentrations*

Location	Soil type	Travel distance,† ft	Percolate phosphorus, mg/L
		SR	
Hanover, N.H.	Sandy loam	5	0.05
Muskegon, Mich.	Loamy sand	5	0.04
Tallahassee, Fla.	Fine sand	4	0.1
Pennsylvania State, Pa.‡	Silt loam	4	0.08
Helen, Ga.‡	Sandy loam	4	0.17
		RI	
Hollister, Calif.	Gravelly sand	22	7.4
Phoenix, Ariz.	Gravelly sand	30	4.5
Ft. Devens, Mass.	Gravelly sand	5	9.0
Calumet, Mich.	Gravelly sand	30	0.1
Boulder, Colo.	Gravelly sand	10	2.3
Lake George, N.Y.	Sand	3	1.0
		600	0.014
Vineland, N.J.	Sand	30	1.5
		400	0.27

*Applied wastewater, typical municipal effluent, TP ≈ 8 to 14 mg/L.
†Total percolate travel distance from soil surface to sampling point SR systems.
‡Forested SR system.

An equation to predict phosphorus removal at SR and RI land treatment sites has been developed from data collected at a number of operating systems.[29] Since the equation was developed from performance with the coarse-textured soils at RI sites, it should provide a very conservative estimate for SR performance.

$$P_x = P_o\,[e^{-(k)(t)}] \tag{3.3}$$

where P_x = total phosphorus in percolate at distance x on the flow path, mg/L
P_o = total phosphorus in applied wastewater, mg/L
k = rate constant, at pH 7, per day
= 0.048 per day (pH 7 gives most conservative value)
t = detention time to point x, days
= $(x)(W)/(K_x)(G)$
x = distance along flow path, ft (m)
W = saturated soil moisture content; assume 0.4
K_x = hydraulic conductivity of soil in direction x, ft/day (m/day)

thus K_v = vertical conductivity, K_H = horizontal conductivity
G = hydraulic gradient for flow system, dimensionless
= 1.0 for vertical flow
= $\Delta h/L$ for horizontal flow
Δh = elevation difference of water surface between origin of horizontal flow and end point x, ft
L = length of horizontal flow path, ft

Equation (3.3) is solved in two steps, first for the vertical flow component, from the soil surface to the subsurface flow barrier (if one exists) and then for the lateral flow to the outlet point x. The calculations are based on an assumed saturated flow conditions, so the shortest possible detention time will result. The actual vertical flow in most cases will be unsaturated, so the actual detention time will be much longer than is calculated with this procedure, and therefore the actual phosphorus removal will be greater. If the equation predicts acceptable phosphorus removal, then there is some assurance that the site will perform reliably and detailed tests should not be necessary for preliminary work. Detailed phosphorus removal tests should be conducted for final design of large-scale projects.

Example 3.6: Phosphorus Removal

Conditions Assume a site where wastewater percolate moves 10 ft vertically through the soil to the groundwater table and then 80 ft horizontally to emergence in a small stream. The initial phosphorus concentration is 10 mg/L, the vertical hydraulic conductivity K_v = 2 ft/day, the horizontal hydraulic conductivity K_H = 10 ft/day, and the difference in groundwater surface elevations between the site and the stream is 3 ft.

Find The phosphorus concentration in the percolate when emerging in the stream and the total detention time in the soil.

Solution Phosphorus concentration at end of vertical flow:

$$t = (10 \text{ ft})[(0.4)/(2 \text{ ft/day})(1)] = 2.0 \text{ days}$$

$$P_x = (10 \text{ mg/L})[e^{-(0.048)(2.0)}]$$

$$= 9.1 \text{ mg/L}$$

Percolate phosphorus concentration at the stream:

$$t = (90 \text{ ft})(0.4)/(10 \text{ ft/day})(3 \text{ ft}/90 \text{ ft}) = 108 \text{ days}$$

$$P_x = (9.1 \text{ mg/L})[e^{-(0.048)(108)}]$$

$$= 0.05 \text{ mg/L}$$

Total detention time in soil = 2 days + 108 days = 110 days

Overland flow

The opportunities for contact between the applied wastewater and the soil are limited to surface reactions in OF systems, and as a result phosphorus removals typically range from 40 to 60 percent. Phosphorus removal in overland flow can be improved by chemical addition and then precipitation on the treatment slope. At Ada, Okla., the U.S. Environmental Protection Agency demonstrated the use of alum additions (Al to TP mole ratio 2:1) to produce a total phosphorus concentration in the treated runoff of 1 mg/L.[41] At Utica, Miss., mass removals ranged between 65 and 90 percent with alum as compared to less than 50 percent removal without alum.[15]

Typical municipal wastewaters will have between 5 and 20 mg/L of total phosphorus. Industrial wastewaters can have much higher concentrations, particularly from the fertilizer and detergent manufacturing. Food processing operations can also have high phosphate effluents. Some typical values are: dairy products 9 to 210 mg/L PO_4, grain milling 5 to 100 mg/L PO_4, cattle feed lots 60 to 1500 mg/L PO_4.

Example 3.7: Determine Phosphorus Loading to Match Useful Life of Site

Conditions Assume a silty loam soil; adsorption tests indicate a useful capacity for phosphorus equal to 3000 lb/acre per foot of depth. Site to be grass-covered, grass uptake of phosphorus is 30 lb/(acre·year), grass to be harvested and taken off site. The projected operational life of the factory and the treatment site is equal to 30 years. The phosphorus concentration in the wastewater is 60 mg/L. The treatment site is underdrained with drainage water discharged to adjacent surface waters with an allowable discharge limit of 1.0 mg/L TP. Because of the underdrains, the practical soil treatment depth is 6 ft.

Find The acceptable annual wastewater loading during the 30-year useful life.

Solution

1. Lifetime crop contribution	= [30 lb/(acre·year)](30 years)	= 900 lb/acre
2. Lifetime soil contribution	= [3000 lb/(acre·ft)](6 ft)	= 18,000 lb/acre
3. Total 30-year phosphorus removal capacity		= 18,900 lb/acre
4. Average annual phosphorus loading	= (18,900 lb/acre)/(30 years)	= 630 lb/(acre·year)
5. Wastewater loading *Q*	= [630 lb/(acre·year)]/ (60 mg/L)(8.34)	= 1,260,000 gal/(acre·year)
	= 3.86 ft of wastewater per year for 30 years	

Note: Design credit is not taken in this example for the 1.0 mg/L TP allowed in the underdrain effluent. This is because the treatment system will essentially remove all of the phosphorus during the useful life of the system until breakthrough occurs; until that point is reached the effluent concentration should be well below the allowable 1 mg/L level.

Potassium and Other Micronutrients

As a wastewater constituent, potassium usually has no health or environmental significance. It is however, an essential nutrient for vegetative growth and is not typically present in wastewaters in the optimum combination with nitrogen and phosphorus. If a land treatment system depends on crop uptake for nitrogen removal, it may be necessary to add supplemental potassium to maintain nitrogen removals at the optimum level. Equation (3.4) can be used to estimate the supplemental potassium that may be required where the in situ soils have a low level of natural potassium. This most commonly occurs in the northeastern part of the United States.

$$K_S = (0.9)\,(U) - K_{WW} \tag{3.4}$$

where K_S = annual supplemental potassium needed, kg/ha
U = estimated annual nitrogen uptake of crop, kg/ha
K_{WW} = potassium applied in wastewater, kg/ha

$$(\text{kg/ha}) \times (0.8922) = \text{lb/acre}$$

Most plants also require magnesium, calcium, and sulfur, and depending on soil characteristics, there may be deficiencies in some locations. Other micronutrients important for plant growth include iron, manganese, zinc, boron, copper, molybdenum, and sodium. Generally, there is a sufficient amount of these elements in municipal wastewaters, and in some cases an excess can lead to phytotoxicity problems, as discussed in the sections which follow.

Inorganic Elements and Salts

This category refers to nonmetallic elements such as boron, selenium, arsenic, sodium, sulfur, potassium, and the compounds, oxides, and salts formed from these materials. The major impact of these substances on land treatment is on the vegetative component and on permeability of certain clays due to high sodium concentrations in the wastewater. Some of these elements, such as potassium, are essential plant nutrients; others serve as micronutrients at low concentrations but can be toxic to plants at high levels. At the concentrations found in typical municipal wastewaters none of these materials are likely to be the LDP for process design. One exception, discussed below, might be high salinity in wastewaters applied to the land in relatively arid climates.

Boron

Boron is an essential micronutrient for plants but becomes toxic at relatively low concentrations (<1 mg/L) for sensitive plants. The soil has some adsorptive capacity for boron if aluminum and iron oxides are present. The soil reactions are similar to those described previously for phosphorus, but the capacity for boron is low. A conservative design approach assumes that any boron not taken up by the plant is available for percolation to the groundwater. Plant uptake of boron in corn silage of about 0.005 lb/(acre·year) and in alfalfa of 0.81 to 1.6 lb/(acre·year) have been reported.[30] At the SR land treatment site in Mesa, Ariz., the applied municipal effluent had 0.44 mg/L boron, and the groundwater beneath the site contained 0.6 mg/L. At another SR operation at Camarillo, Calif., the wastewater boron was 0.85 mg/L and the groundwater beneath the site was 1.14 mg/L. The increase in boron, in both cases, is probably due to water losses from evapotranspiration. Table 3.14 lists the boron tolerance of common vegetation types.

TABLE 3.14 Boron Tolerance of Crops[46]

I Tolerant	II Semitolerant	III Sensitive
Alfalfa	Barley	Fruit crops
Cotton	Corn	Nut trees
Sugar beets	Milo	
Sweet clover	Oats	
Turnip	Tobacco	
	Wheat	

Overcash[30] has suggested that industrial wastewaters with 2 to 4 mg/L boron could be successfully applied to crops in category I in Table 3.14, 1 to 2 mg/L boron for category II, and less than 1 mg/L for category III. Boron is not therefore the LDP for process design but may be the determinant on which crop to select. Both OF and RI systems will be less effective for boron removal than SR systems because of the same factors discussed previously for phosphorus. Injection experiments at the Orange County, Calif., groundwater recharge project injected treated municipal effluent with 0.95 mg/L boron. After 545 ft of travel in the soil the boron concentration was still 0.84 mg/L.[35]

Selenium

Selenium is a micronutrient for animals but is nonessential for plants. However, in high concentrations it is toxic to animals and birds, and many plants can accumulate selenium to these toxic levels without any apparent effect on the crop. Plants containing 4 to 5 ppm selenium are considered toxic to animals.[36] Selenium can be adsorbed weakly by the hydrous iron oxides in soils, and this is of more concern in the southeastern United States where soils tend to have very high iron oxide contents. In arid climates with significant evaporation, surficial soils can eventually accumulate toxic levels of selenium, as occurred at the famous Kesterson Marsh in California. Selenium is not likely to be the LDP for land treatment design with municipal wastewaters. However, selenium is included on the U.S. Environmental Protection Agency's list of priority pollutants, and if concentrations greater than 0.01 mg/L are expected in industrial effluents it may be necessary to avoid SR or OF land treatment options because of long-term adverse impacts if the harvested crops enter the human food chain.

Arsenic

Arsenic is nonessential for all life forms. In significant concentrations it can be moderately toxic to plants and very toxic to animals. The food chain is protected at land treatment sites, since the crops should show adverse effects from arsenic before hazardous levels were reached in the edible portions of the plants. Arsenic is removed in the soil system by adsorption by the soil colloids with clay and the iron and aluminum oxides performing essentially the same function as described previously for phosphorus removal. In general, arsenic will not be the LDP for land treatment of municipal wastewaters. Poultry manure with 15 to 20 ppm arsenic has been applied for up to 20 years [0.2 to 0.4 lb As/(acre·year)] without any adverse effects on either alfalfa or clover.[36] Field tests are recommended for industrial effluents with high arsenic concentrations to develop criteria for loading rates and vegetation to be used at a specific location.

Sodium

Sodium is typically present in all wastewaters. There are no primary drinking water requirements for sodium, but it has been strongly suggested that human consumption of high levels of sodium is related to heart disease. Sodium and calcium can be directly toxic to plants, but most often their influence on soil salinity or soil alkalinity is the more important problem. Growth of sensitive plants becomes impaired where the salt content of the soil exceeds 0.1 percent. Salinity also has a direct bearing on the osmotic pressure of the soil solution which controls the ability of the plant to absorb water. Adverse crop effects can also occur from sprinkler operations in arid climates using water with significant concentrations of sodium or chlorine. The leaves can absorb both elements rapidly, and their accumulation on the leaf surfaces in arid climates can result in toxicity problems.[36] Sodium is not permanently removed in the soil but is rather involved in the soil cation exchange process. These reactions are similar to those occurring in water-softening processes and involve sodium, magnesium, and calcium.

In some cases, where there is an excess of sodium with respect to calcium and magnesium in the water applied to high-clay-content soils, there can be an adverse effect on soil structure.

The resulting deflocculation and swelling of clay particles can significantly reduce the hydraulic capacity of the soil. The relationship between sodium, calcium, and magnesium is expressed as the sodium adsorption ratio (SAR) as defined by Eq. (3.5).

$$SAR = (Na) / [\,(Ca + Mg)/2]^{0.5} \tag{3.5}$$

where SAR = sodium adsorption ratio
Na = sodium concentration, meq/L
Ca = calcium concentration, meq/L
Mg = magnesium concentration, meq/L

Example 3.8: Sodium Adsorption Ratio

Conditions A municipal effluent with Na 37.9 mg/L, Ca 10.8 mg/L, Mg 3.8 mg/L.

Find The SAR of this effluent.

Solution

Atomic weights: Na = 22.99, Ca = 40.08, Mg = 24.32

$$\text{Meq Na} = (1)(37.9\ \text{mg/L})/(22.99) = 1.65$$

$$\text{Meq Ca} = (2)(10.8\ \text{mg/L})/(40.08) = 0.54$$

$$\text{Meq Mg} = (2)(3.8\ \text{mg/L})/(24.32) = 0.31$$

$$SAR = (1.65)/[(0.54 + 0.31)/2]^{0.5} = 2.53$$

An SAR of 10 or less should be acceptable on soils with significant clay content (15 percent clay or greater). Soils with little clay or nonswelling clays can tolerate an SAR up to 20. It is unlikely that problems of this type will occur with application of municipal effluents in any climate since the SAR of typical effluents seldom exceeds 5 to 8. Industrial wastewaters can be of more concern. The washwater from ion exchange water softening could have an SAR of 50, and some food-processing effluents range from about 30 to over 90. SAR problems are affected by the TDS of the wastewater, with more adverse effects occurring with low TDS water.[6]

The common remedial measure for SAR-induced soil swelling or permeability loss is the surface application of gypsum or another inexpensive source of calcium. The addition of water allows the calcium to leach into the soil to exchange with the sodium. An additional volume of water is then required to leach out the salt solution.

Salinity

Salinity problems are of most concern in arid regions, since the wastewater to be applied may already have a high salt content. This concentration will be further increased due to evapotranspiration, and because system design in arid regions is typically based on applying the minimal amount of water needed for the crop to grow. The combination of these factors will result in a rapid buildup of salts in the soil unless mitigation efforts are applied. The standard approach is to determine crop water needs and then add to that a leaching requirement (LR) to ensure that an adequate volume of water passes through the root zone to control salts. The LR can be determined if the salinity or electrical conductivity (EC) of the irrigation water and the required EC in the percolate to protect a specific crop are known.[36] The salt content of irrigation waters is often expressed as mg/L and can be converted to conductivity terms (mmho/cm) by dividing mg/L by 0.640. Equation (3.6) can be used to estimate the LR.

$$\mathrm{LR} = \frac{(\mathrm{EC})_I}{(\mathrm{EC})_D} \times 100 \tag{3.6}$$

where LR = leaching requirement as a percent
EC_I = average conductivity of irrigation water (including natural precipitation) , mmho/cm
EC_D = required conductivity in drainage water to protect the crop, mmho/cm

Typical values of EC_D for crops without yield reduction are given in Table 3.15.

Once the leaching requirement (LR) has been determined, the total water application can be calculated with Eq. (3.7).

$$L_W = (\mathrm{CU}) / (1 - \mathrm{LR}/100) \tag{3.7}$$

where L_W = required total water application, in
CU = consumptive water use by the crop between water applications, in
LR = leaching requirement as a percent

Example 3.9: Leaching Requirement

Conditions Given a wastewater effluent with 800 mg/L salinity; corn is the growing crop with EC_D = 5 mmho/cm; consumptive use between irrigations = 3 in.

Find The total water requirement.

Solution

$$\text{Conductivity of the effluent} = (800/0.640) = 1.25 \text{ mmho/cm}$$

$$\text{LR} = (1.25\ )/(5) \times 100 = 25\%$$

$$L_W = (3)/(1 - 0.25) = 4 \text{ in}$$

TABLE 3.15 Values of EC_D for Crops with No Yield Reduction[6]

Crop	Electrical conductivity EC_D, mmho/cm
Bermuda grass	13
Barley	12
Sugar beets	10
Cotton	10
Wheat	7
Tall fescue	7
Soybeans	5
Corn	5
Alfalfa	4
Orchard grass	3

A rule of thumb for total water needs to prevent salt buildup in arid climates is to apply the crop needs plus about 10 to 15 percent. Salinity problems and leaching requirements are not to be expected for land treatment systems in the more humid portions of the United States because natural precipitation is higher and higher hydraulic loadings are typically used to minimize the land area required.

Sulfur

Sulfur is usually present in most wastewaters in either the sulfate or the sulfite form. The source can be either waste constituents or background levels in the community water supply. Sulfate is not strongly retained in the soil but is usually found in the soil solution. Sulfates are not typically present in high enough concentrations in municipal wastewaters to be a concern for design of land treatment systems. Drinking water standards limit sulfate to 250 mg/L; irrigation standards recommend 200 to 600 mg/L depending on the type of vegetation. Industrial wastewaters from sugar refining, petroleum refining, and kraft process paper mills might all have sulfate or sulfite concentrations requiring special consideration. Crop uptake can account for some sulfur removal. Table 3.16 summarizes typical values for several crops.

If sulfur is the LDP, then the design procedure is similar to that described previously for nitrogen. It is prudent to assume that all of the sulfur compounds applied to the land will be mineralized to sulfate. The 250 mg/L standard for drinking water sulfate would then apply at the project boundary when drinking water aquifers are involved. It should be assumed in sizing the system that the major permanent removal pathway is to the harvested crop, and the values in Table 3.16 can be used for estimating purposes. If industrial wastes have particularly high organic contents, there may be additional immobilization of sulfur. It is recommended that specific pilot tests be run for industrial wastewaters of concern to determine the potential for removal under site-specific conditions.

Organic Priority Pollutants

Many organic priority pollutants are resistant to biological decomposition. Some are almost totally resistant and may persist in the environment for considerable periods of time; others are toxic or hazardous and require special management.

Volatilization, adsorption, and then biodegradation are the principal methods for removing these organic compounds in land treatment systems. Volatilization can occur at the water

TABLE 3.16 Sulfur Uptake by Selected Crops[30]

Crop	Harvested mass	Sulfur removed, lb/acre
Corn	200 bu/acre	44
Wheat	83 bu/acre	22
Barley	100 bu/acre	25
Alfalfa	6 ton/acre	30
Clover	4 ton/acre	18
Coastal Bermuda grass	10 ton/acre	45
Orchard grass	7 ton/acre	50
Cotton	2.5 bale/acre	23

surface of treatment and storage ponds and RI basins, in the water droplets used in sprinklers, in the water films on OF slopes, and on the exposed surfaces of biosolids. Adsorption occurs primarily on the organic matter, such as plant litter and similar residues, present in the system. In many cases microbial activity then degrades the adsorbed materials.

Volatilization

The loss of volatile organics from a water surface can be described with first-order kinetics, since it is assumed that the concentration in the atmosphere above the water surface is essentially zero. Equation (3.8) is the basic kinetic equation and Eq. (3.9) can be used to estimate the half-life of the contaminant of concern.

$$C_t / C_0 = e^{-} (K_{\text{vol}})\,(t)/(y) \tag{3.8}$$

where C_t = concentration at time t, mg/L
C_0 = concentration at t = 0, mg/L
K_{vol} = volatilization mass transfer coefficient, cm/h
= $(K_M)\,(y)$
K_M = overall volatilization rate coefficient, h^{-1}
y = depth of liquid, cm

$$t_{1/2} = (0.6930\,y/(K_{\text{vol}}) \tag{3.9}$$

where $t_{1/2}$ = time when concentration C_t = 1/2 (C_0) , h

The volatilization mass transfer coefficient K_M is a function of the molecular weight of the contaminant and the air-water partition coefficient as defined by the Henry's law constant as shown by Eq. (3.10).

$$K_{\text{VM}} = [(B_1) / (y)][(H) / (B_2 + H)(M^{1/2})] \tag{3.10}$$

where K_{VM} = volatilization mass transfer coefficient, h^{-1}
H = Henry's law constant, 10^5 (atm) (m^3) (mol^{-1})
M = molecular weight of contaminant of concern, g/mol
B_1, B_2 = coefficients specific to system of concern, dimensionless

Dilling[17] determined values for a variety of volatile chlorinated hydrocarbons at a well-mixed water surface:

$$B_1 = 2.211 \qquad B_2 = 0.01042$$

Jenkins et al.[24] determined values for a number of volatile organics on an overland flow slope:

$$B_1 = 0.2563 \qquad B_2 = 5.86\times10^{-4}$$

The coefficients for the overland flow case are much lower because the movement of water down the slope is nonturbulent and may be considered almost laminar flow (Reynolds number 100 to 400). The average depth of flowing water on this slope was about 1.2 cm.

Using a variation of Eq. (3.10), Parker and Jenkins[31] determined the volatilization losses from the droplets at a low-pressure, large-droplet wastewater sprinkler. In this case the y term in the equation is equal to the average droplet radius; as a result, their coefficients K'_{M} are valid only for the particular sprinkler used. Equation (3.11) was developed by Parker and Jenkins for the organic compounds listed in Table 3.17.

$$\text{In } (C_t/C_0) = 4.535\ (K'M + 11.02 \times 10^{-4}) \qquad (3.11)$$

Adsorption

Sorption of trace organics to the organic matter present in the land treatment system is thought to be the primary physicochemical mechanism of removal. The concentration of the trace organic which is sorbed relative to that in solution is defined by the partition coefficient K_P, which is related to the solubility of

TABLE 3.17 Volatile Organic Removal by Wastewater Sprinkling[31]

Substance	Calculated K'_M for Eq. (3.11), cm/min
Chloroform	0.188
Benzene	0.236
Toluene	0.220
Chlorobenzene	0.190
Bromoform	0.0987
n-Dichlorobenzene	0.175
Pentane	0.260
Hexane	0.239
Nitrobenzene	0.0136
m-Nitrotoluene	0.0322
PCB 1242	0.0734
Naphthalene	0.144
Phenanthrene	0.0218

the chemical. This value can be estimated if the octanol-water partition coefficient K_{OW} and the percentage of organic carbon in the system are defined. Jenkins et al.[24] determined that sorption of trace organics on an overland flow slope could be described with first-order kinetics with the rate constant defined by Eq. (3.12).

$$K_{SORB} = (B_3/y)\,[K_{OW}/\,(B_4 + K)\,(M)^{1/2}] \tag{3.12}$$

where K_{SORB} = sorption coefficient, h^{-1}
B_3 = coefficient specific to the treatment system
= 0.7309 for the OF system studied
y = depth of water on OF slope, 1.2 cm
K_{OW} = octanol-water partition coefficient
B_4 = coefficient specific to the system
= 170.8 for the overland flow system studied
M = molecular weight of the organic chemical, g/mol

In many cases the removal of these organics is due to a combination of sorption and volatilization. The overall process rate constant K_{SV} is then the sum of the coefficients defined with Eqs. (3.10) and (3.12), with the combined removal described by Eq. (3.13).

$$C_t/C_0 = e^{-}\,(K_{SV})\,(t) \tag{3.13}$$

where K_{SV} = overall rate constant for combined volatilization and sorption
= $K_{VM} + K_{SORB}$
C_t = concentration at time t, mg/L (or μg/L)
C_0 = initial concentration, mg/L (or μg/L)

Table 3.18 presents the physical characteristics of a number of volatile organics for use in the equations presented above for volatilization and sorption.

Removal performance

A number of land treatment systems have been studied extensively to document the removal of priority pollutant organic chemicals. This is probably due to the concern for groundwater contamination. Results from these studies have generally been positive. Table 3.19 presents removal performance for the three major land treatment concepts. The removals observed in the SR systems were after 5 ft of travel in the soils specified, and a

TABLE 3.18 Physical Characteristics for Selected Organic Chemicals[36]

Substance	K_{OW}*	H†	Vapor pressure‡	M§
Chloroform	93.3	314	194	119
Benzene	135	435	95.2	78
Toluene	490	515	28.4	92
Chlorobenzene	692	267	12.0	113
Bromoform	189	63	5.68	253
m-Dichlorobenzene	2.4×10^3	360	2.33	147
Pentane	1.7×10^3	125,000	520	72
Hexane	7.1×10^3	170,000	154	86
Nitrobenzene	70.8	1.9	0.23	122
m-nitrotoluene	282	5.3	0.23	137
Diethylphthalate	162	0.056	7×10^{-4}	222
PCB 1242	3.8×10^5	30	4×10^{-4}	26
Naphthalene	2.3×10^3	36	8.28×10^{-2}	128
Phenanthrene	2.2×10^4	3.9	2.03×10^{-4}	178
2,4-Dinitrophenol	34.7	0.001	—	184

*Octanol-water partition coefficient.
†Henry's law constant, 10^5 atm(m^3/mol) at 20°C and 1 atm.
‡Vapor pressure at 25°C.
§Molecular weight, g/mol.

low-pressure, large-droplet sprinkler was used for the applications. The removals noted for the OF system were measured after a flow on a terrace about 100 ft long, with application via gated pipe at the top of the slope. The RI data were obtained from sampling wells about 600 ft downgradient of the application basins.

The removals reported in Table 3.19 for SR systems represent concentrations in the applied wastewater ranging from 2 to 111 μg/L and percolate concentrations ranging from 0 to 0.4 μg/L. The applied concentrations in the OF system ranged from 25 to 315 μg/L and from 0.3 to 16 μg/L in the OF runoff. At the RI system influent concentrations ranged from 3 to 89 μg/L and the percolate ranged from 0.1 to 0.9 μg/L.

Phytoremediation

Phytoremediation involves the use of plants to treat or stabilize contaminated soils and groundwater. The technology has emerged as a response to the cleanup efforts for sites contaminated with toxic and hazardous wastes. Contaminants which have been successfully remediated with plants include petroleum hydrocarbons, chlorinated solvents, metals, radionuclides,

TABLE 3.19 Percent Removal of Organic Chemicals in Land Treatment Systems[36]

Substance	SR Sandy soil	SR Silty soil	OF	RI
Chloroform	98.57	99.23	96.50	>99.99
Toluene	>99.99	>99.99	99.00	99.99
Benzene	>99.99	>99.99	98.09	>99.99
Chlorobenzene	99.97	99.98	98.99	>99.99
Bromoform	99.93	99.96	97.43	>99.99
Dibromochloromethane	99.72	99.72	98.78	>99.99
m-Nitrotoluene	>99.99	>99.99	94.03	*
PCB 1242	>99.99	>99.99	96.46	>99.99
Naphthalene	99.98	99.98	98.49	96.15
Phenanthrene	>99.99	>99.99	99.19	*
Pentachlorophenol	>99.99	>99.99	98.06	*
2,4-Dinitrophenol	*	*	93.44	*
Nitrobenzene	>99.99	>99.99	88.73	*
m-Dichlorobenzene	>99.99	>99.99	*	82.27
Pentane	>99.99	>99.99	*	*
Hexane	99.96	99.96	*	*
Diethylphthalate	*	*	*	90.75

*Not reported.

and nutrients such as nitrogen and phosphorus. In 1998 it was estimated by Glass[19] that at least 200 field remediations or demonstrations have been completed or are in progress around the world. However, the "remediation" technology as currently used is not "new" but rather draws on the basic ecosystem responses and reactions documented in this and other chapters in this book. The most common applications depend on the plants to draw contaminated soil water to the root zone, where either microbial activity or plant uptake of the contaminants provides the desired removal. Evapotranspiration during the growing season provides for movement and elimination of the contaminated groundwater. Once taken up by the plant, the contaminants are either sequestered in plant biomass or possibly degraded and metabolized to a volatile form and transpired. In some cases the plant roots can also secrete enzymes which contribute to degradation of the contaminants in the soil.

Obviously, food crops and similar vegetation which might become part of the human food chain are not used on these remediation sites. Grasses and a number of tree species are the most common choices. Hybrid poplar trees have emerged as the most widely used species. These trees grow faster than other northern temperate zone trees, they have high rates of water and nutrient uptake, they are easy to propagate and establish from stem cuttings, and the large number of species varieties permit successful use at a variety of different site conditions. Cottonwood, willow, tulip, eucalyptus, and fir trees have also been used. Wang et al.,[45] for example, have demonstrated the successful removal by hybrid poplar trees (H11-11) of carbon tetrachloride (15 mg/L in solution). The plant degrades and dechlorinates the carbon tetrachloride and releases the chloride ions to the soil and carbon dioxide to the atmosphere.

References

1. Anderson, N., *Notice Paper* 15, Legislative Assembly, Victoria, Australia, 1976.
2. Anthony, R. G., "Effects of Municipal Wastewater Irrigation on Selected Species of Animals," in *Proceedings, Land Treatment Symposium,* U.S.A. CRREL, Hanover, N.H., 1978.
3. Arnold, R. G., D. D. Quanrad, G. Wilson, P. Fox, B. Alsmadi, G. Amy, and J. Debroux, "The Fate of Residual Wastewater Organics During Soil-Aquifer Treatment," presented at Joint AWWA/WEF Water Reuse Conference, San Diego, Calif., 1996.
4. Arizona State University, University of Arizona, University of Colorado, *Soil Treatability Pilot Studies to Design and Model Soil Aquifer Treatment Systems,* AWWA Research Foundation, Denver, Colo., 1998.
5. Asano, T. (Ed.), *Wastewater Reclamation and Reuse,* vol. 10, Water Quality Management Library, Technomic Publishing Co., Lancaster, Pa., 1998.
6. Ayers, R. S., "Quality of Water for Irrigation," *Journal Irrigation Division ASCE,* **103**(IRZ):135–154, ASCE, New York, 1997.
7. Bastian, R. K., *Summary of 40CFR Part 503, Standards for the Use or Disposal of Sewage Sludge,* U.S. Environmental Protection Agency, OWM, Washington, D.C., 1993.
8. Bausmith, D. S., and R. D. Neufeld, "Soil Biodegradation of Propylene Glycol Based Aircraft Deicing Fluids," *Journal WEF,* **71**(4):459–464 (1999).
9. Bell, R. G., and J. B. Bole, "Elimination of Fecal Coliform Bacteria from Soil Irrigated with Municipal Sewage Effluent," *Journal of Environmental Quality,* **7:**193–196 (1978).
10. Benham-Blair, "Long Term Effects of Land Application of Domestic Wastewater, Dickinson, ND Slow Rate," EPA 600/2-79-144, U.S. Environmental Protection Agency ORD, Washington, D.C., 1979.
11. Burken, J. G., and J. L. Schnoor, "Phytoremediation: Plant Uptake of Atrazine and Role of Root Exudates," *Journal ASCE,* EED 122/11 958-963, ASCE, New York, 1996.
12. Camann, D., "Evaluating the Microbiological Hazard of Wastewater Aerosols," *Contract Report* DAMD 17-75-C-5072, U.S. AMBRDL, Ft. Detrick, Md., 1978.
13. Chang, A. C., A. L. Page, and T. Asano, *Developing Human Health-Related Chemical Guidelines for Reclaimed Wastewater and Sewage Sludge Applications in Agriculture,* WHO/EOS/95.20, World Health Organization, Geneva, 114 pp., 1995.
14. Crites, R., and G. Tchobanoglous, *Small and Decentralized Wastewater Management Systems,* McGraw-Hill, New York, 1998.
15. Crites, R. W., Chapter 9, "Land Treatment," WPCF MOP FD-7 Nutrient Control, WPCF, Alexandria, Va., 1983.
16. Demirjian, Y., D. Kendrick, M. Smith, and T. Westman, "Muskegon County Wastewater Management System," EPA 905/2-80-004, U.S. Environmental Protection Agency, R.S. Kerr Laboratory, Ada, Okla, 1980.
17. Dilling, W. L., "Interphase Transfer Processes II, Evaporation of Chloromethanes, Ethanes, Ethylenes, Propanes, and Propylenes from Dilute Aqueous Solutions,

Comparisons with Theoretical Predictions," *Environmental Science Technology,* **11:**405–409 (1977).

18. George, D. B., N. Altman, D. Camann, B. Claborn, P. Graham, M. Guntzel, H. Harding, R. Harris, A. Holguin, K. Kimball, N. Klein, D. Leftwich, R. Mason, B. Moore, R. Northrup, C. Popescu, R. Ramsey, C. Sorber, and R. Sweazy, "The Lubbock Land Treatment System Research and Demonstration Project," U.S. Environmental Protection Agency, EPA/600/2-86/027, R.S. Kerr Laboratory, Ada, Okla, 1986.
19. Glass, D. G., *International Activities in Phytoremediation: Industry and Market Overview, Phytoremediation and Innovative Strategies for Specialized Remedial Applications,* Battelle Press, Columbus, Ohio, 1999, pp. 95–100 (1999).
20. Harrison, R. B., C. Henry, D. Xue, J. Canary, P. Leonard, and R. King, "The Fate of Metals in Land Application Systems," in *Proceedings The Forest Alternative—Principles and Practice of Residuals Use,* University of Washington, Seattle, Wash., 1997.
21. Hossner, L. R., "Sewage Disposal on Agricultural Soils—San Angelo, TX," U.S. Environmental Protection Agency, EPA 600/2/78-131a, ORD, Washington, D.C., 1978.
22. Hutchins, S. R., M. B. Thomsom, P. B. Bedient, and C. H. Ward, "Fate of Trace Organics During Land Application of Municipal Wastewater," *Critical Review Environmental Control,* **15**(4):355–416 (1985).
23. Jenkins, T. F., and A. J. Palazzo, "Wastewater Treatment by a Slow Rate Land Treatment System," *CRREL Report* 81-14, U.S.A. CRREL, Hanover, N.H., 1981.
24. Jenkins, T. F., D. C. Leggett, L. V. Parker, and J. L. Oliphant, "Trace Organics Removal Kinetics in Overland Flow Land Treatment," *Water Research,* **19**(6):707–718 (1985).
25. Kincannon, C. B. "Oily Waste Disposal by Soil Cultivation," U.S. Environmental Protection Agency, EPA-R2-72-110, Washington, D.C., 1972.
26. Koerner, E. L., and D. A. Haws, "Long Term Effects of Land Application of Domestic Wastewater, Roswell, NM," U.S. Environmental Protection Agency, EPA 600/2-79-047, ORD, Washington, D.C., 1979.
27. Kowal, N. E., *Health Effects of Land Application of Municipal Sludge,* NTIS PB86-19745678, NTIS, Springfield, Va., 1985.
28. Lance, J. C., and C. P. Gerba, "Poliovirus Movement During High Rate Land Filtration of Sewage Water," *Journal of Environmental Quality,* **9**(1):31–34 (1980).
29. Leach, L. E., C. G. Enfield, and C. C. Harlin, "Summary of Long Term Rapid Infiltration Studies," U.S. Environmental Protection Agency, EPA 600/2-80-165, R.S. Kerr Laboratory, Ada, Okla., 1980.
30. Overcash, M. R., and D. Pal, *Design of Land Treatment Systems for Industrial Wastes,* Ann Arbor Science, Ann Arbor, Mich., 1979.
31. Parker, L. V., and T. F. Jenkins, "Removal of Trace-Level Organics by Slow-Rate Land Treatment," *Water Research,* **20**(11):1417–1426 (1986).
32. Parsons, W. C., "Spray Irrigation of Wastes from the Manufacture of Hardboard," in *Proceedings Purdue Industrial Waste Conference,* **XXII:**602–607 (1967).
33. Perry, L. E., E. J. Reap, and M. Gilliland, "Pilot Scale Overland Flow Treatment of High Strength Snack Food Processing Wastewater," in *Proceedings, ASCE EED Conference,* Atlanta, Ga., ASCE, New York, July 1981.
34. Pound, C. E., R. W. Crites, and J. V. Olson, "Long Term Effects of Land Application of Domestic Wastewater, Hollister, CA, Rapid Infiltration Site," U.S. Environmental Protection Agency, EPA 600/2-78-084, Cincinnati, Ohio, 1978.
35. Reed, S. C. (Ed.), "Wastewater Management by Disposal on the Land," *Special Report* 171, U.S.A. CRREL, Hanover, N.H., 1972.
36. Reed, S. C., R. W. Crites, and E. J. Middlebrooks, *Natural Systems for Waste Management and Treatment,* 2d ed., McGraw-Hill, New York, 1995.
37. Sheikh, B., P. Cort, W. Kirkpatrick, R. Jaques, and T. Asano, "Monterey Wastewater Reclamation Study for Agriculture," *Research Journal WPCF,* **62:**216–226, WEF, Alexandria, Va., 1990.
38. Shuval, H. I., and B. Teltch, "Hygenic Aspects of the Dispersion of the Enteric Bacteria and Virus by Sprinkled Irrigation of Wastewater," in *Proceedings of AWWA Water Reuse Symposium,* 1979.

39. Smith, J. H., "Treatment of Potato Processing Wastewater on Agricultural Land: Water and Organic Loading and the Fate of Applied Nutrients," in R. C. Loehr (Ed.), *Land as a Waste Management Alternative,* Ann Arbor Science, Ann Arbor, Mich., 1977.
40. Smith, R. G., and E. D. Schroeder, *Demonstration of the Overland Flow Process for the Treatment of Municipal Wastewater, Phase II Field Studies,* Department of Civil Engineering, University of California, Davis, Davis, Calif., 1982.
41. U.S. Environmental Protection Agency, *Process Design Manual for Land Treatment of Municipal Wastewater,* EPA 625/1-81-013, U.S. Environmental Protection Agency CERI, Cincinnati, Ohio, 1981.
42. U.S. Environmental Protection Agency, *Process Design Manual Land Treatment of Municipal Wastewater, Supplement on Rapid Infiltration and Overland Flow,* EPA 625/1-81-013a, U.S. Environmental Protection Agency CERI, Cincinnati, Ohio, 1984.
43. U.S. Environmental Protection Agency, *Estimating Microorganism Densities in Aerosols from Spray Irrigation of Wastewater,* EPA 600/9-82-003, Cincinnati, Ohio, 1982.
44. Wallace, A. T., "Rapid-Infiltration Disposal of Kraft Mill Effluent," in *Proceedings, 30th Industrial Waste Conference,* 506–518, Purdue University, Lafayette, Ind., 1975.
45. Wang, X., L. E. Newman, and M. P. Gordon, Biodegradation of Carbon Tetrachloride by Poplar Trees: Results from Cell Culture and Field Experiments*," in Phytoremediation and Innovative Strategies for Specialized Remedial Applications,* Battell Press, Columbus, Ohio, 1999.
46. Witherow, J. L., and B. E. Bledsoe, "Algae Removal by the Overland Flow Process," *Journal WPCF,* **55**(10):1256–1262 (1983).
47. Zirschky, J., "Meeting Ammonia Limits Using Overland Flow," *Journal WEF,* **61:**1225–1232 (1989).

Chapter

4

Hydraulics of Soil Systems

The hydraulic capacity of the soil to accept and transmit water is crucial to the design of rapid infiltration (RI) systems and important in the design of most slow rate (SR) systems. The important hydraulic factors are infiltration, vertical permeability (percolation), horizontal permeability, groundwater mounding, and the relationship between predicted capacity and actual operating rates.

Soil Properties

The hydraulics of soil systems are controlled by the physical and chemical properties of soil. Important physical properties include texture, structure, and soil depth. Chemical characteristics that can be important include pH, organic matter, and exchangeable sodium percentage. Information on these soil properties and on soil permeability can be obtained from the Natural Resources Conservation Service (NRCS) and their detailed soil surveys.

Soil surveys will normally provide soil maps delineating the apparent boundaries of soil series with their surface texture. A written description of each soil series provides limited information on chemical properties, engineering applications, interpretive and management information, slopes, drainage, erosion potentials, and general suitability for most kinds of crops grown in the particular area. Additional information on soil characteristics and information regarding the availability of soil surveys can be obtained directly from the NRCS. The NRCS serves as the coordinating agency for the National Cooperative Soil Survey and as such cooperates with other government agencies, universities, and agricultural extension services in obtaining and distributing soil survey information.

Soil physical properties

The physical properties of texture and structure are important because of their effect on hydraulic properties. Soil textural classes are defined on the basis of the relative percentage of the three classes of particle size—sand, silt, and clay. Sand particles range in size from 2.0 to 0.05 mm; silt particles range from 0.05 to 0.002 mm; and particles smaller than 0.002 mm are clay. From the particle size distribution, the textural class can be determined using the textural triangle shown in Fig. 4.1.

Fine-textured soils do not drain well and retain large percentages of water for long periods of time. As a result, crop management is more difficult than with more freely drained soils such as loamy soils. Fine-textured soils are generally best suited to overland flow systems. Medium-textured soils exhibit the best balance for wastewater renovation and drainage. Loam (medium-textured) soils are generally best suited for slow rate systems.

Coarse-textured soils (sandy soils) can accept large quantities of water and do not retain moisture very long. This feature is important for crops that cannot withstand prolonged submergence or saturated root zones. Soil structure refers to the aggregation of individual soil particles. If these aggregates resist disintegration when the soil is wetted or tilled, it is well structured. The large pores in well-structured soils conduct water and air, making well-structured soils desirable for infiltration.

Adequate soil depth is needed for retention of wastewater constituents on soil particles, for plant root development, and for bacterial action. Retention of wastewater constituents, as explained in Chap. 3, is a function of residence time of wastewater in the soil. Residence time depends on the application rate and the soil permeability.

The type of land treatment process being considered will determine the minimum acceptable soil depth. For SR, the soil depth can be 2 to 5 ft (0.6 to 1.5 m), depending on the soil texture and crop type. For example, soil depths of 1 to 2 ft (0.3 to

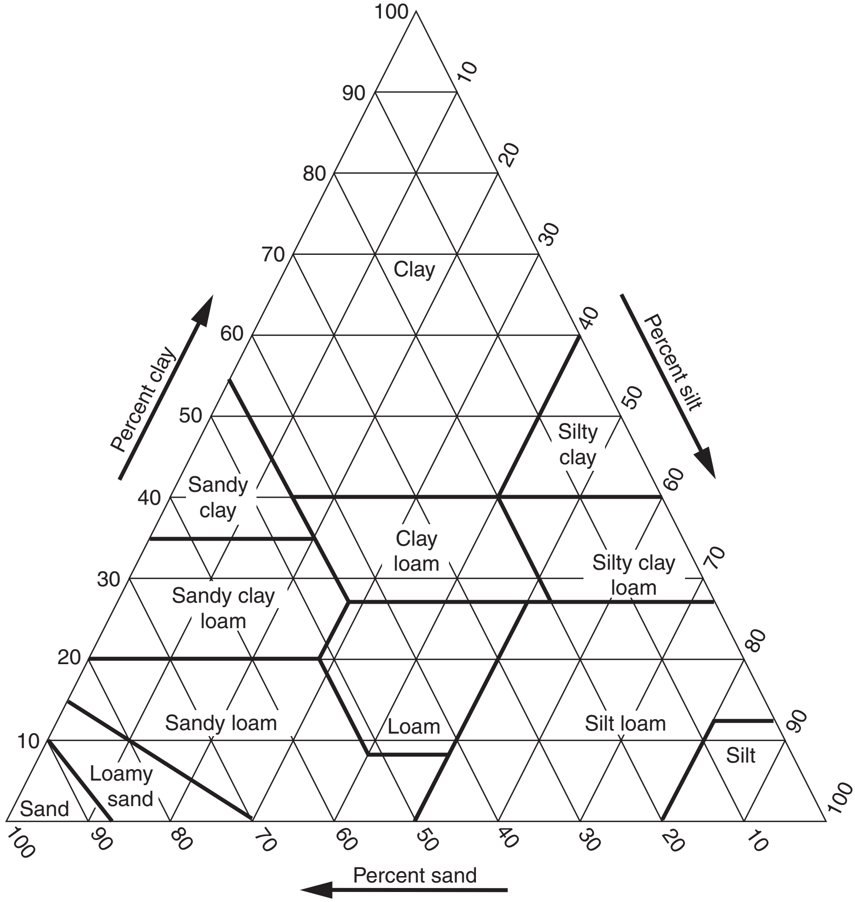


Figure 4.1 Natural Resources Conservation Service (NRCS) soil textural classes. (*After Ref. 14.*)

0.6 m) can support grass or turf, whereas deep-rooted crops do better on soil depths of 4 to 5 ft (1.2 to 1.5 m).

The soil depth for RI should be at least 5 ft and preferably 5 to 10 ft (1.5 to 3 m). Overland flow systems require sufficient soil depth to form slopes that are uniform and to maintain a vegetative cover. A finished slope should have a minimum of 6 to 12 in (0.15 to 0.3 m) of soil depth.

Soil chemical properties

Soil chemical properties affect plant growth and wastewater renovation and can affect hydraulic conductivity. Soil pH affects plant growth, bacterial growth, and retention of elements such as phosphorus in the soil. Organic matter can improve soil structure and thereby improve the hydraulic conductivity. Sodium can reduce the hydraulic conductivity of soil by dispersing clay particles and destroying the structure that allows water movement. Soils containing excessive exchangeable sodium are termed "sodic" or "alkali." A soil is considered sodic if the percentage of the total cation exchange capacity (CEC) occupied by sodium, the exchangeable sodium percentage (ESP), exceeds 15 percent. Fine-textured soils may be affected at an ESP above 10 percent, but coarse-textured soil may not be damaged until the ESP reaches about 20 percent. See Chap. 3 for additional discussion of sodium.

Water Movement in Soil

Infiltration rate

The rate at which water enters the soil surface, measured in inches per hour, is the infiltration rate. The infiltration rate is usually higher at the beginning of water application than it is several hours later. Infiltration rates are related to the extent of large interconnected pore spaces in the soil. Coarse-textured soils with many large pores have higher infiltration rates than fine-textured soils or soils in which the pore space is reduced in size by compaction or a breakdown of soil aggregates.

For a given soil, initial infiltration rates may vary considerably, depending on the initial soil moisture level. Dry soil has a higher initial rate than wet soil because there is more empty pore space for water to enter. The short-term decrease in infiltration rate is primarily due to the change in soil structure and the filling of large pores as clay particles absorb water and swell. Thus, adequate time must be allowed when running field tests to achieve a steady intake rate.

Infiltration rates are affected by the ionic composition of the soil water, the type of vegetation, and tillage of the soil surface. Factors that have a tendency to reduce infiltration rates include clogging by suspended solids in wastewater, classification of fine soil particles, clogging due to biological growths, gases produced by soil microbes, swelling of soil colloids, and air entrapped during a wetting event.[2,3] These influences are all likely to be experienced when a site is developed into a land treatment system. The net result is to restrict the hydraulic loadings of land treatment systems to values substantially less than those predicted from the steady-state intake rates, requiring reliance on field-developed correlations between clean water infiltration rates and satisfactory operating rates for full-scale systems. It should be recognized that good soil management practices can maintain or even increase operating rates, whereas poor practices can lead to substantial decreases.

Intake

The rate at which water in a furrow enters the soil is referred to as the intake rate.[4] Irrigation texts have used the term "basic intake rate" as synonymous with infiltration rate.[5] In furrow irrigation the intake rate is influenced by the furrow size and shape. Therefore, when the configuration of the soil surface influences the rate of water entry, the term intake rate should be used rather than the term infiltration rate (which refers to a relatively level surface covered with water).

Permeability

The permeability or hydraulic conductivity (used interchangeably in this book) is the velocity of flow caused by a unit gradient. Permeability is not influenced by the gradient, and this is an important difference between infiltration and permeability.

Vertical permeability is also known as percolation. Lateral flow is a function of the gradient and the horizontal permeability (which is generally different from the percolation rate). Permeability is affected mostly by the soil physical properties. Changes in water temperature can affect permeability slightly.[4]

Transmissivity

Transmissivity of an aquifer is the product of the permeability K and the aquifer thickness. It is the rate at which water is transmitted through a unit width of aquifer under a unit hydraulic gradient.

Specific yield

The term specific yield is the volume of water released from a known volume of saturated soil under the force of gravity and inherent soil tension.[1] The specific yield is also referred to as the storage coefficient and the drainable voids. The primary use of specific yield is in aquifer calculations such as drainage and mound height analyses.

For relatively coarse-grained soils and deep water tables, it is usually satisfactory to consider the specific yield a constant value. As computations are not extremely sensitive to small changes in the value of specific yield, it is usually satisfactory to estimate it from knowledge of other soil properties, either physical as in Fig. 4.2[6] or hydraulic as in Fig. 4.3.[1] To clarify Fig. 4-2, specific retention is equal to the porosity minus the specific yield.

Water-holding capacity

Soil water can be classified as hygroscopic, capillary, and gravitational. Hygroscopic water is on the surface of soil particles and is not removed by gravity or by capillary forces. Capillary water is the water held in soil pores against gravity.

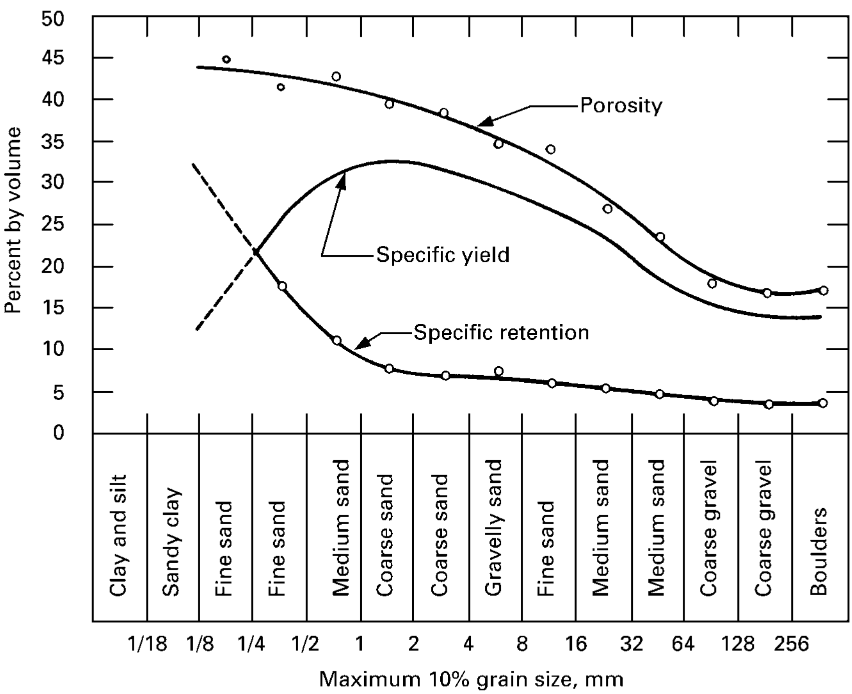


Figure 4.2 Porosity, specific yield, specific retention vs. soil grain size. (*After Ref. 11.*)

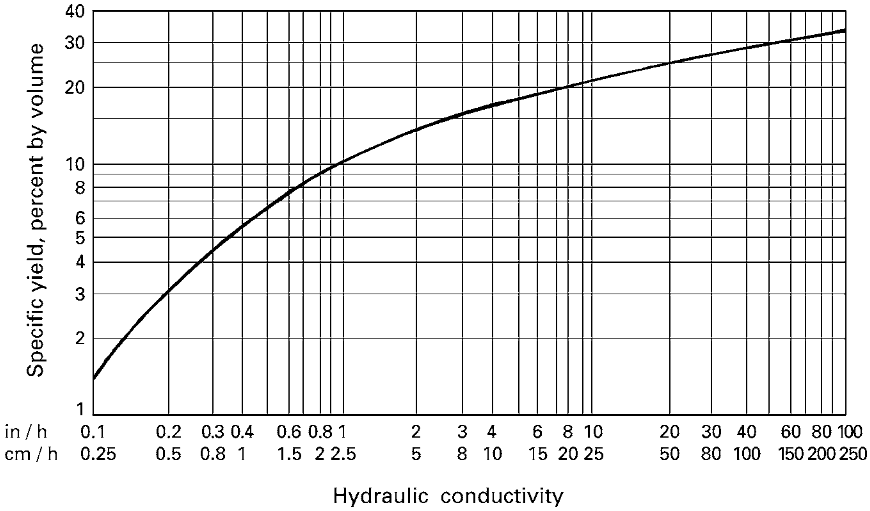


Figure 4.3 Specific yield vs. hydraulic conductivity. (*After Ref. 11.*)

Gravitational water is the water that will drain by gravity if favorable drainage is provided.[4]

Soil water can also be classified according to its availability to plant root systems. As illustrated in Fig. 4.4, the maximum available water occurs at saturation (point 1), when all the pore space is filled with water. When the soil water drops to point 3, only hygroscopic water is left, which is unavailable to plants.

Field capacity. When gravitational water has been removed, the moisture content of the soil is called the field capacity. In practice the field capacity is measured 2 days after water application and can range from 3 percent moisture for fine sand to 40 percent for clay. The range of moisture percentages for field capacity for various soil types is presented in Table 4.1. Relationships of field conditions to soil moisture content are presented in Table 4.2.

Permanent wilting point. The soil moisture content at which plants will wilt from lack of water is known as the permanent wilting point. The available moisture content is generally defined as the difference between the field capacity and the permanent wilting point. This represents the moisture that can be stored in the soil for subsequent use by plants. For SR systems with poorly drained soils, this stored moisture is important to design loadings.

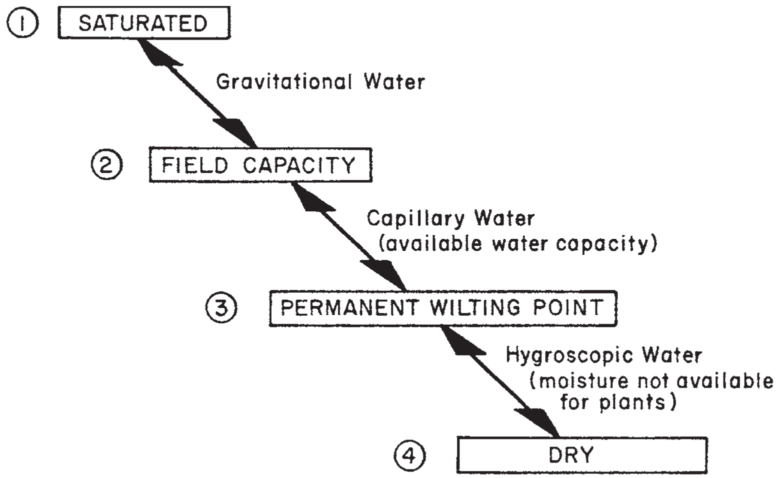


Figure 4.4 Soil moisture characteristics.

TABLE 4.1 Range of Available Soil Moisture for Different Soil Types[2]

Soil type	Moisture percentage: Field capacity	Moisture percentage: Permanent wilting point	Depth of available water per unit depth of soil, in/ft
Fine sand	3–5	1–3	0.3–0.5
Sandy loam	5–15	3–8	0.5–1.3
Silt loam	12–18	6–10	0.7–1.6
Clay loam	15–30	7–16	1.2–2.2
Clay	25–40	12–20	2.0–3.5

As an approximation the permanent wilting percentage can be obtained by dividing the field capacity by 2. For soils with high silt content, divide the field capacity by 2.4 to obtain permanent wilting percentage.

Saturated Hydraulic Conductivity

In general, water moves through soils or porous media in accordance with Darcy's equation:

$$q = \frac{Q}{A} = K\frac{dh}{dl} \tag{4.1}$$

where q = flux of water, the flow Q (ft^3/d) per unit cross-sectional area A (ft^2), ft/d

K = hydraulic conductivity (permeability) , ft/d

dh/dl = hydraulic gradient, ft/ft

TABLE 4.2 Field Estimating of Soil Moisture Content*

Fine texture	Medium texture	Moderately coarse texture	Coarse texture
No free water after squeezing, wet, outline on hand	Same as fine texture	Same as fine texture	Same as fine texture
0.0	0.0	0.0	0.0
Easily ribbons out between fingers, has slick feeling	Forms a very pliable ball, sticks readily if high in clay	Forms weak ball, breaks easily, will not stick	Sticks together slightly, may form a very weak ball . under pressure
0.0–0.6	0.0–0.5	0.0–0.4	0.0–0.2
Forms a ball, ribbons out between thumb and forefinger	Forms a ball, sometimes sticks slightly with pressure	Tends to ball under pressure but will not hold together	Appears dry, will not form a ball when squeezed
0.6–1.2	0.5–1.0	0.4–0.8	0.2–0.5
Somewhat pliable, will form a ball when squeezed	Somewhat crumbly but holds together from pressure	Appears dry, will not form a ball	Appears dry, will not form a ball
1.2–1.9	1.0–1.5	0.8–1.2	0.5–0.8
Hard, baked, cracked	Powdery, dry, sometimes slightly crusted but easily broken down into powdery condition	Dry, loose, flows through fingers	Dry, loose, single-, grained flows through fingers
1.9–2.5	1.5–2.0	1.2–1.5	0.8–1.0

*The numerical values are the amount of water (in) that would be needed to bring the top foot of soil to field capacity.

The total head H can be assumed to be the sum of the soil-water pressure head h and the head due to gravity Z, or $H = h + Z$. The hydraulic gradient is the change in total head dh over the path length dl.

The hydraulic conductivity is defined as the proportionality constant K. The conductivity K is not a true constant but a rapidly changing function of water content. Even under conditions of constant water content, such as saturation, K may vary over time due to increased swelling of clay particles, change in pore size distribution due to classification of particles, and change in the chemical nature of soil water. However, for most purposes, saturated conductivity K can be considered constant for a given soil. The K value for flow in the vertical direction will not necessarily be equal to K in the horizontal direction. This condition is known as anisotropic. It is especially apparent in layered soils and those with large structural units. An illustration of anisotropic conditions is shown in Table 4.3.

The value of K depends on the size and number of pores in the soil or aquifer material. Orders of magnitudes for vertical conductivity (K_v) values in feet per day for typical soils are[10]

Soil or Aquifer Material	K_v, *ft/day*
Clay soils (surface)	0.03–0.06
Deep clay beds	3×10^{-8}–0.03
Clay, sand, gravel mixes (till)	0.003–0.3
Loam soils (surface)	0.3–3.0
Fine sand	3–16
Medium sand	16–66
Coarse sand	66–300
Sand and gravel mixes	16–330
Gravel	330–3300

TABLE 4.3 Measured Ratios of Horizontal to Vertical Conductivity[8,9]

Site	Horizontal conductivity Kh, ft/day	Kh/Kv	Remarks
1	138	2.0	Silty
2	246	2.0	
3	184	4.4	
4	328	7.0	Gravelly
5	236	20.0	Near terminal moraine
6	236	10.0	Irregular succession of sand and gravel layers (from K measurements in field)
6	282	16.0	(From analysis of recharge flow system)

Example 4.1: Subsurface Flow

Conditions The soil on the hillside (Fig. 4.5) is a loam with a hydraulic conductivity as shown in the sketch.

Solution Calculate the transmissivity and the unit flow rate under saturated conditions.

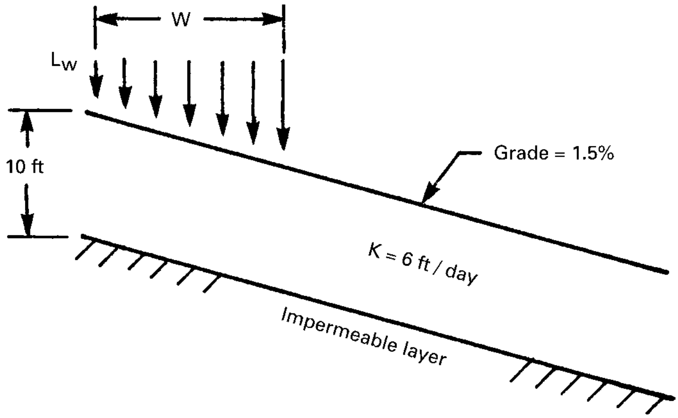


Figure 4.5 Subsurface flow for Example 4.1.

1. Since flow is essentially in the horizontal direction, the grade of the impermeable layer determines the hydraulic gradient.

$$T = KD \tag{4.2}$$

where T = transmissivity, ft²/day [= (6 ft/day) (10 ft) = 60 ft²/day: Converting to gallons per day, multiply by 7.48 to get T = 448.8 gal/(day·ft)]
K = hydraulic conductivity, ft/day
D = depth of aquifer, ft

The flow under saturated conditions is

$$q = Ti$$

where q = gal/ (day · ft)
T = gal/ (day · ft)
i = gradient, ft/ft
q = 448.8 (0.015) = 6.73 gal/ (day · ft)

2. The combination of loading rate L_w and width of application area W cannot exceed the saturated flow q = 6.73 gal/(day·ft). For a loading rate of 0.1 ft/day, calculate the width W.

$$L_w W = \frac{6.73}{7.48} = 0.9 \text{ ft}^2/\text{day}$$

$$W = \frac{0.9}{L_w}$$

$$W = \frac{0.9}{0.1}$$

$$W = 9 \text{ ft}$$

Unsaturated Hydraulic Conductivity

Darcy's law for velocity of flow in saturated soils applies also to unsaturated soils. As the moisture content decreases, however, the cross-sectional area through which the flow occurs also decreases and the conductivity is reduced.

The conductivity of soil varies dramatically as water content is reduced below saturation. As an air phase is now present, the flow channel is changed radically and now consists of an irregular solid boundary and the air-water interface. The flow path becomes more and more tortuous with decreasing water content as the larger pores empty and flow becomes confined to the smaller pores. Compounding the effect of decreasing cross-sectional area for flow is the effect of added friction as the flow takes place closer and closer to solid particle surfaces. The conductivity of sandy soils, although much higher at saturation than loam soils, decreases more rapidly as the soil becomes less saturated. In most cases, the conductivities of sandy soils eventually become lower than those of finer soils. This relationship explains why a wetting front moves more slowly in sandy soils than in medium- or fine-textured soils after irrigation has stopped and why there is little horizontal spreading of moisture in sandy soils after irrigation.

Percolation Capacity

The percolation capacity of SR and RI systems is a critical parameter in planning, design, and operation. The capacity will vary within a given site and may change with time, season, and different management. For planning purposes the infiltration capacity can be estimated from the vertical permeability rates assigned by the NRCS (Fig. 4.6).

Design percolation rate

To account for the needed drying time between applications, the variability of the actual soil permeability within a site, and the potential reduction with time, a small percentage of the vertical permeability is used as the design percolation rate. This small percentage ranges from 4 to 10 percent of the saturated vertical permeability, as shown in Fig. 4.6. The value used for clear water permeability should be for the most restrictive layer in the soil

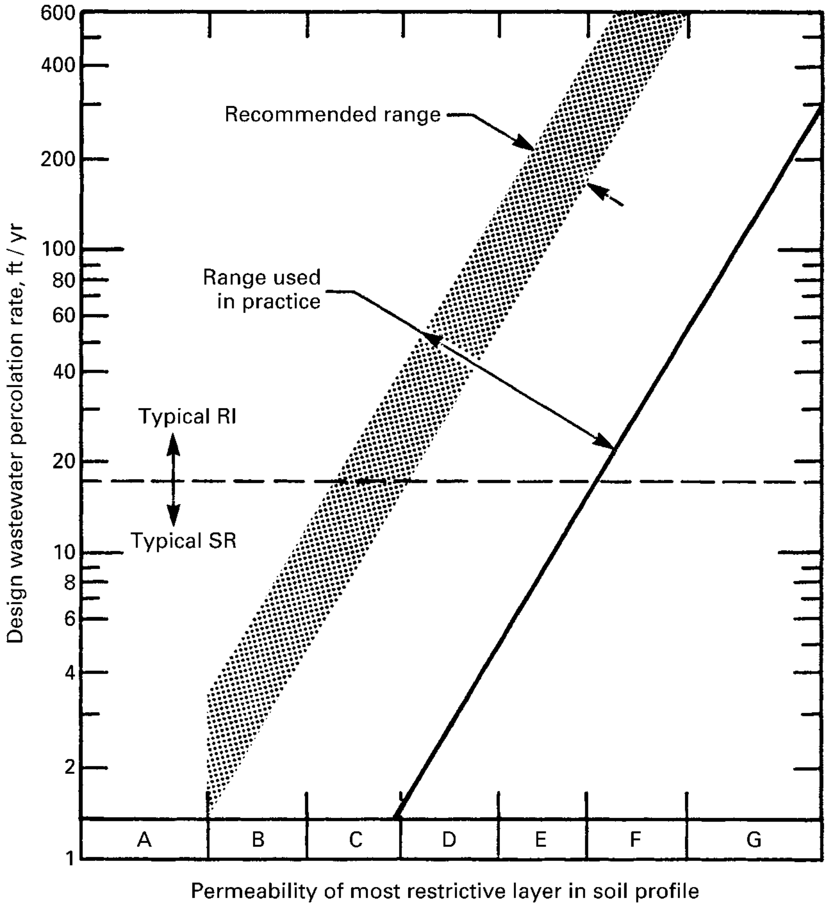


Figure 4.6 Design percolation rate vs. NRCS soil permeability for SR and RI. The zones A through G refer to clearwater permeability for the most restrictive layer in the soil profile (K_v = in/h): A = very slow, <0.06; B = slow, 0.06 to 0.20; C = moderately slow, 0.20 to 0.60; D = moderate, 0.60 to 2.0; E = moderately rapid, 2.0 to 6.0; F = rapid, 6.0 to 20; G = very rapid, >20. (*After Ref. 11.*)

profile. Design rates based on field measurement (Chap. 7) may be calculated using different percentages (Chaps. 10 and 12).

Example 4.2: Determining Design Percolation Rate

Conditions Given a soil with a permeability (most restrictive layer) of 0.6 to 2 in/h (moderate permeability). Determine the design wastewater percolation rate.

Solution Using the 0.6 in/h rate, enter Fig. 4.6 and proceed vertically to the hatched area. For a conservative value, proceed horizontally to the left to a value of 17 ft/year. To obtain the maximum value recommended for planning, proceed vertically to the top of the hatched area (10 percent value) and pick off the design percolation rate of 42 ft/year. If the planned application season is less than 365 days, the percolation rate should be reduced to coincide with the planned application period.

Calculation of vertical permeability

The rate at which water percolates through soil depends on the average saturated permeability K of the profile. If the soil is uniform, K is assumed to be constant with depth. Any differences in measured values of K are then due to normal variations in the measurement technique. Thus, average K may be computed as the arithmetic mean of n samples:

$$K_{\mathrm{am}} = \frac{K_1 + K_2 + K_3 + \cdots + K_n}{n} \tag{4.3}$$

where K_{am} = arithmetic mean vertical conductivity

Many soil profiles approximate a layered series of uniform soils with distinctly different K values, generally decreasing with depth. For such cases, it can be shown that average K is represented by the harmonic mean of the K values from each layer:[12]

$$\mathrm{K}_{\mathrm{hm}} = \frac{D}{\dfrac{d_1}{K_1} + \dfrac{d_2}{K_2} + \cdots + \dfrac{d_n}{K_n}} \tag{4.4}$$

where D = soil profile depth
d_n = depth of nth layer
K_{hm} = harmonic mean conductivity

If a bias or preference for a certain K value is not indicated by statistical analysis of field test results, a random distribution of K for a certain layer or soil region must be assumed. In such cases, it has been shown that the geometric mean provides the best and most conservative estimate of the true K:[12,13,14]

$$K_{\mathrm{gm}} = (K_1 \cdot K_2 \cdot K_3 \cdot \cdots K_{\mathrm{n}})^{1/\mathrm{n}} \tag{4.5}$$

where K_{gm} = geometric mean conductivity

Example 4.3: Geometric Mean Calculation of Permeability

Conditions Consider a soil profile with vertical permeabilities of K_1 = 2 in/h, K_2 = 0.6 in/h, and K_3 = 4 in/h.

Solution Calculate the geometric mean conductivity

$$K_{gm} = [(2)(0.6)(4)]^{1/3}$$
$$= 1.69 \text{ in/h}$$

Profile drainage

For SR and RI systems the soil profile must drain between applications to allow the soil to reaerate. The time required for profile drainage is important to system design and varies with the soil texture and the presence of restrictions (such as fragipans, clay pans, and hardpans). In sandy soils without vertical restrictions, the profile can drain in 1 to 2 days. In clayey soils drainage may take 5 days or more. The drying period between applications also depends on the evaporation rate (Chap. 5).

Groundwater Mounding

If water that infiltrates the soil and percolates vertically through the zone of aeration encounters a water table or an impermeable (or less permeable) layer, a groundwater "mound" will begin to grow (see Fig. 4.7).

If the mound height continues to grow, it may eventually encroach on the zone of aeration to the point where renovation capacity is affected. Further growth may result in intersection of the mound with the soil surface, which will reduce infiltration rates. This problem can usually be identified and analyzed before the system is designed and built if the prior geologic and hydrologic information is available for analysis.

Prediction of mounding

Groundwater mounding can be estimated by applying heat-flow theory and the Dupuit-Forchheimer assumptions.[13] These assumptions are as follows:

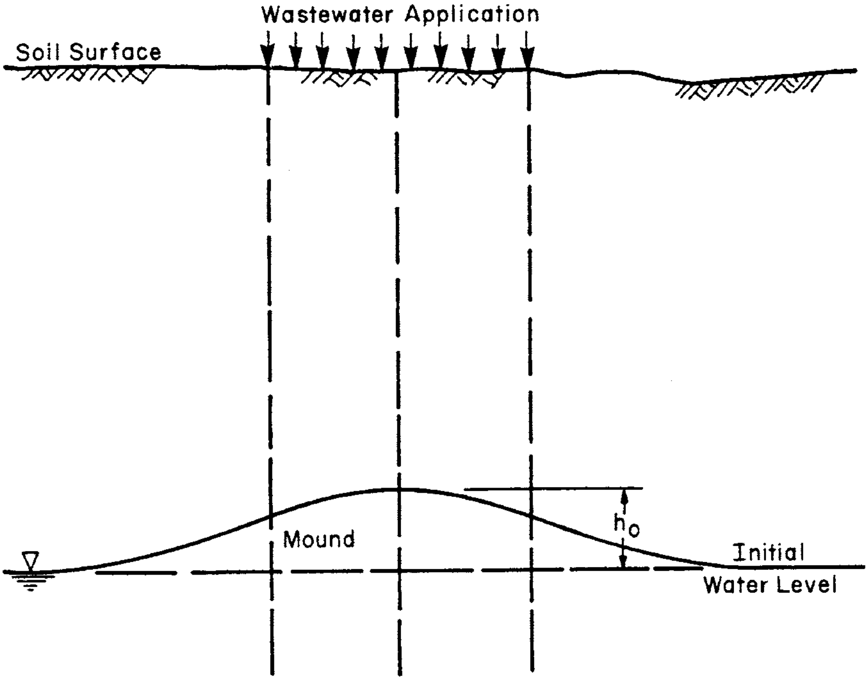


Figure 4.7 Schematic of groundwater mound.

1. Flow within groundwater occurs along horizontal flow lines whose velocity is independent of depth.
2. The velocity along these horizontal streamlines is proportional to the slope of the free water surface.

Using these assumptions, heat-flow theory has been successfully compared to actual groundwater depths at several existing RI sites. To compute the height at the center of the groundwater mound, one must calculate the values of $W/(4\alpha t)^{1/2}$ and Rt.

where W = width of the recharge basin, ft

$$\alpha = \text{aquifer constant} = \frac{KD}{V}, \text{ ft}^2/\text{day}$$

K = aquifer (horizontal) hydraulic conductivity, ft/day
D = saturated thickness of the aquifer, ft
V = specific yield or fillable pore space of the soil, ft^3/ft^3 (Figs. 4.2 and 4.3)
t = length of wastewater application, days

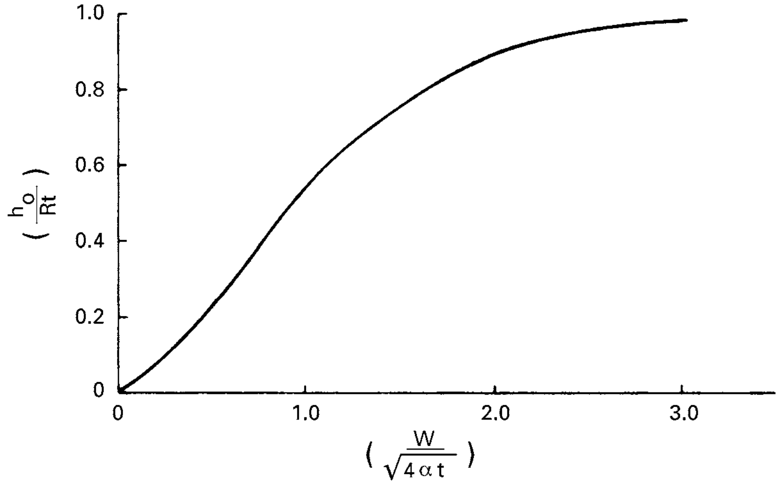


Figure 4.8 Mounding curve for center of a square recharge area. (*After Ref. 11.*)

$R = I/V$, ft/day, rate of rise if no lateral flow occurred
$I =$ application rate, ft/day

Once the value of $W/(4\alpha t)^{1/2}$ is obtained, one can use dimensionless plots of $W/(4\alpha t)^{1/2}$ versus h_o/Rt, provided as Figs. 4.8 (for square recharge areas) and 4.9 (for rectangular recharge areas), to obtain the value of h_o/Rt, where h_o is the rise at the center of the mound. Using the calculated value of Rt, one can solve for h_o.

Example 4.4: Mound Height Analyses

Conditions Consider a situation where an RI system is proposed with square infiltration basins. The saturated thickness D of the aquifer is 50 ft. The horizontal hydraulic conductivity K measured by the auger hole method (see Chap. 7) is 8 ft/day.

Solution Using Fig. 4.3 with this K value, the specific yield is found to be 17.5 percent. The basins are to be 100 ft wide and square; the application rate I is 1 ft/day and the application period t is 2 days.

1. First calculate the aquifer constant:

$$\alpha = \frac{KD}{V} = \frac{8(50)}{0.175} = 2286 \text{ ft}^2\text{/day}$$

2. Next calculate the rate of rise R.

$$R = \frac{I}{V} = \frac{1}{0.175} = 5.7 \text{ ft/day}$$

3. Then calculate the factor $W/(4\alpha t)^{1/2}$

$$\frac{W}{(4\alpha t)^{1/2}} = \frac{100}{[4(2286)(2)]^{1/2}} = 0.74$$

Enter Fig. 4.8 with the value of 0.74 on the abscissa, and the resultant value of h_o/Rt equals 0.37.

4. Finally, calculate h_o, the height of the groundwater mound:

$$h_o = 0.37\,Rt = 0.37\,(5.7)(2) = 4.2 \text{ ft}$$

5. The initial depth to groundwater is 15 ft, and the calculated mound height of 4.2 ft would bring the groundwater to within 10.8 ft of the ground surface. In this situation there would not be a need for engineered drainage. If the calculations should indicate that the groundwater table will rise to within 3 to 5 ft of the basin bottom, additional drainage will be needed.

Figures 4.10 (for square recharge areas) and 4.11 (for recharge areas that are twice as long as they are wide) can be used to esti-

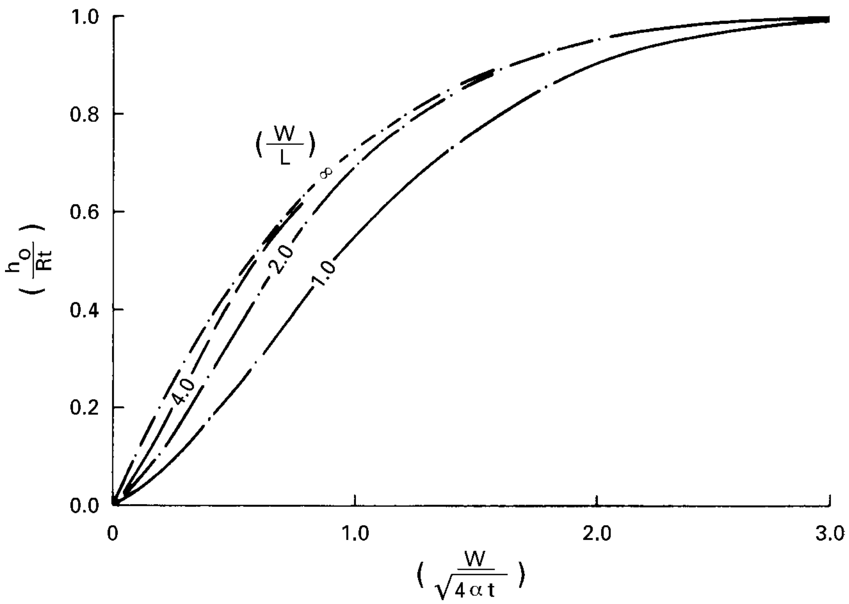


Figure 4.9 Mounding curve for center of a rectangular recharge area, with different ratios of length L to width W. (*After Ref. 11.*)

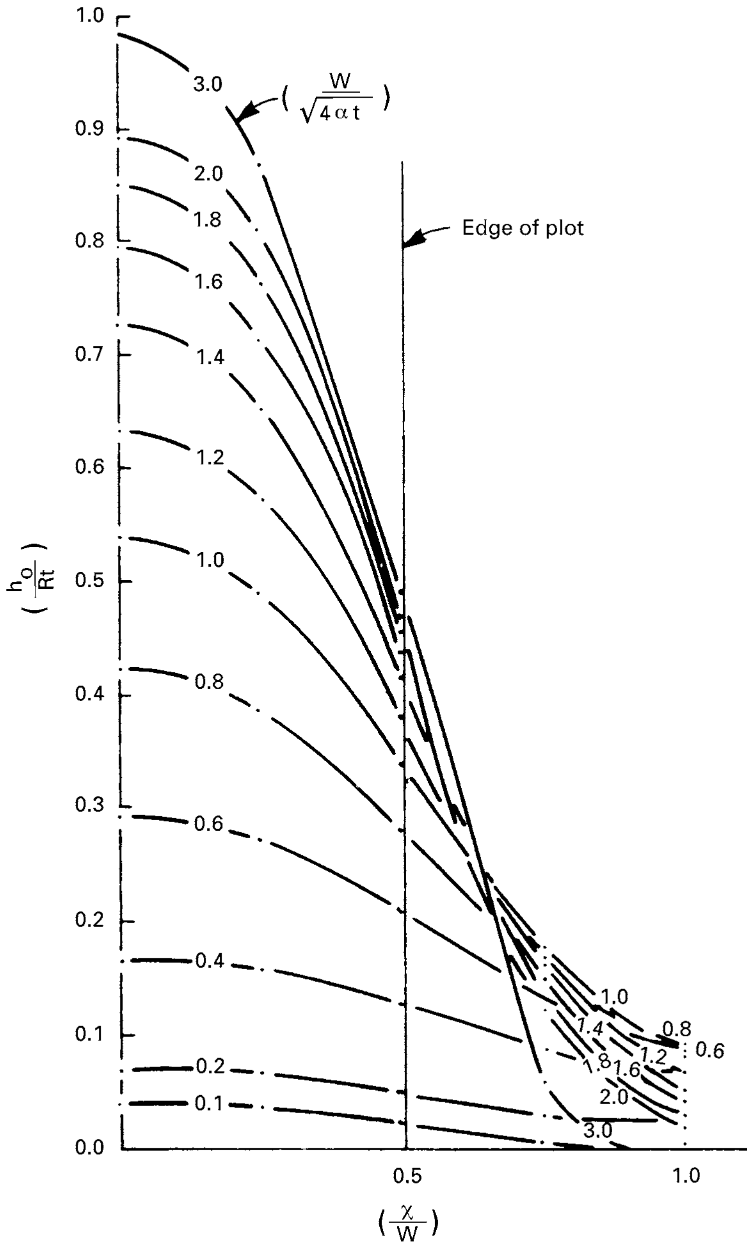


Figure 4.10 Rise and horizontal spread of a mound below a square recharge area. (*After Ref. 11.*)

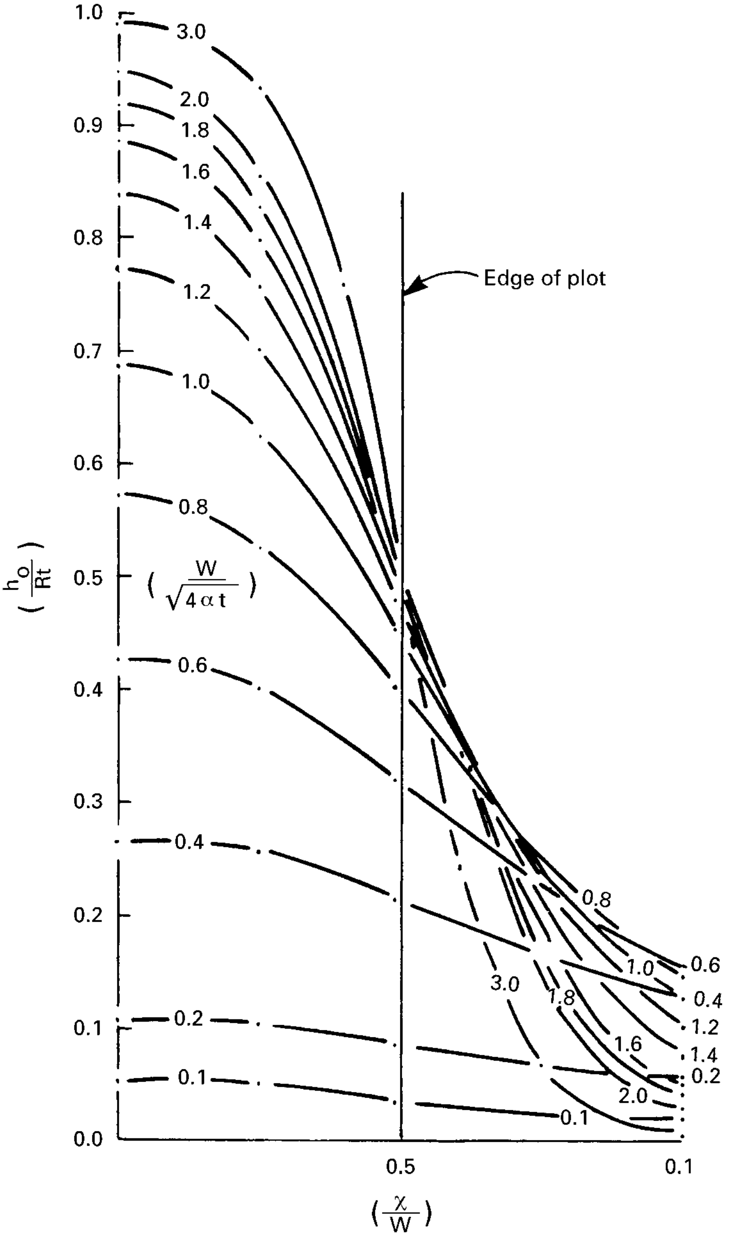


Figure 4.11 Rise and horizontal spread of mounds below a rectangular recharge area when $L = 2W$. (*After Ref. 11.*)

mate the depth to the mound at various distances from the center of the recharge basin. Again, the values of $W/(4\alpha t)^{1/2}$ and Rt must be determined first. Then, for a given value of x/W, where x equals the horizontal distance from the center of the recharge basin, one can obtain the value of h_o/Rt from the correct plot. Multiplying this number by the calculated value of Rt results in the rise of the mound H_o at a distance x from the center of the recharge site. The depth to the mound from the soil surface is then the difference between the distance to the groundwater before recharge and the rise due to the mound.

To evaluate mounding beneath adjacent basins, Figs. 4.10 and 4.11 should be used to plot groundwater table mounds as functions of distance from the center of the plot and time elapsed since initiation of wastewater application. Then, critical mounding times should be determined, such as when adjacent or relatively close basins are being flooded, and the mounding curves of each basin at these times should be superimposed. At sites where drainage is critical because of severe land limitations or extremely high groundwater tables, the engineer should use the approach described in Ref. 14 to evaluate mounding.

Underdrain Spacing

Generally, underdrains are spaced 50 ft (15 m) or more apart. Depths of drains vary from 3 to 8 ft for SR systems and 8 to 15 ft (2.4 to 4.5 m) for RI systems. In soils with high lateral permeability, the underdrains may be as much as 500 ft (150 m) apart. The closer the drain spacing is, the more control there will be over depth of the groundwater table. The cost of drains increases with decreasing drain spacing, so the economics of using more drains must be weighed against finding a site with deeper groundwater or less vertical restriction to percolation, or using a lower application rate.

One method of determining drain spacing is the Hooghhoudt method. The parameters used in the method are shown in Fig. 4.12. The assumptions used in this method are:[17]

1. The soil is homogeneous with a lateral permeability K.
2. The drains are evenly spaced a distance S apart.
3. The hydraulic gradient at any point is equal to the slope of the water table above that point.
4. Darcy's law is valid.

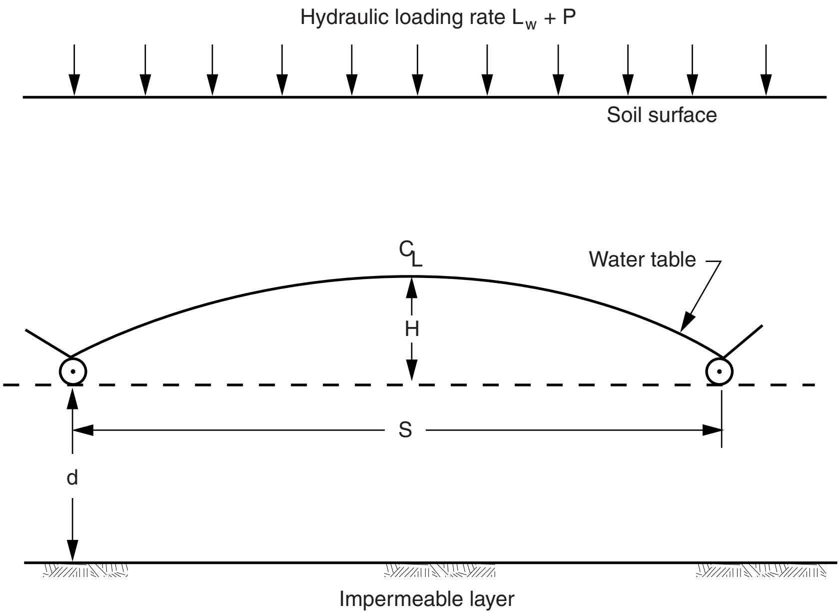


Figure 4.12 Parameters used in drain design.[17]

5. An impermeable layer underlies the drain at a depth *d*.
6. The rate of replenishment (wastewater application plus natural precipitation) is $L_w + P$.

To determine drain placement, the following equation is useful:[17]

$$S = \left[\frac{4KH}{L_w + P} (2d + H) \right]^{0.5} \tag{4.6}$$

where S = drain space, ft
K = horizontal hydraulic conductivity of the soil, ft/day
H = height of the groundwater mound above the drains, ft
L_w = annual wastewater loading rate, expressed as a daily rate, ft/day
P = average annual precipitation rate, expressed as a daily rate, ft/day
d = distance from drains to underlying impermeable layer, ft

Example 4.5: Underdrain Spacing

Conditions RI system to be loaded at 120 ft/year or 0.33 ft/day. K = 20 ft/day, H = 3 ft, d = 2 ft; average precipitation is 0.02 ft/day.

Solution

1. Calculate the hydraulic loading

$$L_w + P = 0.33 + 0.02$$
$$= 0.35 \text{ ft/day}$$

2. Calculate S

$$S = \left[\frac{4KH}{L_w + \mathrm{P}}(2d + H)\right]^{0.5}$$

$$S = \left\{\frac{(4)(20)(3)}{0.35}\left[(2)(2) + 3\right]\right\}^{0.5}$$

$$S = [685.7\ (4+3)]^{0.5}$$

$$S = 69 \text{ ft}$$

References

1. *Drainage Manual,* U.S. Department of the Interior, Bureau of Reclamation, 1st ed., 1978.
2. Jarrett, A. R., and D. D. Fritton, "Effect of Entrapped Soil Air on Infiltration," *Transactions American Society of Agricultural Engineers,* **21:**901–906 (1978).
3. Parr, J. F., and A. R. Bertran, "Water Infiltration into Soils," in Norman, A. G. (Ed.), *Advances in Agronomy,* Academic Press, New York, 1960, pp. 311–363.
4. Hansen, V. E., O. W. Israelson, and G. E. Stringham, *Irrigation Principles and Practices,* 4th ed., John Wiley & Sons, New York, 1980.
5. Pair, C. H., et al., *Sprinkler Irrigation,* 4th ed., Sprinkler Irrigation Association, Silver Spring, Md., 1975.
6. Todd, D. K., "Groundwater," in V. T. Chow (Ed.), *Handbook of Applied Hydrology,* McGraw-Hill, New York, 1964.
7. Booher, L. J., "Surface Irrigation," FAO Agricultural Development Paper 95, Food and Agricultural Organization of the United Nations, Rome, 1974.
8. Weeks, E. P., "Determining the Ratio of Horizontal to Vertical Permeability by Aquifer-Test Analysis," *Water Resources Research,* 5:196–214 (1969).
9. Bouwer, H., "Groundwater Recharge Design for Renovating Wastewater," *Journal Sanitary Engineering Division, ASCE,* **96**(SA-1):59–73 (1970).
10. Bouwer, H., *Groundwater Hydrology,* McGraw-Hill, New York, 1978.
11. "Process Design Manual for Land Treatment of Municipal Wastewater," U.S. Environmental Protection Agency, EPA 625/1-81-013, Oct. 1981.
12. Bouwer, H., "Planning and Interpreting Soil Permeability Measurement," *Journal Irrigation and Drainage Div. ASCE,* 28:391–402 (1969).
13. Rogowski, A. S., "Watershed Physics: Soil Variability Criteria," *Water Resources Research* **8**:1015–1023 (1972).
14. Nielson, D. R., J. W. Biggar, and K. T. Erb, "Spatial Variability of Field-Measured Soil-Water Properties," *Hilgardia,* 42:215–259 (1973).
15. Bianchi, W. C., and C. Muckel, Ground-Water Recharge Hydrology, U.S. Department of Agriculture, Agricultural Research Service, ARS 41161, Dec. 1970.
16. Hantush, M. S., "Growth and Decay of Groundwater-Mounds in Response to Uniform Percolation," *Water Resources Research,* **3**(1):227–234 (1967).
17. Luthin, James N., *Drainage Engineering,* 3d ed., Water Science and Civil Engineering Department, University of California—Davis, Robert E. Krieger Publishing Company, Huntington, N.Y., 1978.

Chapter

5

Vegetation as a Treatment Component

Vegetation in Land Treatment

Vegetation plays different roles in each land treatment process. In slow rate (SR) the vegetation is essential and is generally used for nitrogen removal and, in some cases, for economic return. In overland flow (OF) vegetation is the support medium for biological activity and is needed for erosion protection. The grass in OF systems also removes nutrients and slows the flow of wastewater so that suspended solids can be filtered and settled out of the flow stream.

Vegetation is not always part of rapid infiltration (RI) systems. It can play a role in stabilization of the soil matrix and can maintain long-term infiltration rates but does not appear to have a major impact on treatment performance for RI systems.

In this chapter the characteristics of crops that affect their use in land treatment—water use and tolerance, nutrient uptake, and toxicity concerns—are described. Guidance on crop selection for each land treatment process is provided. Crop management aspects of agronomic and forest crops are also described.

Evapotranspiration

Evapotranspiration (ET) is the combined loss of water from a given area by evaporation from the soil surface, snow, or intercepted precipitation, and by the transpiration and building of tissue by plants. Most water evaporated at plant surfaces is water transpired by the plant, with only about 1 percent of the water taken up by plants actually consumed in the metabolic activity of the plant.[1] The evapotranspiration rate is controlled by atmospheric demand and soil-water availability. If soil-water availability is sufficient, as it will be for land treatment, the potential rate of ET will be determined by solar radiation, air temperature, relative humidity, and wind speed.

For land treatment systems the potential evapotranspiration is important in planning and design. Potential ET is the water lost from an extended surface of short green crop (reference crop) which fully shades the ground and is well supplied with water. Potential evapotranspiration cannot exceed free water evaporation under the same weather conditions.[1]

Evaporation

Most data on evaporation have been obtained from evaporation pans, such as the U.S. Weather Bureau's Class A pan, which is 46.5 in in diameter and 10 in deep. Evaporation pans provide a measure of the combined effects of radiation, temperature, humidity, and wind on evaporation from a specific open water surface. Pans store more heat than crops do; consequently, they cause evaporation measurements to be higher than the reference crop evapotranspiration (ET_0). The pan coefficients, shown in Table 5.1, can be used in convert pan evaporation to reference crop evapotranspiration according to Eq. (5.1).

$$ET_0 = K_{pan} \text{Evap} \tag{5.1}$$

where ET_0 = reference crop evapotranspiration
K_{pan} = pan coefficient
Evap = pan evaporation

Calculating evapotranspiration

The crop ET used in planning is the seasonal total ET. Typical values of seasonal ET for different crops are presented in Table 5.2. In many states, estimates of seasonal ET for various crops can be obtained from local agricultural extension offices, the

TABLE 5.1 Pan Coefficients for Class A Evaporation Pans Placed in a Reference Crop Area[2]

Wind, mi/h	Relative humidity, %		
	Low, <40	Medium, 40–70	High, >70
Light, 4.5	0.75	0.85	0.85
Moderate, 4.5	0.70	0.80	0.80
Strong, 11–18	0.65	0.70	0.75
Very strong, >18	0.55	0.60	0.65

TABLE 5.2 Range of Seasonal Crop Evapotranspiration[2,3,4]

Crop	ET, in	Crop	ET, in
Alfalfa	24–74	Grass	18–45
Avocado	26–40	Oats	16–25
Barley	15–25	Potatoes	18–24
Beans	10–20	Rice	20–45
Clover	34–44	Sorghum	12–26
Corn	15–25	Soybeans	16–32
Cotton	22–37	Sugar beets	18–33
Deciduous trees	21–41	Sugarcane	39–59
Grains (small)	12–18	Vegetables	10–20
Grapes	16–35	Wheat	16–28

land grant university, agricultural research stations, or the NRCS. If crop ET data are not available, they can be calculated from the reference crop ET_0, using crop coefficients.

Crop coefficients can change during the growing season depending on the crop planting date, rate of crop development, length of growing season, and climatic conditions. For annual crops there are four different stages of crop development:

1. Initial growth stage (ground cover 10 percent)
2. Crop-development stage (up to ground cover 80 percent)
3. Midseason stage (effective full ground cover)
4. Late-season stage (full maturity until harvest)

Each stage is characterized by a different crop coefficient. For the first two stages, the curves in Fig. 5.1 can be used to estimate the crop coefficient. To use Fig. 5.1, enter the plot with the reference crop ET_0, proceed up to the recurrence interval between wastewater applications, and then pick off the value of K_c at the left.

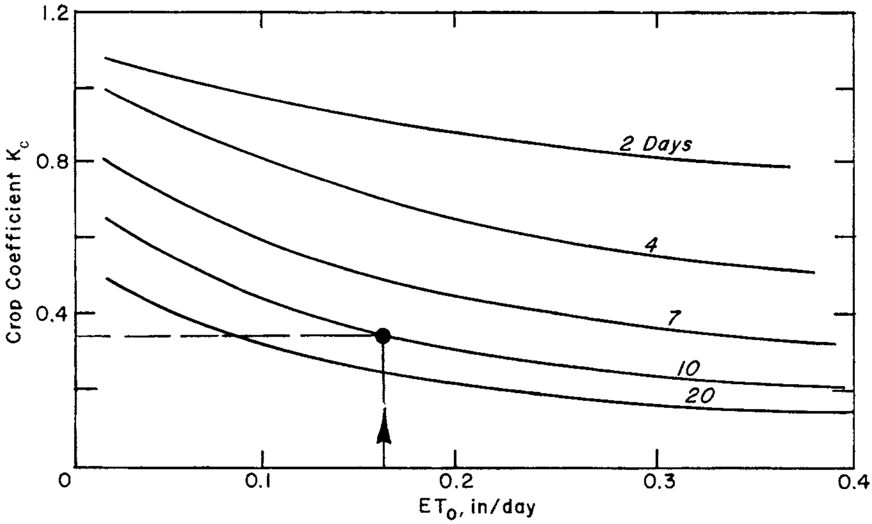


Figure 5.1 Average crop coefficient K_c values for initial and crop development stages. The curves are for average recurrence interval of irrigation, or significant rain. (*After Ref. 2.*)

The third and fourth stages of crop growth produce the largest values of K_c, as presented in Table 5.3. Ranges of lengths of each crop growth stage are presented in Table 5.4. To estimate the crop ET, determine the crop coefficient for each stage, multiply by the number of days in the period, and multiply by the reference crop ET.

Example 5.1: Crop ET Calculation

Conditions Estimate the growing season ET for corn (grain) planted in mid-May. Winds are light and the humidity is low (less than 20 percent). The reference crop ET_0 is 0.20 in/day during the 20-day initial development stage and the 35-day crop-development stage. The ET_0 increases to 0.25 in/day in the 40-day stage 3 and then declines to 0.20 in/day for the 30-day stage 4. The application frequency is 10 days in the first two stages.

Solution A plot of the crop coefficient versus growing period is presented in Fig. 5.2. The growing season ET is as follows:

Stage 1. Enter Fig. 5.1 at $ET_0 = 0.16$ in/day and proceed to the recurrence interval curve for 10 days. Move horizontally to the left and pick off the value of $K_c = 0.35$.

TABLE 5.3 Crop Coefficient, K_c, for Midseason and Late Season Conditions[2]

Crop	Crop stage	Humid*	Dry†
Alfalfa‡	1–4	0.85	0.95
Barley	3	1.05	1.15
	4	0.25	0.20
Clover	1–4	1.00	1.05
Corn	3	1.05	1.15
	4	0.55	0.60
Cotton	3	1.05	1.20
	4	0.65	0.65
Grain	3	1.05	1.15
	4	0.30	0.25
Grapes	3	0.80	0.90
	4	0.65	0.70
Oats	3	1.05	1.15
	4	0.25	0.20
Pasture grass	1–4	0.95	1.00
Rice	3	1.1	1.25
Sorghum	3	1.00	1.10
	4	0.50	0.55
Soybeans	3	1.00	1.10
	4	0.45	0.45
Sugar beets	3	1.05	1.15
	4	0.90	1.00
Wheat	3	1.05	1.15
	4	0.25	0.20

*Humidity 70 percent, light wind 0–16 mi/h.
†Humidity 20 percent, light wind 0–16 mi/h.
‡Peak factors are 1.05 for humid conditions and 1.15 for dry conditions.

TABLE 5.4 Length of Four Crop Growth Stages for Typical Annual Crops, Days[2]

	Growth stage			
Crop	1	2	3	4
Barley	15	25–30	50–65	30–40
Corn	20–30	35–50	40–60	30–40
Cotton	30	50	55–60	45–55
Grain, small	20–25	30–35	60–65	40
Sorghum	20	30–35	40–45	30
Soybeans	20	30–35	60	25
Sugar beets	25–45	35–60	50–80	30–50

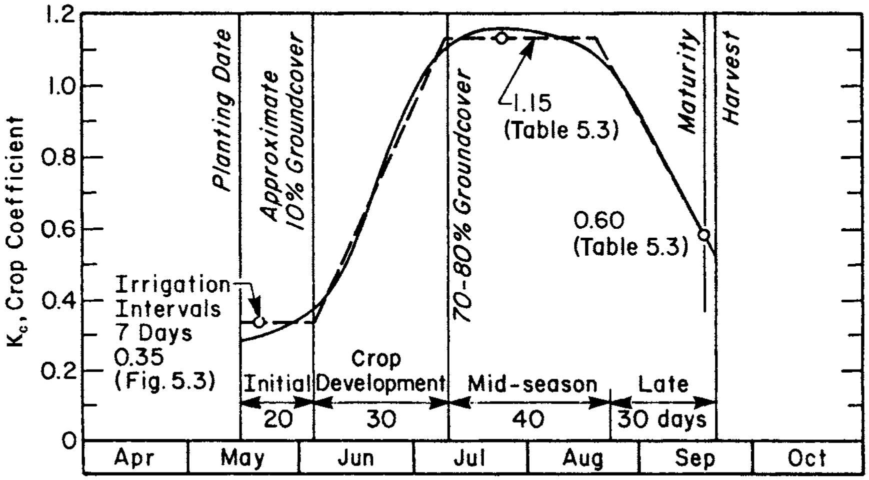


Figure 5.2 Sample crop coefficient curve for corn. (*After Ref. 2.*)

$$\begin{aligned} \text{ET} &= (K_c)(\text{days})(\text{ET}_0) \\ &= (0.35)(20 \text{ days})(0.20 \text{ in/days}) \\ &= 1.40 \text{ in} \end{aligned}$$

Stage 2. For the second stage the value of K_c increases from 0.35 to 1.15 (stage 3 value from Table 5.3). As shown on Fig. 5.2, the increase can be estimated using a straight line between the first and third stages:

$$\begin{aligned} K_c &= \frac{0.35 + 1.15}{2} \\ &= 0.75 \end{aligned}$$

and

$$\begin{aligned} \text{ET} &= (0.75)(35 \text{ days})(0.20 \text{ in/day}) \\ &= 5.25 \text{ in} \end{aligned}$$

Stage 3. From Table 5.3 the value of K_c for dry conditions is 1.15.

$$\begin{aligned} \text{ET} &= (1.15)(40 \text{ days})(0.25 \text{ in/day}) \\ &= 11.50 \text{ in} \end{aligned}$$

Stage 4. From Table 5.3 the stage 4 value of K_c is 0.6. Using the graph in Fig. 5-2, the average value of K_c in stage 4 is

$$K_c = \frac{1.15 + 0.6}{2} = 0.875$$

and

$$\begin{aligned} ET &= (0.875)(30 \text{ days})(0.2 \text{ in/day}) \\ &= 5.25 \text{ in} \end{aligned}$$

Total ET for this 125-day growing season is

$$1.40 + 5.25 + 11.50 + 5.25 = 23.4 \text{ in}$$

Potential evapotranspiration

In humid regions estimates of potential evapotranspiration are usually sufficient for crop water use for perennial full cover crops. The potential ET is also used for forest crops because there is little information on water use of different forest species. Estimated monthly potential ET values are presented for various locations in humid and subhumid climates in Table 5.5.

For perennial forage crops the crop coefficients in Table 5.6 can be used to estimate the ET. For planning purposes the mean ET values will generally suffice. For grasses used for hay, the K_c (maximum) values are reached within 6 to 8 days after cutting. The K_c value for open water ranges from 1.1 for humid conditions to 1.15 for dry conditions.

Prediction of ET

In the absence of ET or pan evaporation data the ET can be predicted from empirical correlations with temperature, humidity, wind, sunshine, and radiation. Over 30 methods have been developed internationally for different agronomic and environmental conditions. Of these, 16 methods were evaluated at 10 different locations.[3] Based on accuracy, the top 5 methods for estimating ET for different climatic regimes were:

TABLE 5.5 Selected Examples of Monthly Potential Evapotranspiration for Humid and Subhumid Climates[5]

	Inches per month					
Month	Paris, Tex.	Central Missouri	Jonesboro, Ga.	Seabrook, N.J.	Hanover, N.H.	Brevard, N.C.
Jan	0.6	0.3	0.5	0.1	0.0	0.1
Feb	0.6	0.5	0.5	0.1	0.0	0.1
Mar	1.4	1.2	1.2	0.8	0.0	0.8
Apr	2.7	2.6	2.3	1.6	1.2	1.8
May	4.0	4.3	4.4	3.0	3.3	3.0
June	5.9	5.8	5.9	4.6	5.2	4.1
July	6.4	6.8	6.3	5.6	5.5	4.6
Aug	6.5	6.1	6.0	5.4	4.8	4.2
Sept	3.9	4.1	4.4	4.0	3.0	3.0
Oct	2.6	2.5	2.3	2.0	1.6	1.8
Nov	1.1	1.0	1.0	0.8	0.1	0.6
Dec	0.6	0.4	0.5	0.1	0.0	0.1
Annual	36.3	35.6	35.3	28.1	24.7	24.2

TABLE 5.6 Crop Coefficients for Perennial Forage Crops[2]

	Condition	
Crop	Humid (light to moderate wind)	Dry (light to moderate wind)
Alfalfa		
Minimum	0.50	0.40
Mean	0.85	0.95
Peak	1.05	1.15
Grass for hay		
Minimum	0.60	0.55
Mean	0.80	0.90
Peak	1.05	1.10
Clover, grass legumes		
Minimum	0.55	0.55
Mean	1.00	1.05
Peak	1.05	1.15
Pasture		
Minimum	0.55	0.50
Mean	0.95	1.00
Peak	1.05	1.10

K_c (minimum) represents conditions just after cutting.
K_c (mean) represents value between cuttings.
K_c (peak) represents conditions before harvesting under dry soil conditions. Under wet conditions increase values by 30 percent.

Coastal	*Inland-Semiarid to Arid*
1. Christiansen	1. Jensen-Haise and van Bavel-Businger, 0.25
2. Turc	2. Penman
3. Kohler	3. Kohler
4. Blaney-Criddle and Ivanov	4. van Bavel-Businger, 0.5
5. Makkink, Penman, and Stephens-Stewart	5. Olivier

On the basis of recommendations made in a publication of the United Nations Food and Agriculture Organization, three methods have potential for widespread use.[2] These are the modified Blaney-Criddle method, the radiation method, and the modified Penman.

The modified Blaney-Criddle method is recommended when only air temperature data are available and is best suited to long periods (1 month or more) of time. In the western United States it has been used extensively and is the standard method used by the NRCS. In the eastern United States it has been less widely used and often produces estimates that are too low.[3]

The radiation method is recommended when temperature and radiation or percent cloudiness data are available. Several versions of the method exist, and because they were mainly derived under cool coastal conditions, the resulting ET generally is underestimated.[3]

The modified Penman method is one of the most accurate methods when temperature, humidity, wind, and radiation data are available. Along with the radiation method, it offers the best results for periods as short as 10 days.

Other methods exist, such as the Thornthwaite method, in which temperature and latitude are correlated with ET. This method was developed for humid conditions in the east-central United States, and its application to arid and semiarid conditions will result in substantial underprediction of ET.[3]

Agronomic Crop Selection

Varieties (cultivars) of major grain, food, and fiber crops are bred specifically for different regions of the United States because of differences in growing seasons, moisture availability, soil type, winter temperatures, and incidence of plant diseases.

A regional approach, therefore, is recommended for selection and management of vegetation at land treatment sites.[6]

Slow rate systems

The crop is an essential component of the SR process for municipal wastewater treatment. In some industrial wastewater SR systems, bare land can be used, particularly if nitrogen removal is unnecessary. The function of the crop in the SR process is to remove nutrients by crop uptake, reduce erosion, and maintain or increase infiltration rates. Crops can also be grown for revenue where local markets are available and the crops are compatible with the wastewater treatment objectives.

Important crop characteristics for SR systems include potential as revenue producer, potential as water user, potential as nitrogen user, and moisture tolerance. Some crops, such as alfalfa, are high water users but cannot tolerate prolonged soil saturation.

Most SR systems are designed to minimize land area by using maximum hydraulic loading rates. Crops that are compatible with high hydraulic loading rates are those having high nitrogen uptake capacity, high consumptive water use, and high tolerance to moist soil conditions. Other desirable crop characteristics for this situation are low sensitivity to wastewater constituents, and minimum management requirements.

Forage and turf crops. Forage and turf crops are most compatible with the SR objective of maximum hydraulic loading. Forage crops that have been used successfully include Reed canarygrass, tall fescue, perennial ryegrass, Italian ryegrass, orchardgrass, and bermudagrass. If forage utilization and value are not a consideration, Reed canarygrass is often a first choice in its area of adaptation because of high nitrogen uptake rate, winter hardiness, and persistence. However, Reed canarygrass is slow to establish and should be planted initially with a companion grass (ryegrass, orchardgrass, or tall fescue) to provide good initial cover.

Of the perennial grasses grown for forage utilization and revenue under high wastewater loading rates, orchardgrass is generally considered to be more acceptable as animal feed than tall fescue or Reed canarygrass. However, orchardgrass is prone to leaf diseases in the southern and eastern states. Tall fescue is generally preferred as a feed over Reed canarygrass but is not suitable for use in the northern tier of states due to lack of winter hardiness. Other crops may be more suitable for local conditions, and advice of local farm advisers or extension specialists will be helpful in making the crop selection.

Turfgrasses are excellent choices for SR systems because they use large amounts of nitrogen and water and use it over much of the year. Golf courses also make good land use candidates for SR systems, being long-term users of irrigation water in most areas. At Tucson, Ariz., research was conducted on Tifway, giant, and common bermuda, overseeded with ryegrass in the winter, and with tall fescue. The Tifway (hybrid warm-season bermudagrass) was the choice for irrigation with wastewater.[7]

In Florida three varieties of turfgrass—Emerald zoysiagrass, Floratam St. Augustinegrass, and Tifway bermudagrass—were grown using brewery wastewater.[8] Similar operations have been established at Houston, Tex., and at Fairfield and Bakersfield, Calif.

Field crops. Corn is an attractive crop because of its potentially high rate of economic return as grain or silage. The limited root biomass early in the season and the limited period of rapid nutrient uptake, however, can present problems for nitrogen removal. Prior to the fourth week, root biomass is too low to renovate the wastewater effectively, and after the ninth week, plant uptake slows. During the rapid uptake period, however, corn removes nitrogen efficiently from percolating wastewater.[6]

Intercropping is a method of expanding the nutrient and hydraulic capacity of a field corn crop system. A dual system of rye intercropped with corn to maximize the period of nutrient uptake was studied in Michigan and Minnesota.[9]. For such dual corn-ryegrass cropping systems, rye can be seeded in the standing corn in August or after the harvest in September. The growth of rye in the spring, before the corn is planted, allows the early application of high-nitrogen wastewater. While planting the corn, a herbicide can be applied in strips to kill some rye so that the corn can be seeded in the killed rows. With the remaining rye absorbing nitrogen, less is leached during the early growth of the corn. Alternatively, forage grasses can be intercropped with corn. This "no-till" corn management consists of planting grass in the fall and then applying a herbicide in the spring before planting the corn. When the corn completes its growth cycle, grass is reseeded. Thus, cultivation is reduced, water use is maximized, nutrient uptake is enhanced, and revenue potential is increased.

The most common agricultural crops grown for revenue using wastewater are corn (silage), alfalfa (silage, hay, or pasture), forage grass (silage, hay, or pasture), grain sorghum, cotton, and grains. However, any crop, including food crops, may be grown with reclaimed wastewater after suitable preapplication treatment.

In areas with a long growing season, such as California, selection of a double crop is an excellent means of increasing the revenue potential as well as the annual consumptive water use and nitrogen uptake of the crop system. Double-crop combinations that are commonly used include (1) short-season varieties of soybeans, silage corn, or sorghum as a summer crop; and (2) barley, oats, wheat, vetch, or annual forage grass as a winter crop.

Nutrient uptake. The highest uptake of nitrogen, phosphorus, and potassium can generally be achieved by perennial grasses and legumes. It should be recognized that whereas legumes normally fix nitrogen from the air, they will preferentially take up nitrogen from the soil-water solution if it is present. The potential for harvesting nutrients with annual crops is generally less than with perennials because annuals use only part of the available growing season for growth and active uptake. Typical annual uptake rates of the major plant nutrients—nitrogen, phosphorus, and potassium—are listed in Table 5.7 for several commonly selected crops.

The nutrient-removal capacity of a crop is not a fixed characteristic but depends on the crop yield and the nutrient content of the plant at the time of harvest. Design estimates of harvest removals should be based on yield goals and nutrient compositions that local experience indicates can be achieved with good management on similar soils.

Nitrogen. The rate of nitrogen uptake by crops changes during the growing season and is a function of the rate of dry matter accumulation and the nitrogen content of the plant. Consequently, the pattern of nitrogen uptake is subject to many environmental and management variables and is crop-specific. Examples of measured nitrogen uptake rates versus time are shown in Fig. 5.3 for annual crops and perennial forage grasses receiving wastewater.

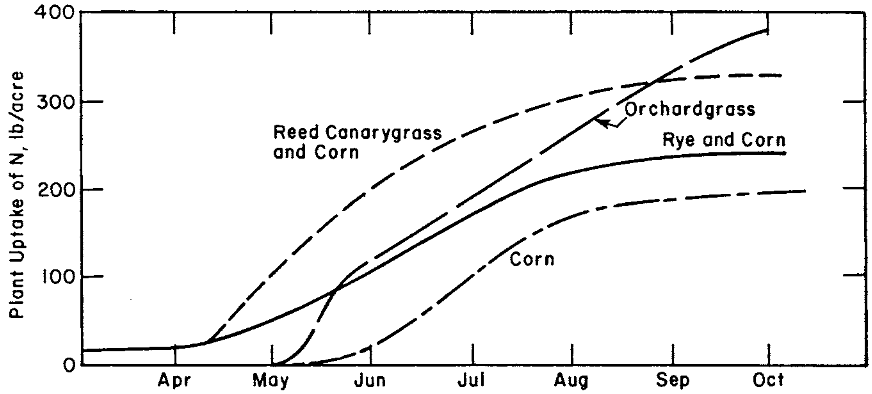


Figure 5.3 Nitrogen uptake vs. growing days for annual and perennial crops. (*After Ref. 5.*)

Some forage crops can have even higher nitrogen uptakes than those in Table 5.7. Californiagrass, a wetland species, widely distributed in the subtropics, was grown with effluent in Hawaii.[10] Mean crop yield was 43 tons/(acre·year) and nitrogen uptake was 1870 lb/(acre·year). The nitrogen crop uptake for turfgrasses in Tucson (common bermudagrass overseeded with winter ryegrass) is 525 lb/(acre·year).[7]

Example 5.2: Nitrogen Uptake

Conditions Determine the nitrogen uptake, given an alfalfa yield of 8 tons/acre and a protein content of 20 percent. The protein content divided by 6.25 gives the nitrogen content.

Solution

1. $\frac{20 \text{ percent}}{6.25} = 3.2 \text{ percent}$
2. Dry matter of 8 tons/acre = 16,000 lb/acre
3. Nitrogen uptake = 0.032 (16,000)

   = 512 lb/acre

Phosphorus. The amounts of phosphorus in applied wastewater are usually much higher than plant requirements. Fortunately, most soils have a high sorption capacity for phosphorus, and very little of the excess passes through the soil.

Potassium. Potassium is used in large amounts by many crops, but typical wastewater is relatively deficient in this element. For

TABLE 5.7 Nutrient Uptake Rates for Selected Crops[5]

Crop	lb/acre·year*		
	Nitrogen, N	Phosphorus, P	Potassium, K
Forage crops			
Alfalfa	200–600	20–30	155–200
Bromegrass	115–200	35–50	220
Coastal bermudagrass	350–600	30–40	200
Kentucky bluegrass	175–240	40	175
Quackgrass	210–250	25–40	245
Reed canarygrass	300–400	35–40	280
Ryegrass	160–250	50–75	240–290
Sweet clover	155	18	90
Tall fescue	130–290	27	270
Orchardgrass	220–310	18–45	200–280
Field crops			
Barley	110	13	18
Corn	155–180	18–27	100
Cotton	65–100	13	36
Grain sorghum	120	13	60
Potatoes	200	18	220–290
Soybeans	220	10–18	27–50
Wheat	140	12	18–50

*lb/acre·year × 1.1208 = kg/ha·year.

example, at 15 mg/L, a typical wastewater contains 40 lb/(acre·ft). In many cases, fertilizer potassium (or sludge potassium) may be needed for optimal plant growth depending on the soil and crop. For soils having low levels of natural potassium, a relationship has been developed to estimate potassium loading requirements:[5]

$$K_f = 0.9U - K_{ww} \tag{5.2}$$

where K_f = annual potassium needed, lb/acre
U = annual crop uptake of nitrogen, lb/acre
K_{ww} = annual wastewater loading of potassium, lb/acre

Other macronutrients taken up by crops include magnesium, calcium, and sulfur; deficiencies of these nutrients are possible in some areas.

The micronutrients important to plant growth (in descending order) are iron, manganese, zinc, boron, copper, molybdenum, and occasionally, sodium, silicon, chloride, and cobalt. Most wastewaters contain an ample supply of these elements; in some cases, phytotoxicity may be a consideration.

Overland flow systems

A perennial close-growing grass crop is required for overland flow systems. The OF grass crop must have high moisture tolerance and long growing season, and be suited to the local climate.

A mixture of grasses is generally preferred over a single species, as shown in Table 5.8. The mixture should contain grasses whose growth characteristics complement each other, such as sod formers and bunch grasses and species that are dormant at different times of the year.

Another advantage of using a mixture of grasses is that, owing to natural selection, one or two grasses will often predominate. A successful combination of grasses has been Reed canarygrass, tall fescue, and ryegrass (see Table 5.8). In the south and southwest, dallisgrass, bermudagrass, and redtop have also been successful. In northern climates, substitution of orchardgrass for the dallisgrass and redtop is recommended.

At Hanover, N.H., barnyardgrass invaded the OF slopes and began to dominate the perennial grasses. Being an annual grass, when the barnyardgrass died, it left bare areas that were subject to erosion.[13]

Grasses to be avoided include those sensitive to salt (like clover) and those that have long slender seed stalks (Johnson grass and yellow foxtail). In the early stages of development grasses Johnson grass will provide an effective cover, however, with maturity the bottom leaves die off and the habitat for microorganisms becomes reduced.

TABLE 5.8 Grasses Used at Overland Flow Sites[11,12]

Site	Type of grass
Ada, Okla.	Annual ryegrass, bermudagrass, and Kentucky 31 fescue
Carbondale, Ill	Tall fescue
Davis, Calif.	Fescue and perennial ryegrass
Easley, S.C.	Kentucky 31 tall fescue
Hanover, N.H.	Orchardgrass, quackgrass, Reed canarygrass, perennial ryegrass
Hunt-Wesson (Davis, Calif.)	Fescue, trefoil, Reed canarygrass
Campbell Soup Co. (Paris, Tex.)	Reed canarygrass, redtop, tall fescue
Utica, Miss.	Reed canarygrass, Kentucky 31 fescue, perennial ryegrass, common bermudagrass

Rapid infiltration systems

Vegetation is generally not used in rapid infiltration systems, but when it is, the use is to maintain high infiltration rates or to stabilize the soils. At Flushing Meadows, Ariz., bermudagrass was used in the early research, showing a 25 percent increase in infiltration rates over bare sand.[11]

At Ft. Devens, Mass., and Whittier Narrows, Calif., natural vegetation is used to maintain long-term infiltration. Equipment is kept off these RI sites to avoid soil compaction.

Vegetation for RI systems must be water-tolerant and in most cases must be able to withstand several days to a week of inundation. Bermudagrass, Kentucky bluegrass, and Reed canarygrass have been shown to survive inundation for up to 10 days.[11,14]

Silty clay loam and clayey sands are marginal soils for RI systems, and use of vegetation with these soils should be investigated. At Brookings, S.D., the vegetated basins consistently provided the highest infiltration rates over a 4-year study using silty clay loam soils for RI.[15]

The effect of different crops on infiltration is shown in Fig. 5.4.

Forest Crop Selection

The most common forest crops used in SR systems have been mixed hardwoods and pines. A summary of representative operational systems and types of forest crops used is presented in Table 5.9. The growth response of trees will vary in accordance with a number of factors; one of the most important is the adaptability of the selected species to the local climate. Local foresters should be consulted for specific recommendations on the likely response of selected species.

Vegetative uptake and storage of nutrients depend on the species and forest stand density, structure, age, length of season, and temperature. In addition to the trees, there is also nutrient uptake and storage by the understory tree and herbaceous vegetation.

The role of the understory vegetation is particularly important in the early stages of tree establishment. Forests take up and store nutrients and return a portion of those nutrients to the soil in the form of leaf fall and other debris such as dead trees. Upon decomposition, the nutrients are released and the

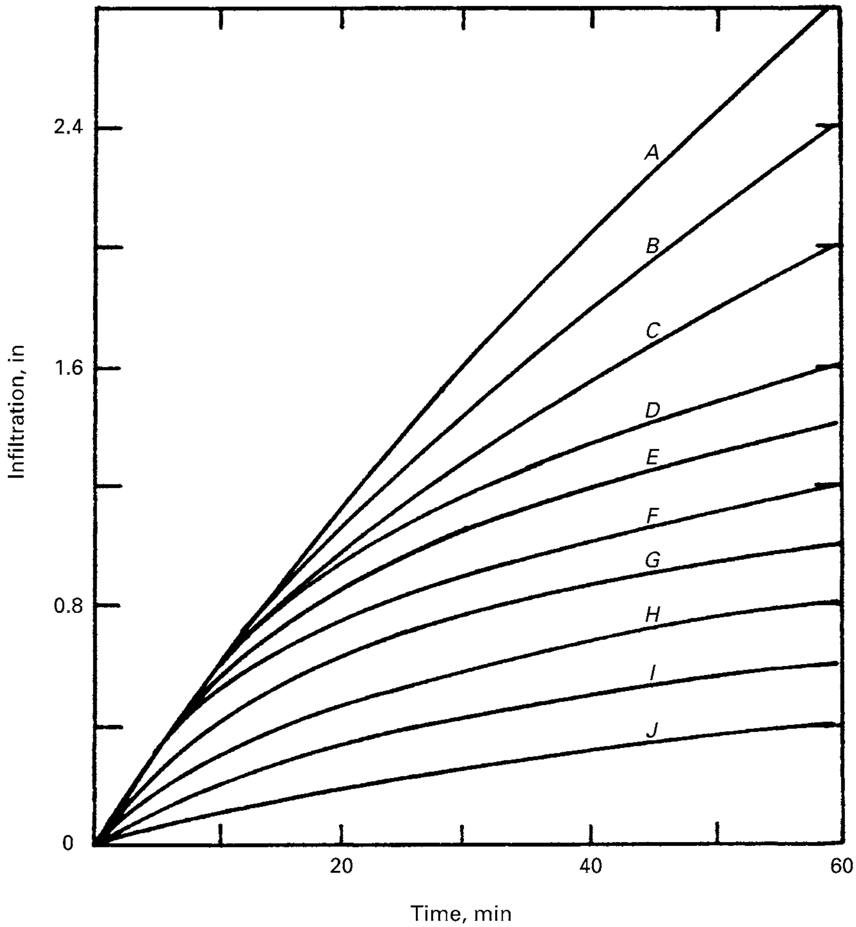


Figure 5.4 Effect of crop cover on infiltration rates for various conditions. Symbols A to J represent the following conditions: A—old permanent pasture or heavy mulch; B—4- to 8-year-old permanent pasture; C—3- to 4-year-old permanent pasture, light grazing; D—permanent pasture, moderate grazing; E—pasture cut for hay; F—permanent pasture, heavily grazed; G—strip cropped or mixed cover; H—weeds or grain; I—clean soil, tilled; and J—bare ground, crusted. (*After Ref. 21.*)

trees take them back up. During the initial stages of growth (1 to 2 years), tree seedlings are establishing a root system; biomass production and nutrient uptake are relatively slow.

To prevent leaching of nitrogen to groundwater during this period, nitrogen loading must be limited or understory vegetation must be established that will take up and store applied nitrogen that is in excess of the tree crop needs.

Nitrogen uptake

The estimated annual nitrogen uptake of forest ecosystems in selected regions of the United States is presented in Table 5.10. These rates are considered maximum estimates of net nitrogen uptake including both the understory and overstory vegetation during the period of active tree growth.

Because nitrogen stored within the biomass of trees is not uniformly distributed among the tree components, the amount of

TABLE 5.9 Forested Land Treatment Systems in the United States

Location	Design flow, mgd	Tree types
Dalton, Ga.	30.0	Pines
Clayton, Co., Ga.	19.5	Loblolly pines, hardwood
Helen, Ga.	0.02	Mixed pine and hardwood
St. Marys, Ga.	0.3	Slash pine
Mackinaw City, Mich.	0.2	Aspen, birch, white pine
State College, Pa.	3.0	Mixed hardwood, pine
West Dover, Vt.	0.55	Hardwood balsam, hemlock, spruce

TABLE 5.10 Nitrogen Uptake for Selected Forest Ecosystems[5]

	Tree age, years	Average annual nitrogen uptake, lb/(acre·year)
Eastern forests:		
Mixed hardwoods	40–60	200
Red pine	25	100
Old field with white spruce plantation	15	200
Pioneer succession	5–15	200
Aspen sprouts	—	100
Southern forests:		
Mixed hardwoods	40–60	250
Loblolly pine with no understory	20	200
Loblolly pine with understory	20	250
Lake states forests:		
Mixed hardwoods	50	100
Hybrid poplar*	5	140
Western forests:		
Hybrid poplar*	4–5	270
Douglas fir plantation	15–25	200

*Short-term rotation with harvesting at 4 to 5 years; represents first-growth cycle from planted seedlings.

nitrogen that can actually be removed with a forest crop system will be substantially less than the storage estimates given in Table 5.10 unless 100 percent of the aboveground biomass is harvested (whole-tree harvesting). If only the merchantable stems are removed from the system, the net amount of nitrogen removed by the system will be less than 30 percent of the amount stored in the biomass.

The distributions of biomass and nitrogen for naturally growing hardwood and conifer (pines, Douglas fir, fir, larch, etc.) stands in temperate regions are shown in Table 5.11. For deciduous species, whole-tree harvesting must take place in the summer when the leaves are on the trees if maximum nitrogen removal is to be achieved.

Following the initial growth stage, the rates of growth and nutrient uptake increase and remain relatively constant until maturity is approached and the rates decrease. When growth rates and nutrient uptake rates begin to decrease, the stand should be harvested or the nutrient loading decreased. Maturity may be reached at 20 to 25 years for southern pines, 50 to 60 years for hardwoods, and 60 to 68 years for some of the western conifers such as Douglas fir. Of course, harvesting may be practiced well in advance of maturity, as with short-term rotation management.

Eastern forests. During the past 35 years wastewater has been applied to several forest ecosystems at the Pennsylvania State University.[17] Satisfactory renovation was obtained in all systems (eastern mixed hardwoods and red pine) when wastewater was applied during the growing season at 1 in/week with annual nitrogen loadings of 134 lb/acre. The white spruce–old field forest ecosystem produced a percolate nitrogen concentration of

TABLE 5.11 Biomass and Nitrogen Distributions by Tree Component for Stands in Temperate Regions[5]

	Conifers, %		Hardwoods, %	
Tree component	Biomass	Nitrogen	Biomass	Nitrogen
Roots	10	17	12	18
Stems	80	50	65	32
Branches	8	12	22	42
Leaves	2	20	1	8

7.4 mg/L when the hydraulic loading was 2 in/week and the annual nitrogen loading was 275 lb/acre.

Southern forests. In a study of a southern mixed hardwood (80 percent hardwood, 20 percent pine) forest near Helen, Ga., on a 30 percent slope with a loading rate of 3 in/week, about 60 percent of the applied nitrogen was accounted for in uptake and denitrification. The nitrogen loading was 608 lb/acre and the percolate nitrate concentration was 3.7 mg/L.[18]

Lake States forests. Studies at Michigan State University have shown rather poor nitrogen removal by mature northern hardwoods. Younger forest systems and poplar plantations have shown greater nitrogen uptake, especially during the years when herbaceous cover is present.[19]

Western forests. The wastewater renovation capacity of a newly established plantation of Douglas fir and a mature 50-year-old Douglas fir forest was studied with wastewater nitrogen loadings of 310 to 360 lb/(acre·year)[20] The uptake rates, presented in Table 5.10, reflect a substantial uptake by the understory grasses.

Phosphorus and trace metals

The assimilative capacity for both phosphorus and trace metals is controlled more by soil properties than plant uptake. The relatively low pH (4.2 to 5.5) of most forest soils is favorable to the retention of phosphorus but not of trace metals. However, the high level of organic matter in forest soil improves the metal-removal capacity. The amount of phosphorus in trees is small, usually less than 27 lb/acre; therefore, the amount of annual phosphorus accumulation in the biomass is quite small.

Crop Management and Water Quality

Crop planting, harvesting, and pest control are management areas requiring proper techniques to ensure a healthy crop. In addition, wastewaters may have constituents that are harmful to plants (phytotoxic) or that reduce the quality of the crop. Water-quality parameters of concern for crop irrigation include salinity, boron, sodium, chloride, and pH. Trace elements, particularly zinc, copper, and nickel, are of concern for phytotoxicity. However, the concentration of these elements in wastewaters is well below the toxic level of all crops, and phytotoxicity could only occur as a result of long-term accumulation of these elements in the soil. See the pertinent sections in Chap. 3 for discussion of all these factors.

Crop planting and harvesting. Local extension services or similar experts should be consulted regarding planting techniques and schedules. Most crops require a period of dry weather before harvest to mature and reach a moisture content compatible with harvesting equipment. Soil moisture at harvest time should be low enough to minimize compaction by harvesting equipment. For these reasons, application should be discontinued well in advance of harvest. The time required for drying will depend on the soil drainage and the weather. A drying time of 1 to 2 weeks is usually sufficient if there is no precipitation. However, advice on this should be obtained from local experts.

Harvesting of grass crops and alfalfa involves regular cuttings, and a decision regarding the trade-off between yield and quality must be made. Advice can be obtained from local agricultural experts. In the northeast and north central states, three cuttings per season have been successful with grass crops.

Grazing. Grazing of pasture by beef cattle or sheep can provide an economic return for SR systems. No health hazard has been associated with the sale of the animals for human consumption.

Grazing animals return nutrients to the ground in their waste products. The chemical state (organic and ammonia nitrogen) and rate of release of the nitrogen reduces the threat of nitrate pollution of the groundwater. Much of the ammonia-nitrogen volatilizes, and the organic nitrogen is held in the soil, where it is slowly mineralized to ammonium and nitrate forms (see Chap. 3).

In terms of pasture management, cattle or sheep must not be allowed on wet fields to avoid severe soil compaction and reduced soil infiltration rates. Wet grazing conditions can also lead to animal hoof diseases. Pasture rotation should be practiced so that wastewater can be applied immediately after the livestock are removed. In general, a pasture area should not be grazed longer than 7 days. Typical regrowth periods between grazings range from 14 to 36 days. Depending on the period of regrowth provided, one to three water applications can be made during the regrowth period. Rotation grazing cycles for 2 to 8 pasture areas are given in Table 5.12. At least 3 to 4 days of drying time following an application should be allowed before livestock are returned to the pasture.

Agricultural pest control. Problems with weeds, insects, and plant diseases are aggravated under conditions of frequent water application, particularly when a single crop is grown year after year or when no-till practices are used. Most pests can be controlled by selecting resistant or tolerant crop varieties and by using pesticides in combination with appropriate cultural practices. State and local experts should be consulted in developing an overall pest control program for a given situation.

Overland flow crop management

After the cover crop has been established, the OF slopes will need little if any maintenance work. It will, however, be necessary to mow the grass periodically. A few systems have been operated without cutting, but the tall grass tends to interfere with maintenance operations. Normal practice has been to cut the grass two or three times a year. The first cutting may be left on the slopes. After that, however, it is desirable to remove the cut grass. The advantages of doing so are that additional nutrient removal is achieved, channeling problems may be more readily observed, and revenue can sometimes be produced by the sale of hay. Depending on the local market conditions, the cost of harvesting can at least be offset by the sale of hay.[5] Slopes must be allowed to dry sufficiently such that mowing equipment can be operated without leaving ruts or tracks that will later

TABLE 5.12 Pasture Rotation Cycles for Different Numbers of Pasture Areas

Number of pasture areas	Rotation cycle, days	Regrowth period, days	Grazing period, days
2	28	14	14
3	30	20	10
4	28	21	7
5	35	28	7
6	36	30	6
7	42	36	6
8	40	35	5

result in channeling of the flow. The drying time required before mowing varies with the soil and climatic conditions and can range from a few days to a few weeks. The downtime required for harvesting can be reduced by a week or more if green-chop harvesting is practiced instead of mowing, raking, and baling. However, local markets for green-chop must exist for this method to be feasible.

It is common for certain native grasses and weeds to begin growing on the slopes. Their presence usually has little impact on treatment efficiency, and it is generally not necessary to eliminate them. However, there are exceptions, and the local extension services should be consulted for advice.

Proper management of the slopes and the application schedule will prevent conditions conducive to mosquito breeding. Other insects are usually no cause for concern, although an invasion of certain pests such as army worms may be harmful to the vegetation and may require periodic insecticide application.

Forest crop management

The type of forest crop management practice selected is determined by the species mix grown, the age and structure of the stand, the method of reproduction best suited and/or desired for the favored species, terrain, and type of equipment and technique used by local harvesters. The most typical forest management situations encountered in land treatment are management of existing forest stands, reforestation, and short-term rotation.

Existing forests. The general objective of the forest management program is to maximize biomass production. The compromise between fully attaining a forest's growth potential and the need to operate equipment efficiently (distribution and harvesting equipment) requires fewer trees per unit area. These operations will assure maintenance of a high nutrient uptake by the forest.

In even-aged forests, trees will all reach harvest age at the same time. The usual practice is to clear-cut these forests at harvest age and regenerate a stand by either planting seedlings, sprouting from stumps (called coppice), or a combination of several of the methods. Even-aged stands may require a thinning at an intermediate age to maintain maximum biomass production.

Coniferous forests, in general, must be replanted, whereas hardwood forests can be reproduced by coppice or natural seeding.

For uneven-aged forests, the desired forest composition, structure, and vigor can be best achieved through thinning and selective harvest. However, excessive thinning can make trees susceptible to wind throw, and caution is advised in windy areas. The objectives of these operations would be to maintain an age class distribution in accordance with the concept of optimum nutrient storage. The maintenance of fewer trees than normal would permit adequate sunlight to reach the understory to promote reproduction and growth of the understory. Thinning should be done initially prior to construction of the distribution system and only once every 10 years or so to minimize soil and site damage.

The concept of "whole-tree harvesting" should be considered for all harvesting operations, whether it be thinning, selection harvest, or clear-cut harvest. Whole-tree harvesting removes the entire standing tree: stem, branches, and leaves. Thus, 100 percent of nitrogen accumulated in the aboveground biomass would be removed.

Prescribed fire is a common management practice in many forests to reduce the debris or slash left on the site during conventional harvesting methods. During the operation, a portion of the forest floor is burned and nitrogen is volatilized. Although this represents an immediate benefit in terms of nitrogen removal from the site, the buffering capacity that the forest floor offers is reduced and the likelihood of a nitrate leaching to the groundwater is increased when application of wastewater is resumed.

Reforestation. Wastewater nutrients often stimulate the growth of the herbaceous vegetation to such an extent that they compete with and shade out the desirable forest species. Herbaceous vegetation is necessary to act as a nitrogen sink while the trees are becoming established, and therefore, cultural practices must be designed to control but not eliminate the herbaceous vegetation. As the tree crowns begin to close, the herbaceous vegetation will be shaded and its role in the renovation cycle reduced. Another alternative to control of the herbaceous vegetation is to eliminate it completely and reduce the hydraulic and nutrient loading during the establishment period.

Short-term rotation. Short-term rotation forests are plantations of closely spaced hardwood trees that are harvested repeatedly on cycles of less than 10 years. The key to rapid growth rates and biomass development is the rootstock that remains in the soil after harvest and then resprouts. Short-term rotation harvesting systems are readily mechanized because the crop is uniform and relatively small.

Using conventional tree spacings of 8 to 12 ft (2.4 to 3.6 m), research on systems where wastewater has been applied to short-term rotation plantations has shown that high growth rates and high nitrogen removal are possible.[5] Planted stock will produce only 50 to 70 percent of the biomass produced following cutting and resprouting.[5] If nitrogen and other nutrient uptake is proportional to biomass, the first rotation from planted stock will not remove as much as subsequent rotations from coppice. Therefore, the initial rotation must receive a reduced nutrient load or other herbaceous vegetation must be employed for nutrient storage. Alternatively, closer tree spacings may be used to achieve desired nutrient uptake rates during initial rotation.

References

1. Rosenberg, N. J., *Microclimate: The Biological Environment,* John Wiley & Sons, New York, 1974.
2. Doorenbos, J., and W. O. Pruitt, "Crop Water Requirements," FAO Irrigation and Drainage Paper 24, Food and Agricultural Organization of the United Nations, Rome, 1977.
3. Jensen, M. E., et al., "Consumptive Use of Water and Irrigation Water Requirements," ASCE Committee on Irrigation Water Requirements, Sept. 1973.
4. California Department of Water Resources, "Vegetative Water Use in California, 1974," *Bulletin* 113-3, Sacramento, Calif., Apr. 1975.
5. "Process Design Manual for Land Treatment of Municipal Wastewater," U.S. Environmental Protection Agency, EPA 625/1-81-013, Oct. 1981.
6. D'Itri, F. M., *Land Treatment of Municipal Wastewater: Vegetation Selection and Management,* Ann Arbor Science, Ann Arbor, Mich., 1982.
7. Pepper, I. L., "Land Application of Municipal Effluent on Turf," in *Proceedings of the 1981 Technical Conference Silver Spring, Maryland,* The Irrigation Association, 1981.
8. White, R. W., "Utilizing Food Processing Wastewater for Turf Production," in *Proceedings of the 1980 Technical Conference Silver Spring, Maryland,* The Irrigation Association, 1980.
9. Brockway, D. G., et al., "The Current Status on the Selection and Management of Vegetation for Slow Rate and Overland Flow Application Systems to Treat Municipal Wastewater in the North Central Region of the United States," in F. M. D'Itri (Ed.), *Land Treatment of Municipal Wastewater,* Ann Arbor Science, Ann Arbor, Mich., 1982, pp. 5–18.
10. Handley, L. L., "Effluent Irrigation of Californiagrass," *Proceedings Water Reuse Symposium II,* vol. 2, AWWA Research Foundation, Washington, D.C., Aug. 23–28, 1981.

11. Pound, C. E., and R. W. Crites, "Wastewater Treatment and Reuse by Land Application," vol. II, U.S. Environmental Protection Agency, EPA-660/2-73-006B, Aug. 1973.
12. Hinrichs, D. J., et al., "Assessment of Current Information on Overland Flow Treatment of Municipal Wastewater," U.S. Environmental Protection Agency, EPA 430/9-80-002, MCD-66, May 1980.
13. Palazzo, A. J., T. F. Jenkins, and C. J. Martel, "Vegetation Selection and Management for Overland Flow Systems," in F. M. D'Itri (Ed.), *Land Treatment of Municipal Wastewater,* Ann Arbor Science, Ann Arbor, Mich., 1982, pp. 135–154.
14. Erbisch, F. H., and K. L. Stark, "Effects of Inundation on Six Varieties of Turfgrass," U.S. Army Corps of Engineers, *CRREL Special Report* 82-12, May 1982.
15. Dornbush, J. N., "Infiltration Land Treatment of Stabilization Pond Effluent," U.S. Environmental Protection Agency, EPA-600/2-81-226, Sept. 1981.
16. U.S. Environmental Protection Agency, *Process Design Manual—Land Application of Municipal Sludge,* EPA-625/1-83-016, Oct. 1983.
17. Sopper, W. E., and S. N. Kerr, "Renovation of Municipal Wastewater in Eastern Forest Ecosystems," in W. E. Soper and S. N. Kerr (Eds.), *Utilization of Municipal Sewage Effluent and Sludge on Forest and Disturbed Land,* The Pennsylvania State University Press, University Park, Pa., 1979, pp. 61–76.
18. Nutter, W. L., R. C. Schultz, and G. H. Brister, "Land Treatment of Municipal Wastewater on Steep Forest Slopes in the Humid Southeastern United States," *Proceedings of the International Symposium on Land Treatment of Wastewater,* vol. 1, Hanover, N.H., 1978, pp. 265–274.
19. McKim, H. L., et al., "Wastewater Applications in Forest Ecosystems," U.S. Army Corps of Engineers, CRREL Report 82-19, Aug. 1982.
20. Cole, D. W., and P. Schiess, "Renovation of Wastewater and Response of Forest Ecosystems: the Pack Forest Study," *Proceedings of the International Symposium on Land Treatment of Wastewater,* vol. 1, Hanover, N. H., 1978, pp. 323–331.
21. Hart, R. H., "Crop Selection and Management," *Factors Involved in Land Application of Agricultural and Municipal Wastes*, U.S. Department of Agriculture, Agricultural Research Service, Beltsville, Maryland, 1974.

Chapter

6

Site Identification and Selection

Process and site selection in land treatment are interrelated. The ability of the land treatment processes to remove wastewater constituents described in Chap. 3, the discharge quality criteria, and the soil and other site characteristics affect the choice of the appropriate land treatment process. The presence of a suitable site within an economical transmission distance from the wastewater source will determine if a land treatment system can be implemented.

Because the selection of a process and selection of a site for land treatment are related, a two-phased planning procedure is often used. The two phases are presented in Fig. 6.1.

The first phase involves estimating preliminary land area requirements based on wastewater and climate characteristics, identifying potential sites in the area, evaluating the sites based on technical and economic factors, and selecting potential sites.

The second phase, assuming sites are selected, involves field investigations, preliminary design and cost estimates, comparison to other alternatives, and selection of the most economical alternative.

Preliminary Land Requirements

Preliminary land requirements can be estimated for each land treatment process, based on wastewater characteristics and climatic conditions. Wastewater characteristics include average

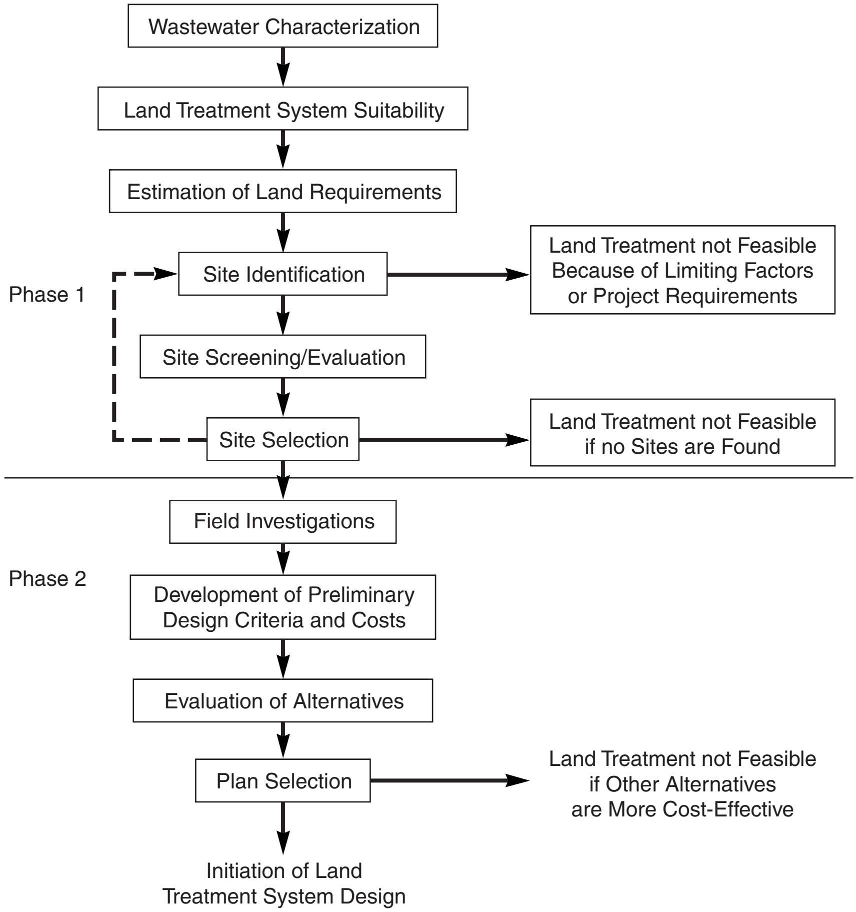


Figure 6.1 Two-phase planning process.

annual flows and concentrations of constituents such as BOD, suspended solids, nitrogen, phosphorus, and trace elements.

Wastewater characteristics

Municipal wastewater flows range typically from 65 to 100 gal per capita per day. Industrial wastewater flows are too variable to generalize and must be estimated from information specific to the product and wastewater-producing operations. Existing wastewater flow records or water use records should be used where available.

Constituent concentrations that are seen typically in municipal wastewater are presented in Table 6.1.[12] These characteristics represent medium-strength wastewater.

Site Identification and Selection 117

TABLE 6.1 Typical Characteristics of Municipal Wastewater

Constituent	Concentration, mg/L
BOD	200
Suspended solids	200
Nitrogen, total	30
Organic nitrogen	15
Ammonia nitrogen	15
Phosphorus, total	10
Potassium	15

TABLE 6.2 Characteristics of Food Processing Wastewaters Applied to the Land[1]

Constituent	Concentration, mg/L*
BOD	200–33,000
Suspended solids	200–3,000
Total fixed dissolved solids	<1,800
Total nitrogen	10–1,900
pH, units	3.5–12.0
Temperature, °C	<65

*Except as noted.

Industrial wastewaters vary widely in their characteristics, especially for organics, metals, and nitrogen. Characteristics of food-processing wastewaters that have been applied directly to the land are presented in Table 6.2. Wastewater characterization is necessary in planning for industrial land application systems.

Preliminary loading rates

In the absence of site information, typical loading rates can be assumed to initiate the planning process. For slow rate (SR) systems the degree of preapplication treatment (either primary or secondary) has little effect on the loading rate. For overland flow (OF) and rapid infiltration (RI) systems, higher loading rates can usually be used with higher-quality effluent. Typical loading rates for preliminary estimates of land requirements are presented in Table 6.3.

The rates in Table 6.3 are necessarily conservative. Once a potential site has been analyzed and the ability to meet discharge requirements is assessed, the loading rates can usually be increased.

TABLE 6.3 Preliminary Loading Rates for Initial Estimate of Land Requirements

Process	Loading rate, in/week
Slow rate	
Agricultural	1.5
Forest	1.0
Rapid infiltration	
Primary effluent	12
Secondary effluent	20
Overland flow	
Screened wastewater and primary effluent	4
Secondary effluent	8

Storage needs

Storage of wastewater may be necessary due to cold weather, excessive precipitation, or crop management. For preliminary estimates it is usually sufficient to base storage needs on climatic factors. A map showing storage days based on cold weather and excessive precipitation is presented in Fig. 6.2. This figure should be used for a preliminary estimate of storage needed for OF systems. For SR systems using agricultural crops, the crop management time for harvesting and planting should be added to the storage days taken from Fig. 6.2. The values in Fig. 6.2 are not valid for RI and forested SR systems, since both can be operated during subfreezing weather. For RI and forested SR systems, a minimum storage of 7 to 14 days can be assumed for preliminary estimates of land area.

Site area estimate

Preliminary site area requirements can be estimated from wastewater flows, storage needs, and preliminary loading rates. The relationship between field area, loading rates, and operating period is shown in Eq. (6.1).

$$F = 13{,}443 \frac{Q}{L\,P} \tag{6.1}$$

where F = field area, acres

Q = average flow, mgd

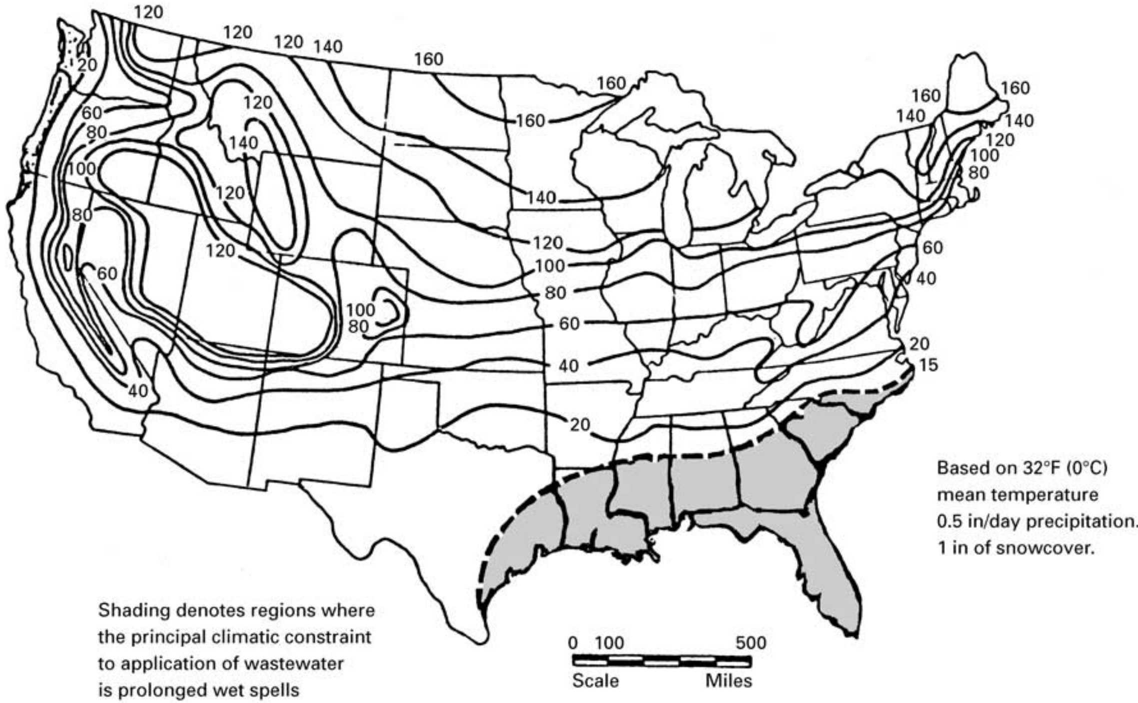


Figure 6.2 Estimated storage days based on climatic factors alone.

L = loading rate, in/week
P = period of application, weeks/year

$$13{,}443 = \text{conversion factor} = 3.069\ \frac{\text{acre} \cdot \text{ft}}{\text{mgd}} \times \frac{12 \text{ in} \times 365 \text{ days}}{\text{year}}$$

The period of application can be approximated by subtracting the estimated storage period from 52 weeks/year. Site areas for a 1 mgd flow for all three systems are presented in Table 6.4. For SR and RI systems the numbers in Table 6.4 include 20 percent extra area over the calculated field area to account for unusable land. For OF systems the extra land in Table 6.4 is 40 percent to account for the additional inefficiency in constructing overland flow slopes.

Site Identification

To identify potential land treatment sites it is necessary to obtain data on land use, soil types, and topography. The types

TABLE 6.4 Site Identification Land Requirements

System	Land requirements, acres/mgd
Slow rate, agricultural:	
No storage	200
1 month's storage	225
2 months' storage	250
3 months' storage	275
4 months' storage	315
5 months' storage	350
6 months' storage	415
Slow rate, forest:	
No storage	310
1 month's storage	335
Rapid infiltration:	
Primary effluent	30
Secondary effluent	15
Overland flow:	

Storage (months)	Screened wastewater	Secondary effluent
0	90	180
1	100	200
2	110	220
3	120	240
4	140	280

and sources of data needed to identify and evaluate potential sites are presented in Table 6.5.

Use of map overlays

The complexity of site identification depends on the size of the study area and the nature of the land use. One approach is to start with land use plans and identify undeveloped land. Map overlays can then help the planner or engineer to organize and study the combined effects of land use, slope, relief, and soil permeability. Criteria can be set on these four factors, and areas that satisfy the criteria can then be located. If this procedure is used as a preliminary step in site identification, the criteria should be reassessed during each successive iteration. Otherwise, strict adherence to such criteria may result in overlooking either sites or land treatment opportunities.

TABLE 6.5 Types and Sources of Data Required for Land Treatment Site Evaluation

Type of data	Principal source
Topography	USGS topographic quads
Soil type and permeability	NRCS soil survey
Temperature (mean monthly and growing season)	NRCS soil survey, NOAA, local airports, newspapers
Precipitation (mean monthly, maximum monthly)	NRCS soil survey, NOAA, local airports, newspapers
Evapotranspiration and evaporation (mean monthly)	NRCS soil survey, NOAA, local airports, newspapers, agricultural extension service
Land use	NRCS soil survey, aerial photographs from the Agricultural Stabilization and Conservation Service, and county assessor's plats
Zoning	Community planning agency, city or county zoning maps
Agricultural practices	NRCS soil survey, agricultural extension service, country agents
Surface and groundwater discharge requirements	State or EPA
Groundwater (depth and quality)	State water agency, USGS, driller's logs of nearby wells

Site suitability factors

Potential land treatment sites are identified using a deductive approach. First, any constraints that might limit site suitability are identified. In most study areas, all land within the area should be evaluated for each land treatment process. The next step is to classify broad areas of land near the area where wastewater is generated according to their land treatment suitability. Factors that should be considered include current and planned land use, topography, soils, geology, groundwater, and surface water hydrology.

Land use. Land use in most communities is regulated by local, county, and regional zoning laws. Land treatment systems must comply with the appropriate zoning regulations. For this reason, the planner should be fully aware of the actual land uses and proposed land uses in the study area. The planner should attempt to develop land treatment alternatives that conform to local land use goals and objectives.

Land treatment systems can conform with the following land use objectives:

- Protection of open space that is used for land treatment
- Production of agricultural or forest products using renovated water on the land treatment site
- Reclamation of land by using renovated water to establish vegetation on scarred land
- Augmentation of parklands by irrigating such lands with renovated water
- Management of floodplains by using floodplain areas for land treatment, thus precluding land development on such sites
- Formation of buffer areas around major public facilities, such as airports

To evaluate present and planned land uses, city, county, and regional land use plans should be consulted. Because such plans often do not reflect actual current land use, site visits are recommended to determine existing land use. Aerial photographic maps may be obtained from the Natural Resources Conservation Service (NRCS) or the local assessor's office. Other useful information may be available from the U.S. Geological Survey (USGS) and the Environmental Protection Agency (EPA), including true color, false color infrared, and color infrared aerial photographs of the study area.

Once the current and planned land uses have been determined, they should be plotted on a study area map. Then, land use suitability may be plotted using the factors shown in Table 6.6.

Both land acquisition procedures and treatment system operation are simplified when few land parcels are involved and contiguous parcels are used. Therefore, parcel size is an important parameter. Usually, information on parcel size can be obtained from county assessor or county recorder maps. Again, the information should be plotted on a map of the study area.

Topography. Steep grades limit a site's potential because the amount of runoff and erosion that will occur is increased, crop cultivation is made more difficult, if not impossible, and saturation of steep slopes may lead to unstable soil conditions. The maximum acceptable grade depends on soil characteristics and the land treatment process used.

Grade and elevation information can be obtained from USGS topographic maps, which usually have scales of 1:24,000 (7.5-min series) or 1:62,500 (15-min series). Grade suitability may be plotted using the criteria listed in Table 6.7.

Relief is another important topographical consideration and is the difference in elevation between one part of a land treatment system and another. The primary impact of relief is its effect on the cost of conveying wastewater to the land application site. Often, the economics of pumping wastewater to a nearby site must be compared with the cost of constructing gravity conveyance to more distant sites.

TABLE 6.6 Land Use Suitability Factors for Identifying Land Treatment Sites[3]

	Type of system			
Land use factor	Agricultural slow rate	Forest slow rate	Overland rate	Rapid infiltration
Open or cropland	High	Moderate	High	High
Partially forested	Moderate	Moderately high	Moderate	Moderate
Heavily forested	Low	High	Low	Low
Built upon (residential, commercial, or industrial)	Low	Very low	Very low	Very low

TABLE 6.7 Grade Suitability Factors for Identifying Land Treatment Sites[3]

Grade factor, %	Slow rate systems		Overland flow	Rapid infiltration
	Agricultural	Forest		
0–12	High	High	High	High
12–20	Low	High	Moderate	Low
20	Very low	Moderate	Eliminate	Eliminate

A site's susceptibility to flooding also can affect its desirability. The flooding hazard of each potential site should be evaluated in terms of both the possible severity and frequency of flooding as well as the areal extent of flooding. In some areas, it may be preferable to allow flooding of the application site provided offsite storage is available. Further, crops can be grown in floodplains if flooding is infrequent enough to make farming economical.

Overland flow sites can be located in floodplains provided they are protected from direct flooding which could erode the slopes. Backwater from flooding, if it does not last more than a few days, should not be a problem. Floodplain sites for RI basins should be protected from flooding by the use of levees.

Summaries of notable floods and descriptions of severe floods are published each year as the USGS Water Supply Papers. Maps of certain areas inundated in past floods are published as Hydrologic Investigation Atlases by the USGS. The USGS also has produced more recent maps of flood-prone areas for many regions of the country as part of the Uniform National Program for Managing Flood Losses. These maps are based on standard 7.5-min (1:24,000) topographic sheets and identify areas that lie within the 100-year floodplain. Additional information on flooding susceptibility is available from local offices of the U.S. Army Corps of Engineers and local flood control districts.

Soils. Common soil-texture terms and their relationship to the NRCS textural class names are listed in Table 6.8.

Fine-textured soils do not drain well and retain water for long periods of time. Thus, infiltration is slower and crop management is more difficult than for freely drained soils such as loamy soils. Fine-textured soils are best suited for the OF process.

TABLE 6.8 Soil Textural Classes and General Terminology Used in Soil Descriptions

General terms		Basic soil textural class names
Common name	Texture	
Sandy soils	Coarse	Sand, loamy sand
	Moderately coarse	Sandy loam, fine sandy loam
Loamy soils	Medium	Very fine sandy loam, loam, silt loam, silt
	Moderately fine	Clay loam, sandy clay loam, silty clay loam
Clayey soils	Fine	Sandy clay, silty clay, clay

Loamy or medium-textured soils are desirable for the SR process, although sandy soils may be used with certain crops that grow well in rapidly draining soils. Soil structure and soil texture are important characteristics that relate to permeability and acceptability for land treatment. Structure refers to the degree of soil particle aggregation. A well-structured soil is generally more permeable than unstructured material of the same type. The RI process is suited for sandy or loamy soils.

Soils surveys are usually available from the NRCS. Soil surveys normally contain maps showing soil series boundaries and textures to a depth of about 5 ft (1.5 m). In a survey, limited information on chemical properties, grades, drainage, erosion potential, general suitability for locally grown crops, and interpretive and management information is provided. Where published surveys are not available, information on soil characteristics can be obtained from the NRCS, through the local county agent.

Although soil depth, permeability, and chemical characteristics significantly affect site suitability, data on these parameters are often not available before the site investigation phase. If these data are available, they should be plotted on a study area map along with soil texture. In identifying potential sites, the planner should keep in mind that adequate soil depth is needed for root development and for thorough wastewater treatment. Further, permeability requirements vary among the land treatment processes. Desirable permeability ranges are shown by process in Table 6.9 together with desired soil texture. The NRCS permeability class definitions are also shown in Fig. 4.6.

TABLE 6.9 Typical Soil Permeabilities and Textural Classes for Land Treatment Processes

	Land treatment processes		
	Slow rate	Rapid infiltration	Overland flow
Soil permeability range, in/h	0.06–2.0	>2.0	<0.2
Permeability class range	Moderately slow to moderately rapid	Rapid	Slow
Textural class range	Clay loams to sandy loams	Sandy and sandy loams	Clays and clay loams
Unified soil classification	GM-d, SM-d, ML, OL, MH, PT	GW, GP, SW, SP	GM-u, GC, SM-u, SC, CL, OL, CH, OH

Geology. Certain geological formations are of interest during phase 1 investigations. Discontinuities and fractures in bedrock may cause short-circuiting or other unexpected groundwater flow patterns. Impermeable or semipermeable layers of rock, clay, or hardpan can result in perched groundwater tables. The USGS and many state geological surveys have maps indicating the presence and effects of geological formations. These maps and other USGS studies may be used to plot locations within the study area where geological formations may limit the suitability for land treatment.

Groundwater. A knowledge of the regional groundwater conditions is particularly important for potential rapid infiltration and slow rate sites. Overland flow will not usually require an extensive hydrogeologic investigation. Sufficient removal of pollutants in the applied wastewater before reaching a permanent groundwater resource is the primary concern. The depth to groundwater and its seasonal fluctuation are a measure of the aeration zone and the degree of renovation that will take place.

When several layers of stratified groundwater underlie a particular site, the occurrence of the vertical leakage between layers should be evaluated. Direction and rate of groundwater flow and aquifer permeability together with groundwater depth are useful in predicting the effect of applied wastewater on the groundwater regime. The extent of recharge mounding, interconnection of aquifers, perched water tables, the potential for surfacing groundwater, and design of monitoring and withdrawal wells are dependent on groundwater flow data.

Much of the data required for groundwater evaluation may be determined through use of existing wells. Wells that could be used for monitoring should be listed and their relative location described. Historical data on quality, water levels, and quantities pumped from the operation of existing wells may be of value. Such data include seasonal groundwater-level variations, as well as variations over a period of years. The USGS maintains a network of about 15,800 observation wells to monitor water levels nationwide. Records of about 3500 of these wells are published in Water Supply Paper Series, "Groundwater-Levels in the United States." Many local, regional, and state agencies compile drillers' boring logs that are also valuable for defining groundwater hydrology.

Land treatment of wastewater can provide an alternative to discharge of conventionally treated wastewater. However, the adverse impact of percolated wastewater on the quality of the groundwater must also be considered. Existing groundwater quality should be determined and compared to quality standards for its current or intended use. The expected quality of the renovated wastewater can then be compared to determine which constituents in the renovated water might be limiting. The USGS "Groundwater Data Network" monitors water quality in observation wells across the country. In addition, the USGS undertakes project investigations or areal groundwater studies in cooperation with local, state, or other federal agencies to appraise groundwater quality. Such reports may provide a large part of the needed groundwater data.

Surface water hydrology. Surface water hydrology is of interest in land treatment processes mostly because of the runoff of stormwater. Considerations relating to surface runoff control apply to both slow rate and overland flow. Rapid infiltration processes are designed for no runoff.

The control of stormwater runoff both onto and off a land treatment site must be considered. First, the facilities constructed as part of the treatment system must be protected against erosion and washout from extreme storm events. For example, where earthen ditches and/or terraces are used, erosion control from stormwater runoff must be provided. The degree of control of runoff to prevent the destruction of the physical system should be based on the economics of replacing equipment and structures.

There is no standard extreme storm event in the design of drainage and runoff collection systems, although a 10-year return event is suggested as a minimum. See Chap. 11 for further discussion of stormwater runoff of overland flow sites.

Climatic Factors

Local climate may affect (1) the water balance (and thus the acceptable wastewater hydraulic loading rate), (2) the length of the growing season, (3) the number of days per year that a land treatment system cannot be operated, (4) the storage capacity requirement, (5) the loading cycle of RI systems, and (6) the amount of stormwater runoff. For this reason, local precipitation, evapotranspiration, temperature, and wind values must be determined before design criteria can be established. Whenever possible, at least 10 years of data should be used to obtain these values.

Three publications of the National Oceanic and Atmospheric Administration (NOAA) provide sufficient data for most communities. The *Monthly Summary of Climatic Data* provides basic information, including total precipitation, temperature maxima and minima, and relative humidity, for each day of the month and every weather station in a given area. Whenever available, evaporation data are included. An annual summary of climatic data, entitled *Local Climatological Data,* is published for a small number of major weather stations. Included in this publication are the normals, means, and extremes of all the data on record to date for each station. The *Climate Summary of the United States* provides 10-year summaries of the monthly climatic data. Other data included are:

- Total precipitation for each month of the 10-year period
- Mean number of days that precipitation exceeded 0.10 and 0.50 in during each month
- Total snowfall for each month of the period
- Mean temperature for each month of the period
- Mean daily temperature maxima and minima for each month
- Mean number of days per month that the temperature was less than or equal to 32°F or greater than or equal to 90°F

A fourth reference that can be helpful is EPA's "Annual and Seasonal Precipitation Probabilities."[5] This publication includes precipitation probabilities for 93 stations throughout the United States. Data requirements for planning purposes are summarized in Table 6.10.

Water Rights and Potential Conflicts

Land application of wastewaters may cause several changes in drainage and flow patterns:[6]

1. Site drainage may be affected by land preparation, soil characteristics, slope, method of wastewater application, cover crops, climate, buffer zones, and spacing of irrigation equipment.
2. Land application may alter the pattern of flow in the body of water that would have received the wastewater discharge. Although this may diminish the flow in the body of water, it also may increase the quality. The change may be continuous or seasonal.
3. Land application may cause surface water diversion, because wastewaters that previously would have been carried away by surface waters are now applied to land and often diverted to a different watershed.

Two basic types of water rights laws exist in the United States: riparian laws, which emphasize the right of riparian landowners along a watercourse to use of the water, and appropriative laws, which emphasize the right of prior users of the water.[6] Most riparian or land ownership rights are in effect east

TABLE 6.10 Summary of Climatic Analyses

Factor	Date required	Analysis	Use
Precipitation	Annual average, maximum, minimum	Frequency balance	Water
Rainfall storm	Intensity, duration	Frequency	Runoff estimate
Temperature	Days with average below freezing	Frost-free period	Storage, treatment efficiency, crop growing season
Wind	Velocity, direction	—	Cessation of sprinkling
Evapotranspiration	Annual, monthly average	Annual distribution	Water balance

of the Mississippi, whereas most appropriative rights are in effect west of the Mississippi River.

Most states divide their water laws into three categories: (1) waters in well-defined channels or basins (natural watercourses), (2) superficial waters not in channels or basins (surface waters), and (3) underground waters not in well-defined channels or basins (percolating waters or groundwaters).

The state or local water master or water rights engineer should be consulted to avoid potential problems. Other references to consider are the publications, A *Summary Digest of State Water Laws,* available from the National Water Commission,[5] and *Land Application of Wastewater and State Water Law,* vols. I and II.[7,8] If problems develop or are likely with any of the feasible alternatives, a water rights attorney should also be consulted.

Site Selection

Once the data on site characteristics are collected and mapped, the site evaluation and selection process can proceed. If the number of sites are few and their relative suitability clearly apparent, a simple economic comparison will lead to selection of the best site. If a number of sites are to be compared, a site screening procedure can be used.

Site screening procedure

The general procedure for site suitability rating can be used to compare different sites or it can be used to screen a large site that may have portions suitable to different land treatment processes. A procedure incorporating economic factors is presented for RI and OF systems. A procedure specific to SR forest systems is also included.

The general procedure is to assign numerical values to various site characteristics, with larger numbers indicating highest suitability. The individual numbers for each site or subarea are then added together to obtain the overall suitability rating. The rating factors in Table 6.11 are applicable to all processes. Site-selection factors in Table 6.11 are applicable to all processes. Site-selection factors and weightings should vary to suit the needs of the local area and type of sites available.

TABLE 6.11 Rating Factors for Site Selection[9]

Characteristic	Slow rate systems		Overland flow	Rapid infiltration
	Agricultural	Forest		
Soil depth, ft*				
1–2	E†	E	0	E
2–5	3	3	4	E
5–10	8	8	7	4
>10	9	9	7	8
Minimum depth to groundwater, ft				
<4	0	0	2	E
4–10	4	4	4	2
>10	6	6	6	6
Permeability, in/h‡				
<0.06	1	1	10	E
0.06–0.2	3	3	8	E
0.2–0.6	5	5	6	1
0.6–2.0	8	8	1	6
>2.0	8	8	E	9
Grade, %				
0–5	8	8	8	8
5–10	6	8	5	4
10–15	4	6	2	1
15–20	0	5	E	E
20–30	0	4	E	E
30–35	E	2	E	E
>35	E	0	E	E
Existing or planned land use				
Industrial	0	0	0	0
High-density residential/urban	0	0	0	0
Low-density residential/urban	1	1	1	1
Forested	1	4	1	1
Agricultural or open space	4	3	4	4

TABLE 6.11 Rating Factors for Site Selection[9] (*Continued*)

Characteristic	Slow rate systems: Agricultural	Slow rate systems: Forest	Overland flow	Rapid infiltration
Overall suitability rating§				
Low	<15	<15	<16	<16
Moderate	15–25	15–25	16–25	16–25
High	25–35	25–35	25–35	25–35

Note: The higher the maximum number in each characteristic, the more important the characteristic; the higher the ranking, the greater the suitability.
*Depth of the profile to bedrock.
†Excluded; rated as poor.
‡Permeability of most restrictive layer in soil profile.
§Sum of values.

Example 6.1: Site Suitability Rating

Conditions Compare the suitabilities of three sites being considered for RI. The characteristics of the three sites are given in Table 6.12.

Solution Assign the numerical ratings to each site characteristic using the values in Table 6.11. The assigned numbers are shown in Table 6.13. Based on these five characteristics, site 1 is the preferred site. Site 2 should be retained for consideration, although its permeability rating makes it less suitable than site 1. Site 3 should be eliminated because of inadequate soil depth.

Screening procedure with economic factors. In addition to the technical factors listed in Table 6.11, the economics of site development are often critical. These include distance from the wastewater source, elevation differences, and the costs for land acquisition and management. Table 6.14 presents rating factors for these concerns.

Procedure for forested SR systems. A procedure has been developed for forested SR systems that incorporates climatic, soil, geologic, hydrologic, and vegetation factors.[11] The procedure involves the use of rating values for subsurface factors (Table 6.15), soils (Table 6.16), and surface factors (Table 6.17).

Based on the ratings in these tables, an estimate of the preliminary hydraulic loading can be made using Table 6.18. This procedure was developed for sprinkler irrigation of forested sites in the southeastern United States.

TABLE 6.12 Site Characteristics for Example 6.1

Characteristics	Site 1	Site 2	Site 3
Soil depth, ft	>10	5–10	2–5
Depth to groundwater, ft	>10	>10	4–10
Permeability, in/h	>2	0.6–2.0	>2
Grade, %	0–5	0–5	0–5
Land use	Forested	Agricultural	Industrial

TABLE 6.13 Site Comparison for Example 6.1

	Rating values		
Characteristics	Site 1	Site 2	Site 3
Soil depth	8	4	E
Depth to groundwater	6	6	2
Permeability	9	6	9
Grade	8	8	8
Land use	1	4	0
Total	32	28	19 (E)
Rating	High	High	Eliminate

TABLE 6.14 Economic Rating Factors for Site Selection

Characteristic	Rating value
Distance from wastewater source, miles	
0–2	8
2–5	6
5–10	3
>10	1
Elevation difference, ft	
<0	6
0–50	5
50–200	3
>200	1
Land cost and management	
No land purchase, farmer-operated	5
Land purchased, farmer-operated	3
Land purchased, city- or industry-operated	1

TABLE 6.15 Subsurface Factors for Forested SR[11]

Characteristics	Rating value*
Depth to groundwater on barrier, ft	
<4	0
4–10	4
>10	6
Depth to bedrock, ft	
<5	0
5–10	4
>10	6
Type of bedrock	
Shale	2
Sandstone	4
Granite-gneiss	6
Exposed bedrock, % of total area	
<33	0
10–33	2
1–10	4
None	6

*0–9, site not feasible; 10–13, poor; 14–19, good; and 20–24, excellent.

TABLE 6.16 Soil Factors for Forested SR[11]

Characteristics	Rating value*
Infiltration rate, in/h	
<2	2
2–6	4
>6	6
Hydraulic conductivity, in/h	
>6	2
<2	4
2–6	6
CEC, meq/100 g	
<10	1
10–15	2
>15	3
Shrink-swell potential (NRCS)	
High	1
Low	2
Moderate	3
Erosion classification (NRCS)	
Severely eroded	1
Eroded	2
Not eroded	3

*5–11, poor; 12–16, good; and 17–21, excellent.

TABLE 6.17 Surface Factors for Forested SR[11]

Characteristics	Rating value*
Dominant vegetation	
Pine	2
Hardwood or mixed	3
Vegetation age, years	
Pine	
>30	3
20–30	3
<20	4
Hardwood	
>50	1
30–50	2
<50	3
Mixed pine/hardwood	
>40	1
25–40	2
<25	3
Slope, %	
>35	0
0–1	2
2–6	4
7–35	6
Distance to flowing stream, ft	
50–100	1
100–200	2
>200	3
Adjacent land use	
High-density residential/urban	1
Low-density residential/urban	2
Industrial	2
Undeveloped	3

*3–4, not feasible; 5–9, poor; 9–14, good; and 15–19, excellent.

TABLE 6.18 Composite Evaluation of SR Forested Sites[11]

Evaluation ratings from Tables 6.15 to 6.17			Hydraulic loading, in/week
Poor	Good	Excellent	
3	0	0	Not feasible
2	1	0	<1.0
2	0	1	<1.0
1	2	0	1.0–1.5
1	1	1	1.0–1.5
1	0	2	1.5–2.0
0	3	0	2.0–2.5
0	2	1	2.0–2.5
0	1	2	2.5–3.0
0	0	3	2.5–3.0

References

1. Crites, R. W., "Land Treatment and Reuse of Food Processing Waste," in *Proceedings of 55th Annual Industrial Wastes Symposia,* Water Pollution Control Federation. St. Louis, Mo., Oct. 3–8, 1982.
2. Whiting, D. M., "Use of Climatic Data in Estimating Storage Days for Soil Treatment Systems," U.S. Environmental Protection Agency, EPA-600/2-76-250, Nov. 1976.
3. Moser, M. A., "A Method for Preliminary Evaluation of Soil Series Characteristics to Determine the Potential for Land Treatment Processes," *Proceedings of Symposium on Land Treatment of Wastewater,* Hanover, N.H., Aug. 1978.
4. Loehr, R. C., *Agricultural Waste Management: Problems, Processes, and Approaches,* Academic Press, New York, 1974.
5. Thomas, R. E., and D. M. Whiting, "Annual and Seasonal Precipitation Probabilities," U.S. Environmental Protection Agency, EPA-600/2-77-182, Aug. 1977.
6. Dewsnup, R. L., and D. W. Jensen (Eds.), *A Summary Digest of State Water Laws,* National Water Commission, Washington, D.C., May 1973.
7. Large, D. W., *Land Application of Wastewater and State Water Law: An Overview,* vol. I, U.S. Environmental Protection Agency, EPA-600/2-77-232, Nov. 1977.
8. Large, D. W., *Land Application of Wastewater and State Water Law: State Analyses,* vol. II. U.S. Environmental Protection Agency, EPA-600/2-78-175, Aug. 1978.
9. U.S. Environmental Protection Agency, *Process Design Manual for Land Treatment of Municipal Wastewater,* U.S. Environmental Protection Agency, EPA 625/1-81-013, Oct. 1981.
10. Metcalf & Eddy, Inc., *Land Application of Wastewater in the Salinas-Monterey Peninsula Area,* U.S. Army Engineer District San Francisco, Calif., Apr. 1976.
11. Taylor, G. L., "Land Treatment Site Evaluation in Southeastern Mountainous Areas," *Bulletin of the Association of Engineering Geologists,* **18:**261–266 (1981).
12. Crites, R. W., and G. Tchobanoglous, *Small and Decentralized Wastewater Management Systems,* McGraw-Hill, New York, 1998.

Chapter 7

Field Investigation Procedures

The factors described in Chaps. 4 and 6 regarding groundwater conditions, soil properties, and other site factors not only influence the initial site selection and concept feasibility decisions but are critical for the final system design. The investigation and testing procedures that are commonly used to obtain these data are described in this chapter.

As with all other engineering projects, the type of test required and the specific procedure are relatively easy to describe. The more difficult decision is deciding on how many tests, and in what locations, are adequate for a particular project. Too little field data may lead to erroneous conclusions while too much will result in unnecessarily high costs with little refinement in the design concept. Experience indicates that where uncertainty exists, it is prudent to adopt a conservative posture relative to data-gathering requirements.

Table 7.1 is a flowchart which presents a logical sequence of field testing for a land treatment project. When possible, available data are first used for calculations or decisions that may then necessitate additional field tests.

Guidance on testing for wastewater constituents and soil properties is provided for each land treatment process in Table 7.2. Generally relatively modest programs of field testing and data analysis will be satisfactory, especially for small systems.

TABLE 7.1 Sequence of Field Testing[17]—Typical Order of Testing

	Field tests			
	Test pits	Bore holes	Infiltration rate	Soil chemistry
Remarks	Usually with a backhoe, includes inspection of existing NRCS reports, road cuts, etc.	Drilled or augered includes inspection of driller's logs for local wells, water table levels	Match the expected method of application, if possible	Includes review of NRCS survey
Information to obtain	Depth of profile, texture, structure, soil layers restricting percolation	Depth to groundwater, depth to impermeable layer(s)	Expected minimum infiltration rate	Specific data relating to crop and soil management, phosphorus and heavy metal retention
Estimates now possible	Need for vertical conductivity testing	Groundwater flow direction	Hydraulic capacity based on soil permeability (subject to drainage restrictions)	Crop limitations. Soil amendments. Possible preapplication requirements
Additional field tests	Vertical conductivity (optional)	Horizontal conductivity		
Additional estimates	Refinement of loading rates	Mounding analysis, dispersion, need for drainage	—	Quality of percolate
Number of tests	Depends on size, soil uniformity, needed soil tests, type of system. Typical minimum of 3–5 per site	Depends on system type more for RI than SR), soil uniformity, site size. Typical minimum of 3 per site	Depends on size of site, uniformity of soil. Typical minimum of 2 per site	Depends on uniformity of soil types, type of test, size of site

TABLE 7.2 Summary of Field Tests for Land Treatment Processes

Properties	Processes		
	Slow rate (SR)	Rapid infiltration (RI)	Overland flow (OF)
Wastewater constituents	Nitrogen, phosphorus, SAR,* EC,* boron	BOD, SS, nitrogen, phosphorus	BOD, SS, nitrogen, phosphorus
Soil physical properties	Depth of profile Texture and structure	Depth of profile Texture and structure	Depth of profile Texture and structure
Soil hydraulic properties	Infiltration rate Subsurface permeability	Infiltration rate Subsurface permeability	Infiltration rate (optional)
Soil chemical properties	pH, CEC, exchangeable cations (% of CEC), EC,* metals,† phosphorus adsorption (optional)	pH, CEC, phosphorus adsorption	pH, CEC, exchangeable cations (% of CEC)

*May be more significant for arid and semiarid areas.

†Background levels of metals such as cadmium, copper, or zinc in the soil should be determined if food chain crops are planned.

Soil Properties

A critical element in site selection and process design is the capability of the site soils to move the design quantities of water in the expected direction at the expected rates. These are important requirements for slow rate (SR) systems and are absolutely critical for rapid infiltration (RI) because of the much higher hydraulic loadings. The physical and chemical soil properties of concern are defined and discussed in detail in Chap. 6.

Physical characteristics

Site identification and selection as described in Chap. 6 will ordinarily be based on existing field data available from a NRCS county soil survey and other sources. The next step involves some physical exploration on the site. This preliminary exploration is of critical importance to subsequent phases of the project. Its two purposes are: (1) verification of existing data and (2) identification of probable, or possible, site limitations; and it should be performed with reasonable care. For example, the presence of wet areas, water-loving plant species, or surficial salt crusts should alert the designer to the need for detailed field studies directed toward the problem of drainage. The presence of rock outcroppings would signify the need for more detailed subsurface investigations than might normally be required. If a stream were located near the site, there would need to be additional study of the surface and near-surface hydrology; nearby wells require details of the groundwater flow, and so on. These points may seem obvious. However, there are examples of systems that have failed because of just such obvious conditions: limitations that were not recognized until after design and construction were complete.

The methods of construction and system operation that will be used can also be critically important, depending on the soil properties encountered, and must be considered in the site and concept selection process. The characteristics of the soil profile in the undisturbed state may be completely altered when the design surface is exposed or by inadvertent compaction during construction. Fine-textured soils are particularly susceptible to compaction. For example, if the design surface layer contains a significant clay fraction and if that surface is exposed for growth of row crops in an SR system, the impact of rainfall and sprinkler droplets may result in sorting of the clay fines and a partial sealing of the surface. Such problems can be managed, but the field investigation must provide sufficient data so that such conditions can be anticipated in the design.

RI systems. Soil properties, topography, and construction methods are particularly critical for RI systems. A site with a heterogeneous mixture of soil types containing scattered lenses of fine-textured soil may be impossible to adequately define with a typical investigation program. If such a site cannot be avoided for RI, a large-scale pilot test basin is suggested for definition of site hydraulic characteristics. If the pilot test is successful, the test basin, if properly located, can then be included in the full-scale system.

Sorting of soil fines due to rainfall or turbulent flooding of the RI basin can result in system failure. At Fresno, Calif.,[1] for example, the groundwater recharge RI site was on very flat terrain composed of permeable sandy soils at the surface. A borrow strip was included around the perimeter of each basin to obtain material for dike construction. As a result, the final elevation of this borrow strip was depressed relative to the general basin bottom. These borrow strips have been rendered impermeable during the first 10 years of operation due to sorting and deposition of soil fines and accumulation of organic matter. The applied liquid in this case was high-quality river water, not wastewater, and the infiltration capacity could not be restored by disking the soil.

An RI site with undulating topography may require a scattered array of basins to remain in desirable soils or may necessitate major cut-and-fill operations for a compact site. RI basins should always be constructed in cut section if at all possible. Experience[2] has shown that construction in fill sections with soils have a fine fraction (passing No. 200 sieve) of more than 5 percent can result in problems. Clayey sands with fines exceeding 10 percent by weight should be avoided altogether as fill material for basin infiltration surfaces. Pilot-scale test basins are recommended whenever RI systems are to be designed on backfilled soils.

Construction. Construction activity in either cut or fill for RI or SR systems can have a drastic effect on soil permeability if clayey sands are present. Such activity should be permitted only when the soil moisture is on the dry side of "optimum." Inadvertent compaction with the soil on the wet side of optimum moisture content could result in the same bulk density for the soil but an order-of-magnitude reduction in permeability. If such compaction is limited to the top foot of the surface layer, a final ripping and disking may correct the problem. Compaction of this type on sequential layers of fill may not be correctable.

The importance of soil texture for concept and site selection was described in Chap. 4, based on the U.S. Department of Agriculture (USDA) soil classes (Fig. 4.1).

Other suitable soil-classification procedures are also in use. These were developed by the American Association of State Highway Officials (AASHO) and the U.S. Army Corps of Engineers (USACE).

Table 7.3 summarizes the interpretation of these physical and hydraulic properties.

TABLE 7.3 Interpretation of Soil Physical and Hydraulic Properties

Depth of soil profile, ft	
<1–2	Suitable for OF*
>2–5	Suitable for SR and OF
5–10	Suitable for all processes
Texture and structure	
Fine texture, poor structure	Suitable for OF
Fine texture, well-structured	Suitable for SR and possibly OF
Coarse texture, well-structured	Suitable for SR and RI
Infiltration rate, in/h	
0.2–6	Suitable for SR
>2.0	Suitable for RI
<0.2	Suitable for OF
Subsurface permeability	
Exceeds or equals infiltration rate	Infiltration rate limiting
Less than infiltration	May limit application rate

*Suitable soil depth must be available for shaping of overland flow slopes. Slow rate process using a grass crop may also be suitable.

Chemical properties

The influence of soil chemical properties on permeability and infiltration was discussed in Chap. 4. The importance of pH and soil minerals on fertility is discussed in a later section of this chapter. Adverse chemical reactions between the wastewater and the soil are not expected for municipal and most industrial effluents. The main concern is usually retention or removal of a particular chemical by the soil system, and Chap. 3 should be consulted for those details.

Differences in the chemical characteristics between the applied wastewater and the soil may induce chemical changes. At Muskegon, Mich., for example, the initial wastewater applications flushed dissolved iron out of the soil profile, showing up as a reddish turbidity in the drain water. At the Fresno, Calif., system high-quality river water (snowmelt) was applied to relatively saline soils.[1] This low-salinity water dispersed the submicron soil colloids in the upper 12 ft of the soil profile. The colloids are then flocculated as mixing occurs with the more saline groundwater. This turbidity problem has persisted for 10 years but does not affect water quality in downgradient wells.

Soil chemistry data are usually obtained via routine laboratory tests on representative samples obtained from test pits or borings. Table 7.4 summarizes the interpretation of typical soil chemical tests.

Test pits and borings

Following an initial field reconnaissance, some subsurface exploration will be needed. In the preliminary stages, this consists of digging pits, usually with a backhoe, at several carefully selected locations. Besides exposing the soil profile for inspection and sampling, the purpose is to identify subsurface features that could develop into site limitations, or that point to potential adverse features. Conditions such as fractured, near-surface rock, hardpan layers, evidence of mottling in the profile, lenses of gravel, and other anomalies should be carefully noted. For OF site evaluations, the depth of soil profile evaluation can

TABLE 7.4 Interpretation of Soil Chemical Tests[17]

Test result	Interpretation
pH of saturated soil paste	
<4.2	Too acid for most crops to do well
4.2–5.5	Suitable for acid-tolerant crops
5.5–8.4	Suitable for most crops
>8.4	Too alkaline for most crops; indicates a possible sodium problem
CEC, meq/100 g	
1–10	Sandy soils (limited adsorption)
12–20	Silt loam (moderate adsorption)
>20	Clay and organic soils (high adsorption)
Exchangeable cations, % of CEC (desirable range)	
Sodium	5
Calcium	60–70
Potassium	5–10
ESP, % of CEC	
<5	Satisfactory
>10	Reduced permeability in fine-textured soils
>20	Reduced permeability in coarse-textured soils
EC_e, mmhos/cm at 25° of saturation extract	
<2	No salinity problems
2–4	Restricts growth of very salt-sensitive crops
4–8	Restricts growth of many crops
8–16	Restricts growth of all but salt-tolerant crops
>16	Only a few very salt-tolerant crops make satisfactory yields

be the top 3 ft (0.9 m) or so. The evaluation should extend to 5 ft (1.5 m) for SR and 10 ft (3 m) or more for RI systems.

Representative samples are obtained from the test pits and analyzed to determine the physical and chemical properties discussed above. It is possible with experience to estimate soil texture in the field with small samples taken directly from the walls of the test pit. To determine the soil texture, moisten a sample of soil about 0.5 to 1 in (12.7 to 25 mm) in diameter. There should be just enough moisture so that the consistency is like putty. Too much moisture results in a sticky material, which is hard to work. Press and squeeze the sample between the thumb and forefinger. Gradually press the thumb forward to try to form a ribbon from the soil. By using this procedure, the texture of the soil can be easily described with the criteria given in Table 7.5.

If the soil sample ribbons (loam, clay loam, or clay), it may be desirable to determine if sand or silt predominates. If there is a gritty feel and a lack of smooth talclike feel, then sand very likely predominates. If there is a lack of a gritty feel but a smooth talclike feel, then silt predominates. If there is not a predominance of either the smooth or gritty feel, then the sample should not be called anything other than a clay, clay loam, or loam. If a sample feels quite smooth with little or no grit in it and will not form a ribbon, the sample would be called silt loam.

Beginning at the top or bottom of the pit sidewall, obvious changes in texture with depth are noted. Boundaries that can be seen are marked. When the textures have been determined for each layer, its depth, thickness, and texture layer are recorded.

Soil structure (Table 7.6) has a significant influence on the soil's acceptance and transmission of water. Soil structure refers to the aggregation of soil particles into clusters of particles, called peds, that are separated by surfaces of weakness. These surface of weakness are often seen as cracks in the soil. These planar pores can greatly modify the influence of soil texture on water movement. Well-structured soils with large voids between peds will transmit water more rapidly than structureless soils of the same texture, particularly if the soil has become dry before the water is added. Fine-textured, massive soils (soils with little structure) have very slow percolation rates.

Soil structure can be examined in the pit with a pick or similar device to expose the natural cleavages and planes of weakness.

TABLE 7.5 Textural Properties of Mineral Soils[18]

	Feeling and appearance	
Soil class	Dry soil	Moist soil
Sand	Loose, single grains which feel gritty. Squeezed in the hand, the soil mass falls apart when the pressure is released	Squeezed in the hand, it forms a cast which crumbles when touched. Does not form a ribbon between thumb and forefinger
Sandy loam	Aggregates easily crushed; very faint velvety feeling initially, but with continued rubbing the gritty feeling of sand soon dominates	Forms a cast which bears careful handling without breaking. Does not form a ribbon between thumb and forefinger
Loam	Aggregates are crushed under moderate pressure; clods can be quite firm. When pulverized, loam has velvety feel that becomes gritty with continued rubbing. Casts bear careful handling	Cast can be handled quite freely without breaking. Very slight tendency to ribbon between thumb and forefinger. Rubbed surface is rough
Silt loam	Aggregates are firm but may be crushed under moderate pressure. Clods are firm to hard. Smooth, flourlike feel dominates when soil is pulverized	Cast can be freely handled without breaking. Slight tendency to ribbon between thumb and forefinger. Rubbed surface has a broken or rippled appearance
Clay loam	Very firm aggregates and hard clods that strongly resist crushing by hand. When pulverized, the soil takes on a somewhat gritty feeling due to the harshness of the very small aggregates which persist	Cast can bear much handling without breaking. Pinched between the thumb and forefinger, it forms a ribbon whose surface tends to feel slightly gritty when dampened and rubbed. Soil is plastic, sticky, and puddles easily
Clay	Aggregates are hard; clods are extremely hard and strongly resist crushing by hand. When pulverized, it has a gritlike texture due to the harshness of numerous very small aggregates which persist	Cast can bear considerable handling without breaking. Forms a flexible ribbon between thumb and forefinger and retains its plasticity when elongated. Rubbed surface has a very smooth, satin feeling. Sticky when wet and easily puddled

TABLE 7.6 Soil Structure Grades[18]

Grade	Characteristics
Structureless	No observable aggregation
Weak	Poorly formed and difficult to see. Will not retain shape on handling
Moderate	Evident but not distinct in undisturbed soil. Moderately durable on handling
Strong	Visually distinct in undisturbed soil. Durable on handling

The color and color patterns in soil are also good indicators of the drainage characteristics of the soil. It is often advantageous to prepare the soil pit so the sun will be shining on the face during the observation period. Natural light will give true color interpretations. Artificial lighting should not be used.

Color may be described by estimating the true color for each horizon or by comparing the soil with the colors in a soil color book. In either case, it is particularly important to note the colors or color patterns.

Seasonally high groundwater tables are preferably detected by borings made during the wet season of the year for the site. An indication of seasonally high groundwater can be observed by the presence of mottles or discolored soils in the wall of the test pit. Mottling in soils is described by the color of the soil matrix and the color or colors, size, and number of the mottles. Each color may be given a Munsell designation and name. However, it is often sufficient to say the soil is mottled. A classification of mottles used by the U.S. Department of Agriculture is shown in Table 7.7. Reference 8 includes some color photographs of typical soil mottles and can be used to assist in identification.

All of the data collected in the test pit on texture, structure, color, and presence of water should be recorded in the field. A sample log is shown in Fig. 7.1.

In some site evaluations, the backhoe pits will not yield sufficient information on the profile. Auger holes or bore holes are frequently used to explore soil deposits below the limits of pit excavation. Augers are useful to relatively shallow depths compared to other boring techniques. Depth limitation for augering varies with soil type and conditions, as well as hole diameter. In unconsolidated materials above water tables, 5-in diameter holes have been augered beyond 115 ft. Cuttings that are continuously brought to the surface during augering are not suitable for logging the soil materials. Withdrawal of the auger flights for removal of the cuttings near the tip represents an improvement as a logging technique. The best method is to withdraw the flights and obtain a sample with a Shelby tube or split-spoon sampler.

TABLE 7.7 Description of Soil Mottles[18]

Character	Class	Limit
Abundance	Few	2% of exposed face
	Common	2–20% of exposed face
	Many	20% of exposed face
Size	Fine	0.25 in longest dimension
	Medium	0.25–0.75 in longest dimension
	Coarse	7–75 in longest dimension
Contrast	Faint	Recognized only by close observation
	Distinct	Readily seen but not striking
	Prominent	Obvious and striking

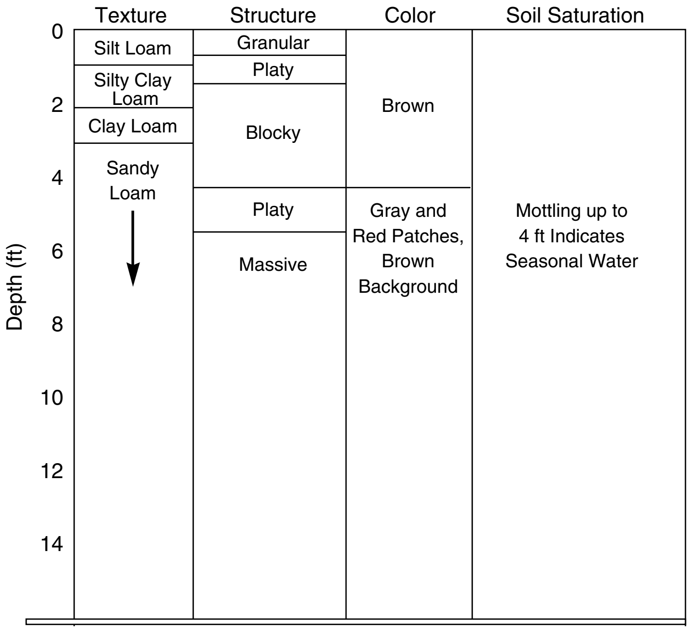


Figure 7.1 Sample log for test pit data.

Boring methods, which can be used to probe deeper than augering, include churn drillings, jetting, and rotary drilling. When using any of these methods, it is preferable to clean out the hole and secure a sample from the bottom of the hole with a Shelby tube or split-spoon sampler.

Groundwater Conditions

The position, the rate of flow, and the direction of flow of the natural groundwater beneath the site are critical elements in the field investigation. Some key questions to be answered by the investigation are:

1. How deep beneath the surface is the (undisturbed) water table?
2. How does the natural water table depth fluctuate seasonally?
3. How will the groundwater table respond to the proposed wastewater loadings?
4. In what direction and how fast will the mixture of percolate and groundwater move from beneath the area of application? Is there any possibility of transport of contaminants to deeper potable aquifers?
5. What will be the quality of this mixture as it flows away from the site boundaries?
6. If any of the conditions measured or predicted above are found to be unacceptable, what steps can be taken to correct the situation?

Groundwater depth and hydrostatic head

A groundwater table is defined as the contact zone between the free groundwater and the capillary zone. It is the level assumed by the water in a hole extended a short distance below the capillary zone. Groundwater conditions are regular when there is only one groundwater surface and when the hydrostatic pressure increases linearly with depth. Under this condition, the piezometric pressure level is the same as the free groundwater level regardless of the depth below the groundwater table at which it is measured. Referring to Fig. 7.2, the water level in the "piezometer" would stand at the same level as the "well" in this condition.

In contrast to a well, a piezometer is a small-diameter open pipe driven into the soil such that (theoretically) there can be no

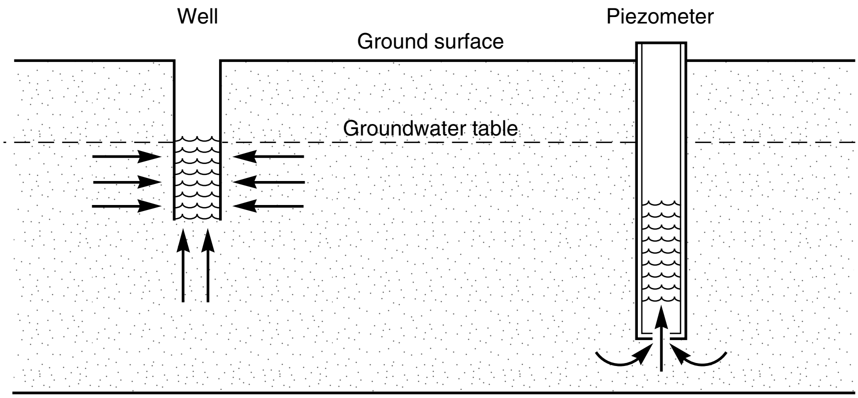


Figure 7.2 Well and piezometer installations. (*After Ref. 17.*)

leakage around the pipe. As the piezometer is not slotted or perforated, it can respond only to the hydrostatic head at the point where its lower open end is located. The basic difference between water level measurement with a well and hydrostatic head measurement with a piezometer is shown in Fig. 7.2.

Occasionally there may be one or more isolated bodies of water "perched" above the main water table because of lenses of impervious strata that inhibit or even prevent seepage past them to the main body of groundwater below.

Reliable determination of either groundwater levels or pressures requires that the hydrostatic pressures in the bore hole and the surrounding soil be equalized. Attainment of stable levels may require considerable time in impermeable materials. Called hydrostatic time lag, this may be from hours to days in materials of practical interest.

Two or more piezometers located together, but terminating at different depth, can indicate the presence, direction, and magnitude (gradient) of components of vertical flow if such exists. Their use is indicated whenever there is concern about movement of contaminants downward to lower living aquifers. Figure 7.3 shows several observable patterns with explanations. Reference 6 contains details on the proper installation of wells and piezometers.

Groundwater flow

Exact mathematical description of flow in the saturated zones beneath and adjacent to (usually downgradient) land treatment systems is a practical impossibility. However, for the majority of

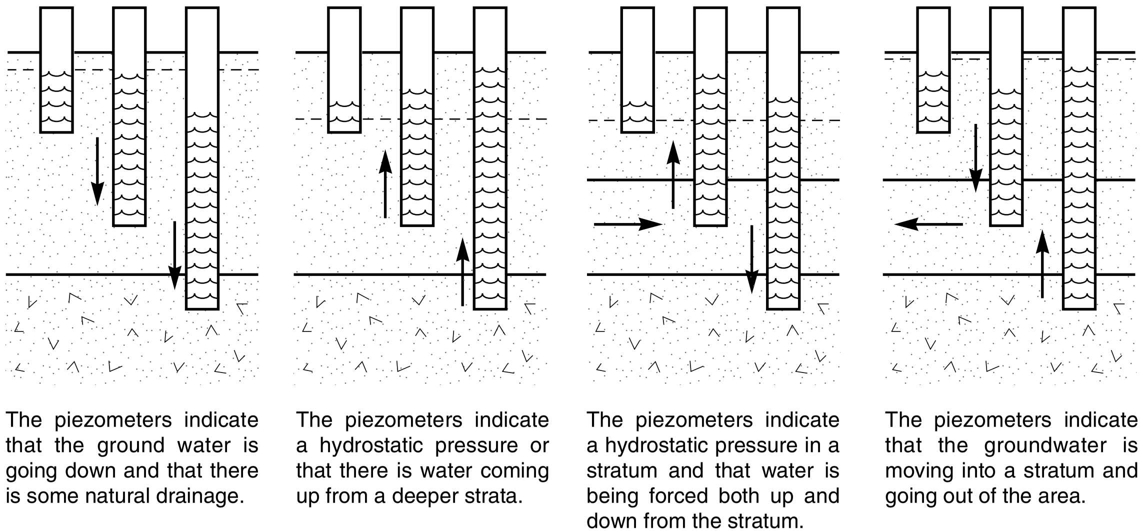


Figure 7.3 Vertical flow direction indicated by piezometers. (*After Ref. 17.*)

cases the possession of sufficient field data will allow an application of Darcy's equation [see Eq. (4.1) and related discussion in Chap. 4] to determine the volume of flow and the mean travel time as well as estimating the mounding that will be created by the wastewater applications. The calculation procedures are presented in detail in Chap. 4. The necessary field data include:

1. Depth to groundwater.
2. Depth to any impermeable barrier.
3. Hydraulic gradient determined from water levels in several observation wells at known distances apart. Establishing the gradient also determines the direction of flow.
4. Specific yield (see Chap. 4).
5. Hydraulic conductivity in the horizontal direction (see Chap. 4 for discussion, a later section in this chapter for test procedures).

Data for items 1 and 3 can be obtained from periodic water-level observations, over a period of months, from simple wells installed on the site. Figure 7.4 illustrates a typical shallow well.

The number and locations required will depend on the size of the project and the complexity of the groundwater system. Typical locations are upgradient of the site, several on the site, and on the downgradient boundary. In general, groundwater levels will tend to reflect the surface contours and flow toward adjacent surface waters. In a complex situation it may be necessary to install a few exploratory wells and then complete the array based on the preliminary data. If properly located, many of these wells can also serve for performance monitoring during system operation. It is necessary to determine the elevation at the top of each well. The depth to water can then be determined with a weighted, chalked tape or other sensing devices. Contours showing equal groundwater elevation can then be interpolated from the well data and plotted on a site map. This in turn allows determination of the hydraulic gradient and the flow direction.

Example 7.1: Groundwater Movement

Conditions Determine the direction of flow and hydraulic gradient for the situation shown in Fig. 7.5. Six monitoring wells were installed on the site. Observed April through October, June had the highest groundwater levels, and Fig. 7.5 depicts the interpolated contours for that month.

Solution The flow direction is perpendicular (and downgradient) to the groundwater contours, or in this case to the east. The hydraulic gradient is

$$\frac{\text{Difference in groundwater elevation}}{\text{Horizontal distance}} = \frac{h}{d} = \frac{112\ 2\ 106}{1200} = 0.5\%$$

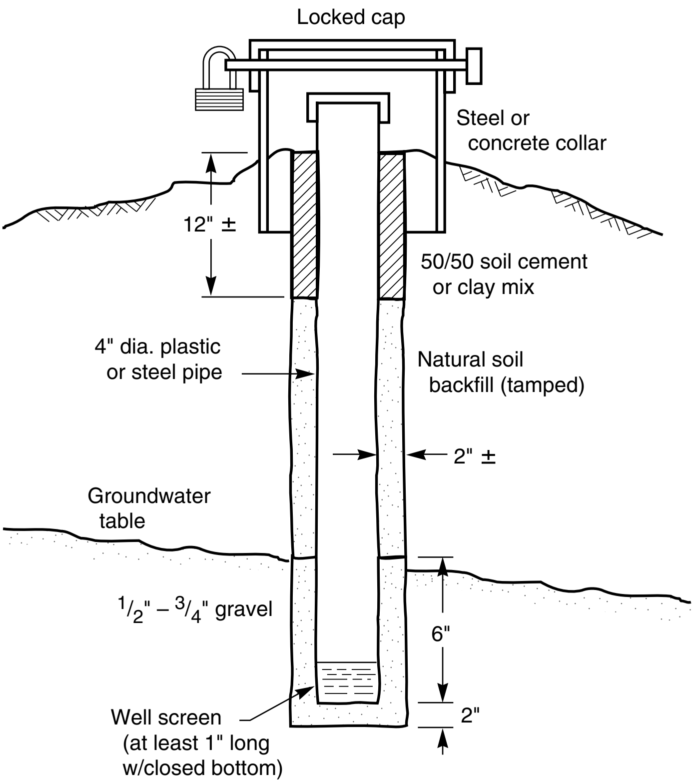


Figure 7.4 Typical shallow monitoring well.

Subsurface Permeability

The groundwater flow path will be parallel to the hydraulic gradient. In general situation this is essentially horizontal, except immediately beneath an application zone when mounding occurs. The flow of water will be vertical at the center of the mound and at an angle parallel to the gradient at the edge of the

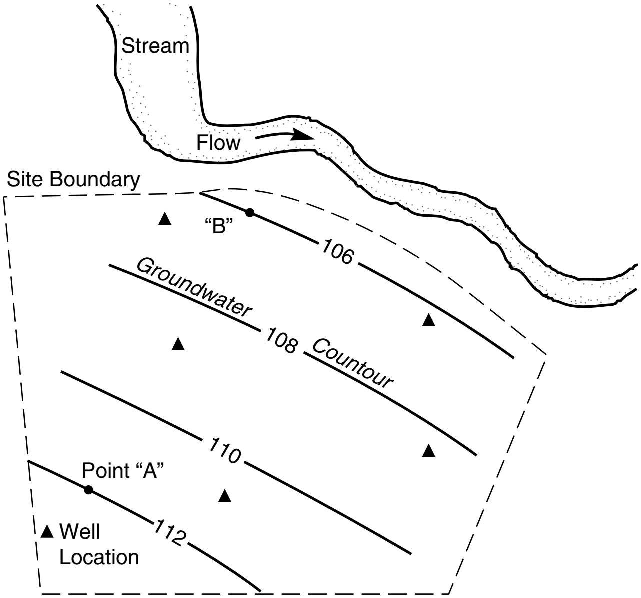


Figure 7.5 Hypothetical groundwater levels for Example 7.1. The horizontal distance from A to B = 1200 ft.

mound. The capability of the soil at the edge of the mound to transmit the applied flow in a lateral direction will control both the vertical development of the mound and its duration in time. The determination of this horizontal conductivity is therefore essential, particularly for RI systems.

Most soils are not homogeneous but rather are at least somewhat stratified, reflecting deposition or consolidation patterns. There are often thin layers or lenses of fine-textured material that will impede vertical flow between highly permeable layers of soil. As a result the potential for flow in the horizontal direction is often many times greater than in the vertical direction. This is illustrated by the ratios in Table 4.3. These values are often used for preliminary design calculations. However, in situations with shallow groundwater or where mounding or lateral flow are a significant factor for design it is necessary to measure the horizontal conductivity K_h in the field.

Auger hole test

The auger hole test is the most common and most useful of the field tests available for determining horizontal hydraulic conductivity. A hole is bored to a certain distance below the water table. The water in the hole is then pumped out. The rate at which the hole refills is a function of the hydraulic conductivity of the soil and the geometry of the hole. It is possible to calculate the K_h with the measured rate of rise and the other factors defined in Fig. 7.6. The general setup for the test is shown in Fig. 7.7. The equipment required includes a suitable pump, an auger, a stopwatch, and a device for measuring the depth of water in the hole as it rises. In unstable soils a perforated casing or well screens will be necessary to maintain an open hole. The Bureau of Reclamation uses 4-in thin-wall pipe with sixty 1/8-in by 1-in slots per ft of length.

The determination of hydraulic conductivity is affected by the location of the barrier or lower impermeable layer. In the case where the barrier is at the bottom of the hole, K_h can be defined as (terms as shown in Fig. 7.6)

$$K_h = \frac{15{,}000\ r^2}{(H + 10r)\,(2 - y/H)\,y}\,\frac{\Delta y}{\Delta t} \tag{7.1}$$

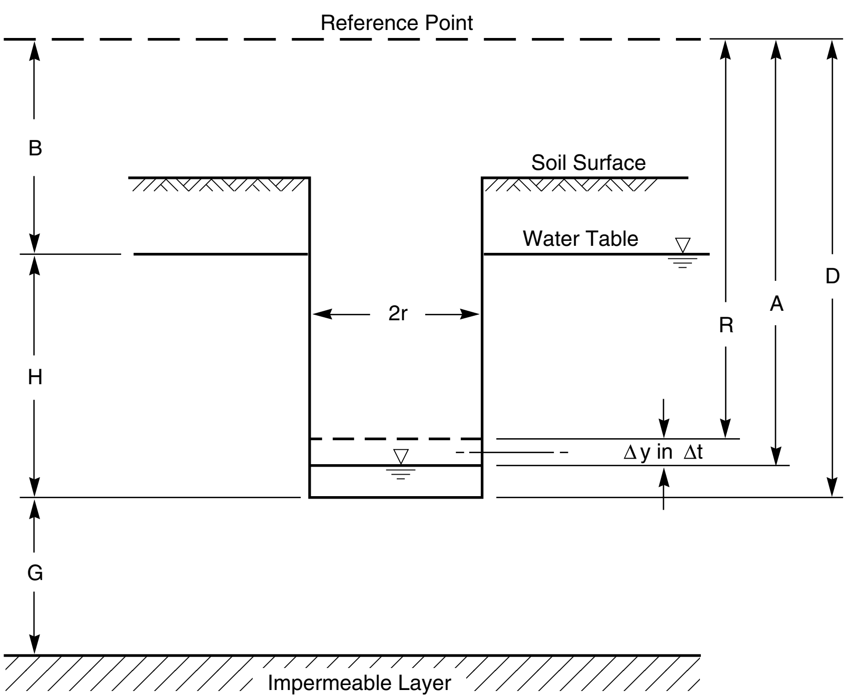


Figure 7.6 Definition sketch for auger hole technique.

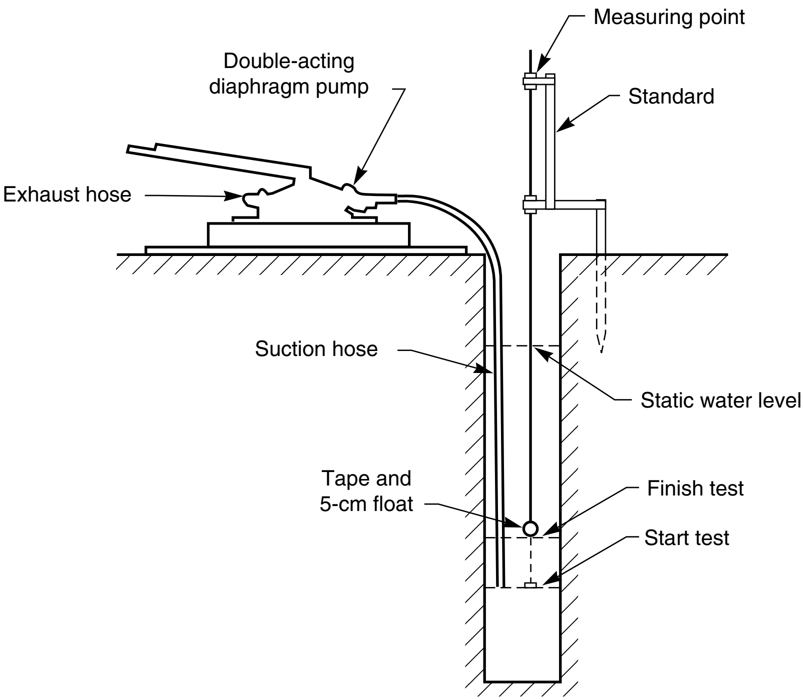


Figure 7.7 Equipment setup for auger hole test.

where K_h = horizontal hydraulic conductivity, in/h
r = radius of hole, in
H = initial depth of water in hole, in ($= D - \text{B}$)
A = depth (from reference point) to water after pumpout, in
R = depth (from reference point) to water after refill, in
y = average depth to water in hole during the refill period, in [$= (R - B) - \frac{1}{2}\,\Delta y$]
Δy = raise of water level in the timed interval Δt, in ($= A - R$)
Δt = time required to give Δy, s

The more usual case is when the impermeable layer is some distance below the bottom of the hole; in this case K_h is given by

$$K_h = \frac{16{,}667r^2}{(H + 20r)\,[2 - (y/H)\,y]}\left(\frac{\Delta y}{\Delta t}\right) \tag{7.2}$$

all terms as defined previously.

This equation is valid only when

$$2\tfrac{1}{2}\ \text{in} < 2r < 5\tfrac{1}{2}\ \text{in}$$

$$10\ \text{in} < H < 80\ \text{in}$$

$$y > 0.2H$$

$$G > H$$

$$y < \tfrac{1}{4}H - (D - A)$$

Example 7.2: Auger Hole Test

Conditions Find K_h for the following test conditions: 4-in-diameter hole, 84 in deep, reference point 12 in aboveground surface.

Solution

$$D = 96\ in \qquad y = 9\ \text{in}$$

$$B = 43\ \text{in} \qquad t = 180\ \text{s}$$

$$A = 81\ \text{in} \qquad R = 72\ \text{in}$$

$$H = D - B = 96 - 43 = 53\ \text{in}$$

$$r = \frac{4}{2} = 2\ \text{in}$$

$$y = R - B - \tfrac{1}{2}\,\Delta y$$

$$= 72 - 43 - \tfrac{1}{2}(9)$$

$$= 24.5\ \text{in}$$

$$G = 12\ \text{ft} = 144\ \text{in} > H\ (53\ \text{in})$$

so, use Eq. (7.2)

$$K_h = \frac{(16{,}667)(2)^2}{[53 + (20)(2)]\,[2 - (24.5/53)]24.5}\left(\frac{9}{180}\right)$$

$$= 0.96\ \text{in/h}$$

Measurement of horizontal hydraulic conductivity may still be necessary in the absence of a groundwater table. An example might be the presence of fragipan or other hard pan layers at shallow depth. These would restrict vertical flow and might result in unacceptable mounding unless the horizontal conductivity of the overlying material is suitable. The shallow well pump-in test described in Ref. 6 can be used in such cases. In effect, it is the reverse of the auger hole test described above. Chapter 15 also describes field tests for small-scale systems that can be used to evaluate mounding and lateral flow.

Mixing of wastewater percolate with groundwater

An analysis of the mixing of percolate with native groundwater is needed for SR and RI systems that discharge to groundwater if the quality of this mixture as it flows away from the site boundaries is a concern. The concentration of any constituent in this mixture can be calculated as follows:

$$C_{mix} = \frac{C_P Q_P + C_{gw} Q_{gw}}{Q_P + Q_{gw}} \tag{7.3}$$

where C_{mix} = concentration of constituent in mixture
C_p = concentration of constituent in percolate
Q_p = flow of percolate
C_{gw} = concentration of constituent in groundwater
Q_{gw} = flow of groundwater

The flow of groundwater can be calculated from Darcy's law [Eq. (4.1)] if the gradient and horizontal hydraulic conductivity are known. This is not the entire groundwater flow, but only the flow within the mixing depth. Eq. (7.3) is valid only if there is complete mixing between the percolate and the native groundwater. This is usually not the case. Mixing in the vertical direction may be substantially less than mixing in the horizontal direction. Density, salinity, and temperature differences between the percolate and groundwater may inhibit mixing, and the percolate may in some cases "float" as a plume on top of the groundwater for some distance. The percolation of natural rainfall downgradient of the application site can also serve to dilute the plume.

An alternative approach to estimating the initial dilution is to relate the diameter of the mound developed by the percolate to the diameter of the application area. This ratio has been estimated to be 2.5 to 3.0. This ratio indicates the relative spread of the percolate and can be used to relate the mixing of percolate with groundwater. Thus, an upper limit of 3 for the dilution ratio can be used when groundwater flow is substantially (5 to

10 times) more than the percolate flow. If the groundwater flow is less than 3 times the percolate flow, the actual groundwater flow should be used in Eq. (7.3).

Infiltration Rate

The infiltration rate of a soil is defined as the rate at which water enters the soil from the surface. When the soil profile is saturated with negligible ponding above the surface, the infiltration rate is equal to the effective saturated conductivity of the soil profile.

Although the measured infiltration rate on a particular site may decrease in time due to surface clogging phenomena, the subsurface vertical permeability at saturation will generally remain constant. Thus, the short-term measurement of infiltration serves reasonably well as an estimate of the long-term saturated vertical permeability if infiltration is measured over a large area.

The value that is required in land treatment design is the long-term acceptance rate of the entire soil surface on the proposed site for the actual wastewater effluent to be applied. The value that can be measured is only a short-term equilibrium acceptance rate for a number of particular areas within the overall site.

There are many potential techniques for measuring infiltration including flooding basin, cylinder infiltrometers, sprinkler infiltrometers, and air-entry permeameters. A comparison of these four techniques is presented in Table 7.8. In general, the test area and the volume of water used should be as large as practical. The two main categories of measurement techniques are those involving flooding (ponding over the soil surface) and rainfall simulators (sprinkling infiltrometer). The flooding type of infiltrometer supplies water to the soil without impact, whereas the sprinkler infiltrometer provides an impact similar to that of natural rain. Flooding infiltrometers are easier to operate than sprinkling infiltrometers, but they almost always give higher equilibrium infiltration rates. The sprinkler test is especially useful for agricultural SR operations. As discussed previously, soil sorting and surface sealing can occur with some soils, and a sprinkler test will evaluate the possibility. Sprinkler tests are not really needed for grassed or forested sites or where surface application of wastewater is anticipated.

TABLE 7.8 Comparison of Infiltration Measurement Techniques[17]

Measurement technique	Water use per test, gal	Time per test, h	Equipment needed	Comments
Flooding basin	600–3000	4–12	Backhoe or blade	Tensiometers may be used
Cylinder infiltrometer	100–200	1–6	Cylinder or earthen berm	Should use large-diameter cylinders (3 ft diameter)
Sprinkler infiltrometer	250–300	1.5–3	Pump, pressure tank sprinkler, cans	For sprinkler applications, soil should be at field capacity before test
Air entry permeameter (AEP)	3	0.5–1	AEP apparatus, standpipe with reservoir	Measures vertical hydraulic conductivity. If used to measure rates of several different soil layers, rate is harmonic mean of conductivities from all soil layers

Because the basic intent of all these tests is to define the saturated vertical hydraulic conductivity of the soil K_v and since wastewater will typically be "clean" after a few inches of travel it is usually acceptable to use clean water for these tests. There are exceptions, and the actual wastewater should be used when:

1. High suspended solids or algae are expected in effluents used for RI.
2. Industrial effluents have significantly different pH or ionic composition than the soil and soil water.
3. Effluents contain toxic or hazardous materials with potential for reaction with the soil components.

Basin tests

All infiltration tests should always be run at the actual locations and depths that will be used for the operational system. This is especially important for RI systems. Pilot-scale basin tests are strongly recommended. These should be at least 100 ft^2 in area, located in the same soil zone that will be used in the full-scale system. Construction of the test basin should be done with the same techniques that will be employed full-scale. The test basin should then be operated for several weeks using the same wet and dry cycles that are planned for full-scale. Figure 7.8 illustrates a typical small scale pilot test basin.

The number of test basins required will depend on the system size and the uniformity of the soils and topography. One will serve for relatively small systems with uniform soils. In larger systems a separate basin should be used for every major soil type, which may require one basin for every 5 to 10 acres (2 to 4 ha) of total system area. When extremely variable conditions are encountered, the test basin should be full-sized (1 to 3 acres or 0.4 to 1.3 ha) to ensure reliability. If successful, it can then be incorporated into the operational system.

A smaller-scale basin-type test has been developed by the U.S. Army Corps of Engineers.[9] The purpose was to have a reproducible procedure with a larger surface area and zone of influence than existing infiltrometers and permeameters. Figure 7.9 shows the test facility prior to flooding (note the cylinder infiltrometer in the right foreground). The metal ring is aluminum

Figure 7.8 Small-scale pilot test basin.

Figure 7.9 U.S. Army Corps of Engineers (USACE) basin test. (*From G. Abele.*)

flashing and is 10 ft (3 m) in diameter. Figures 7.10 and 7.11 provide installation details.

Tensiometers are used in the central part of the test area to ensure that saturated conditions prevail during the test period. One should be placed in each soil horizon. In soils lacking

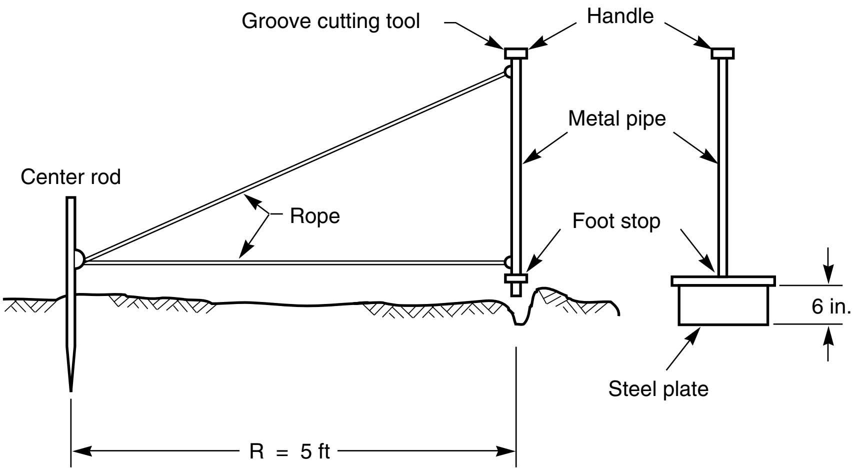


Figure 7.10 Groove preparation for USACE test.

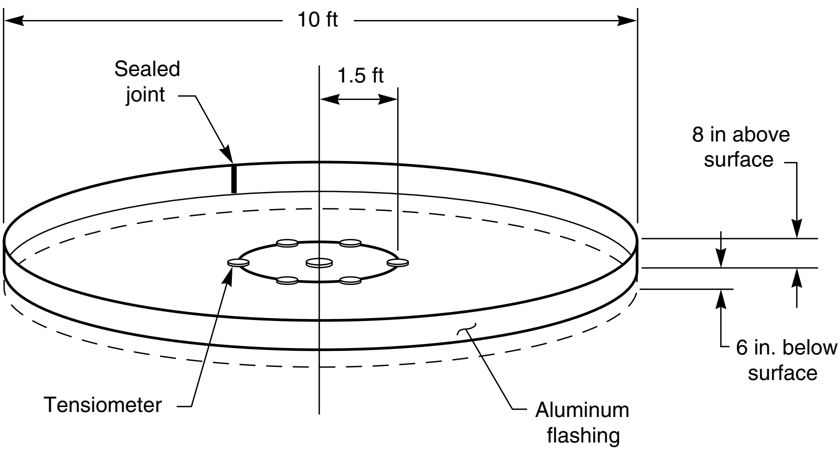


Figure 7.11 Finished installation, USACE test.

well-developed horizons a uniform spacing down to about 2 ft will be suitable. Following installation and calibration of the tensiometers, a few preliminary flooding events are executed to achieve saturation. Evidence of saturation is the reduction of tensiometer readings to near zero through the upper soil profile. Then a final flooding event is monitored to derive a cumulative intake versus time curve.

Figure 7.12 illustrates typical test results; the "limiting" value of 0.25 in/h was selected for design in this case.

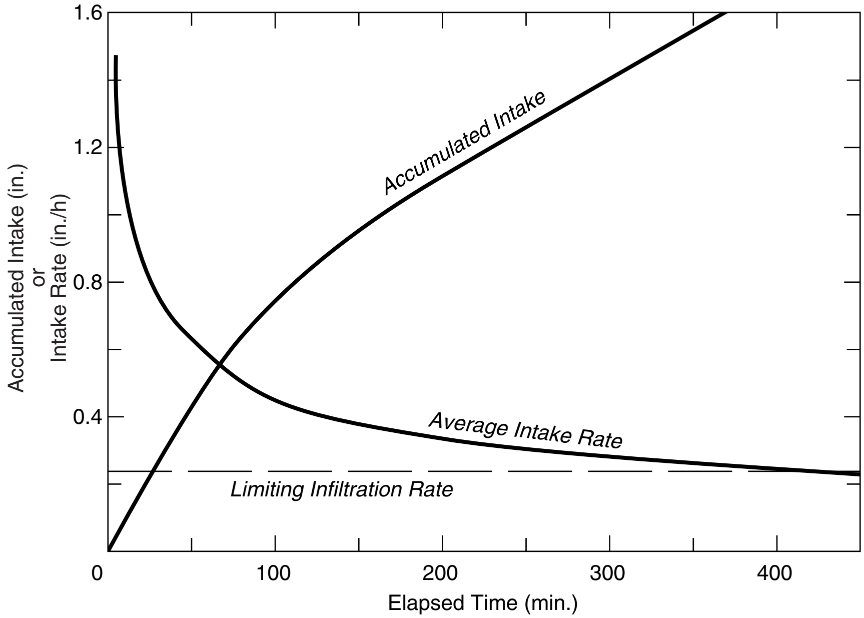


Figure 7.12 Typical test results, USACE infiltration test.

Cylinder infiltrometers

The equipment setup for a test is shown in Fig. 7.13. To run a test, a metal cylinder is carefully driven or pushed into the soil to a depth of about 4 to 6 in (100 to 150 mm). Cylinders from 6 to 14 in (150 to 350 mm) in diameter have generally been used in practice, with lengths of about 10 to 12 in (250 to 300 mm). Lateral flow is minimized by means of a "buffer zone" surrounding the central ring. The buffer zone is commonly provided by another cylinder 16 to 30 in (400 to 750 mm) in diameter, driven to a depth of 2 to 4 in (50 to 100 mm) and kept partially full of water during the time of infiltration. This particular mode of making measurements has come to be known as the double-cylinder or double-ring infiltrometer method. Care must be taken to maintain the water levels in the inner and outer cylinders at the same level during the measurements. Alternately, buffer zones are provided by diking the area around the intake cylinder with low (3 to 4 in or 75 to 100 mm) earthen dikes.

If the cylinder is installed properly and the test is carefully performed, the technique should produce data that at least approximates the vertical component of flow. In most soils, as

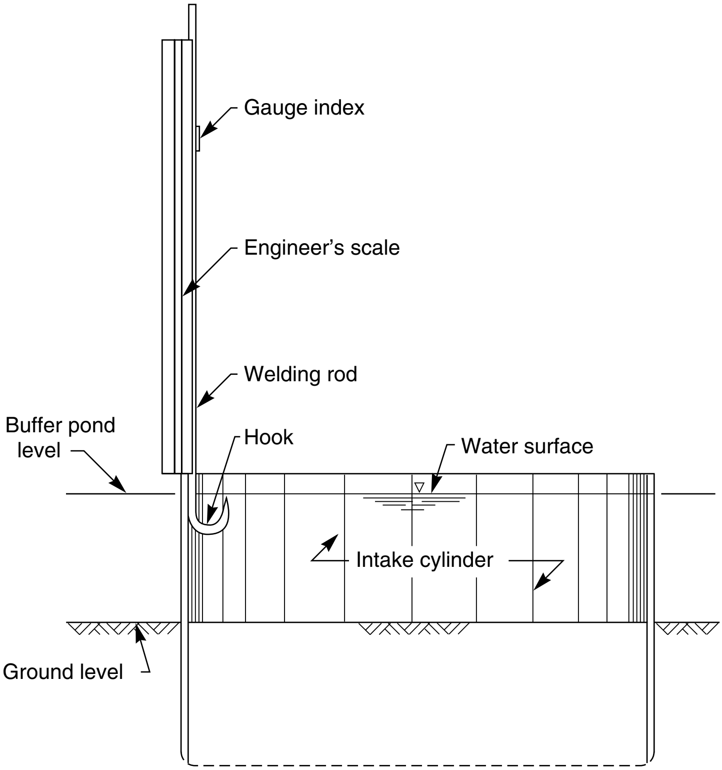


Figure 7.13 Test installation for cylinder infiltrometer.

the wetting front advances downward through the profile, the infiltration rate will decrease with time and approach a steady-state value asymptotically. This may require as little as 20 to 30 min in some soils and many hours in others.

Test results can be plotted as shown in Fig. 7.12 and design values derived. The procedure is relatively simple and quick and uses a small amount of water. The test has been commonly used for some time in agricultural projects and is familiar to most field investigation firms. However, the small size of the test limits the zone of influence. A large number of tests would be required for most situations. An ASTM standard exists for the test.

Air entry permeameters (AEP)

This device, developed by Dr. Herman Bouwer,[10] has been successfully used for the investigation and design of a number of land treatment systems. A sketch of the device is shown in Fig.

7.14, and Fig. 7.15 illustrates the device in use. The cylinder is steel, about 10 in (250 mm) in diameter and about 5 in (125 mm) deep. Operating instructions for the unit are:[11]

1. The cylinder is driven into the ground to a depth of 3 to 4 in (75 to 100 mm) (a cylinder driver with sliding weight is used for this purpose).

2. Using a section of 1-× 2-in (25- to 50-mm) lumber and a hammer, the soil along the inner perimeter of the cylinder is packed down and against the cylinder wall to ensure a good bond between the cylinder and the soil. In loose or cracked soil, compacting around the outside of the cylinder may also be necessary.

3. In case of a bare soil surface, the soil is covered with a $^1/_2$- to 1-in (12.5- to 25-mm) layer of coarse, clean sand. A disk or

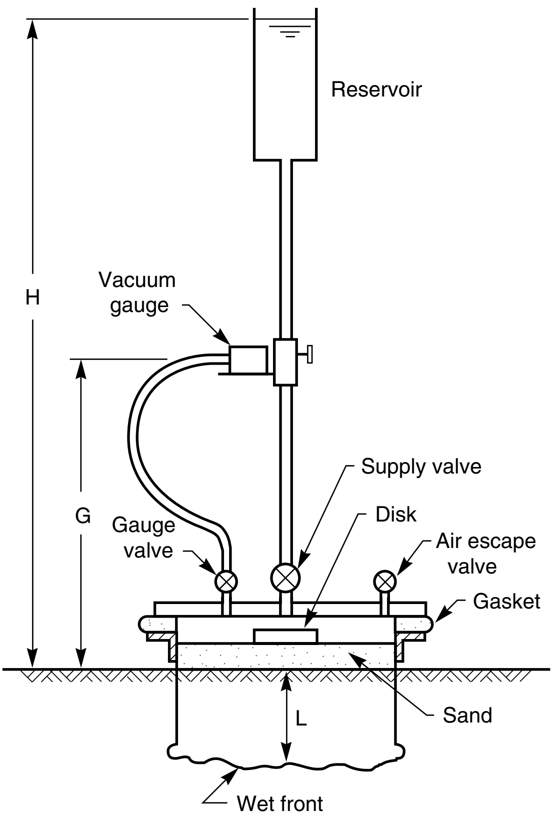


Figure 7.14 Definition sketch for air entry permeameter (AEP). (*From H. Bouwer.*)

Figure 7.15 Air entry permeameter in use. (*From H. Bouwer.*)

similar object is placed on the sand in the center of the cylinder to break the water stream from the supply pipe.

4. The surface of the foam rubber gasket is cleaned and a thin coat of grease is applied.

5. The lid assembly with the air valve open and the gauge and supply valves closed is placed on the cylinder. The gauge should be properly primed and air bubbles should not be present in the tubing connecting the gauge to the cylinder. A round bubble level is placed on the lid to determine the highest point. The

lid assembly is then rotated so that the air escape valve is at the highest point.

6. The lid is fastened with four small C-clamps or welder's vice-grip pliers until it rests firmly on the rim of the metal cylinder. Lead weights are placed on the lid to offset the upward hydrostatic force when the supply valve is open.

7. The plastic reservoir at the top of the galvanized pipe is filled with water, and the air in the pipe is allowed to escape. The supply valve at the bottom of the galvanized pipe is opened while maintaining the water supply to the plastic reservoir. When the water has driven out the air from inside the cylinder, the air valve is closed.

8. The vacuum gauge is removed from the holder and lifted to about the water level in the plastic reservoir. The gauge valve at the plastic lid is opened, which causes the needle on the gauge to go to zero. Tilting the gauge will then reset the memory pointer to zero. The gauge valve is closed and the gauge is replaced on the gauge holder.

9. Time and water-level readings are taken so that the rate of fall of the water level in the reservoir dH/dt (just before closing the supply valve) can be calculated.

10. When the depth of the wet front is expected to be at about 4 in (100 mm), the supply valve is closed. Experience will tell how much or how long water needs to be applied to achieve this depth.

11. The gauge valve is opened. When the gauge indicates approximately atmospheric pressure inside the cylinder, the weights are removed from the plastic lid.

12. When the memory pointer has lost contact with the gauge needle, minimum pressure has occurred. As soon as loss of contact is observed, the memory pointer is read, the gauge valve is closed, and the air escape valve is opened. The lid assembly is removed and the depth of the wet front is measured. This can be done by pushing a $^1/_4$-in rod into the soil and observing the depth where the penetration resistance is considerably increased. Another way is to quickly remove any remaining water in the cylinder, taking the cylinder out of the soil, and digging with a spade to visually determine the position of the wet front. Dyes and electric-conductivity probes may also offer possibilities for wet-front detection. To facilitate accurate assessment of the depth of the wet front, the soil should not be too wet at the time of the test.

13. Calculate P_a as

$$P_a = P_{min} + G + L \tag{7.4}$$

where P_a = entry value of soil
$P_{\min}$ = minimum pressure head (as determined by maximum reading on vacuum gauge)
G = height of gauge above soil surface, in
L = depth of wet front, in

If, for example, the maximum gauge reading corresponds to −33 in water and $L + G = 18$ in, P_a is calculated as −14 in water.

14. Calculate the water entry (air exit) value P_w as 0.5 P_a.

15. Calculate the saturated hydraulic conductivity K_s as

$$K_s = \frac{2\,(dH/dt)\,L\,R_r^{\,2}}{H_t + L - 0.5P_a R_c} \tag{7.5}$$

where $dH\backslash dt$ = rate of fall of water level in reservoir just before closing supply valve
H_t = height above soil surface of water level in reservoir when supply valve is closed
R_r = radius of plastic reservoir
R_c = radius of permeameter cylinder

16. Calculate K at zero soil water pressure head for sorption as 0.5 K_s.

Note. For most agricultural and coarse-textured soils, P_a numerically will be small compared to H_t. Under those conditions, P_a is not important and can be taken as zero (or as some arbitrary small value, for example, 4 in) in the above equation. This greatly simplifies the equipment and the field procedure, since the vacuum gauge and the measurement of minimum pressure inside the cylinder are then not needed.

The AEP test takes less time and less water than cylinder infiltrometers, and the simplicity of the test permits a very large number of repetitions with very small quantities of water. However, the small size of the apparatus limits the zone of influence so the results are only valid for the few inches below the test surface. Several repetitions with depth will be necessary to characterize the soil profile at a particular location. A successful approach is to dig a test pit with a backhoe with one end of the pit inclined to the surface. Benches can then be excavated by hand in the different horizons or at depths of choice and an AEP test run on each "step." The bench should be about 3 ft wide. The other walls of the test pit can then be used for the routine soils investigations. A combination of test basins on the site, supplemented by AEP tests in the remaining areas, is recommended as the investigation technique for most projects.

Agronomic Factors

Since SR and OF systems depend on vegetation as an active treatment component, it is essential that the field investigation provide sufficient data for reliable design and successful performance of the crop. Important chemical soil properties affecting the vegetation on land treatment systems include pH, cation exchange capacity, percent base saturation, exchangeable sodium percentage, salinity, plant nutrients, phosphorus, and potassium. These factors were discussed in detail in Chap. 3; this section covers only the sampling or testing procedure.

It is recommended that soil samples be collected from each field that will be used. If a given field exceeds 25 acres, individual soil samples should be collected from each soil series within the field. Valid soil-sampling procedures are essential. Information can be obtained from university or private soil testing laboratories on proper procedures for obtaining and handling soil samples. The soil analysis should at least determine (1) plant available P and K; and (2) soil pH and lime requirement. These tests are routinely performed for most farmers every 2 to 4 years.

In many regions of the United States, a specific soil test is not used to develop N fertilizer needs. Some midwestern states relate N fertilizer applications to soil organic matter, while the nitrate contained in the soil profile is considered in some western states where crops are grown under irrigation.

Samples should be air-dried (at temperatures less than 40°C), ground, and passed through a 2-mm sieve as soon as possible after collection. Chemical analyses are generally performed on air-dried samples and do not require special preservation for most parameters. However, samples collected for nitrate, ammonia, and pathogen analyses should be refrigerated under field moisture conditions and analyzed as soon as possible.

pH

Soil is prepared for pH determination by making a soil-water paste. When interpreting or using pH data, it is important to know which test method was used because of the influence of the procedure on results. Acid soil conditions (low pH) can be corrected in many cases by the addition of calcium carbonate (lime) to the soil. Alkaline soil conditions (high pH) can be corrected by the addition of acidifying agents. A routine laboratory test procedure is used to estimate the amount of agricultural limestone required to adjust the soil pH. Clover, alfalfa, peas, and beans require routine pH adjustment. In the typical case it is not usually economical to apply more than 3 to 4 tons of finely ground limestone per acre at any one time.[12] Figure 7.16 shows the amount of ground limestone that would be required to raise the soil pH to 7.0 for typical soils in New York State.[13]

Plant available phosphorus and potassium

The amount of plant available P is determined by analyzing the amount of P removed from soil by a particular extractant. The extractant used varies in different regions of the United States

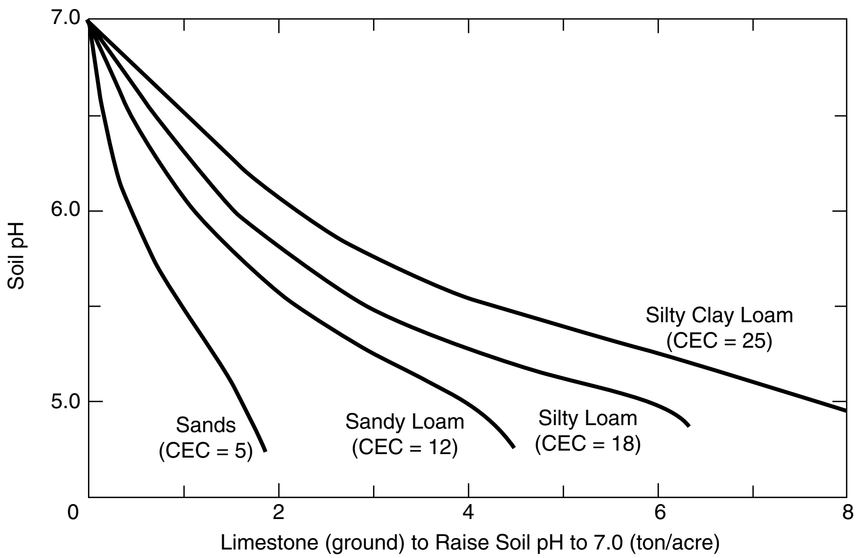


Figure 7.16 Limestone requirements to raise soil pH. (*After Ref. 12.*)

but is typically a dilute acid or a bicarbonate solution. Essentially all P taken up by crops is present in insoluble forms in soils rather than being in the soil solution. In all states, it has been determined that there is a relationship between the amount of extractable P in a soil and the amount of P fertilizer needed for various yields of different crops. Such information can be obtained from extension services, universities, etc.

As with P, an extractant is used to determine the plant available K in a soil. Potassium available for plant uptake is present in the soil solution and is also retained as an exchangeable cation on the cation exchange complex of the soil. The amount of plant available K is then used to determine the K fertilizer rate for the crop grown. Wastewater effluents are usually deficient in K, relative to crop needs in central and eastern parts of the United States.

Salinity and sodium

Soils containing excessive exchangeable sodium are termed "sodic" soils. A soil is considered sodic when the percentage of the total CEC occupied by sodium, the exchangeable sodium percentage (ESP), exceeds 15 percent. These levels of sodium cause clay particles to disperse in the soil because of the chemical nature of the sodium ion. The dispersed clay particles cause low soil permeability, poor soil aeration, and difficulty in seedling emergence. The level of ESP at which these problems are encountered depends on the soil texture. Fine-textured soil may be affected at an ESP above 10 percent, but coarse-textured soil may not be damaged until the ESP reaches about 20 percent.

These factors are discussed in detail in Chap. 3. If the field investigation reveals sodic soils or if high-salinity wastewater is anticipated, less sensitive crops must be selected as described in Chap. 5.

Test procedures

References 14, 15, and 16 are the standard sources for soil testing procedures. Most soils laboratories with agronomic capabilities have the capacity for the basic tests discussed in this chapter.

References

1. Nightingale, H. I., et al., "Leaky Acres Recharge Facility: A Ten Year Evaluation," *AWRA Water Resources Bulletin,* **19**(3):429 (June 1983).

2. Reed, S. C., *The Use of Clayey Sands for Rapid Infiltration Wastewater Treatment,* U.S.A. CRREL IR 805, 55 pp., Dec. 1982.
3. Lambe, T. W., and R. V. Whitman, *Soil Mechanics,* John Wiley & Sons, New York, 1969.
4. FHA, *Engineering Soil Classification for Residential Development,* FHA No. 373, U.S. GPO, Washington, D.C., August 1959.
5. U.S. ACE, "The Unified Soil Classification System," *Tech. Memo.* 3-357, vol. 1 (1960 revision) USAE-WES, Vicksburg, Miss., 1960.
6. U.S. DOI, *Drainage Manual,* U.S. Department of the Interior, Bureau of Reclamation, 1978.
7. Parr, J. F., P. B. Marsh, and J. M. Kla, *Land Treatment of Hazardous Wastes,* Noyes Data Corp., New Jersey, 1983.
8. U.S. Environmental Protection Agency, *Design Manual—Onsite Wastewater Treatment and Disposal Systems,* EPA 625/1-80-012, U.S. Environmental Protection Agency, Cincinnati, Ohio, Oct. 1980.
9. Abele, G., H. McKim, B. Brockett, and J. Ingersol, *Infiltration Characteristics of Soils at Apple Valley, Minn., Clarence Cannon Dam, Mo., and Deer Creek, Ohio, Land Treatment Sites,* 1980.
10. Bouwer, H., *Groundwater Hydrology,* McGraw-Hill, New York, 1978.
11. Bouwer, H., personal communication, 1982.
12. Brady, N. C., *The Nature and Properties of Soils,* Macmillan, New York, 1974.
13. Peech, M., *Lime Requirements vs. Soil pH Curves for Soils of New York State,* Department of Agronomy, Cornell University, Ithaca, N.Y., 1961.
14. Black, C. A. (Ed.), *Methods of Soil Analysis,* American Society of Agronomy, Madison, Wis., 1965, 1572 pp.
15. Walsh, L. M., and J. D. Beaton (Eds.), *Soil Testing and Plant Analysis,* Soil Science of America, Madison, Wis., 1973.
16. Page, A. L., et al. (Eds.), *Methods of Soil Analysis,* Part 2, *Chemical and Microbiological Properties,* 2d ed., Soil Science of America, Madison, Wis., 1983.
17. U.S. Environmental Protection Agency, *Process Design Manual for Land Treatment of Municipal Wastewater,* U.S. Environmental Protection Agency, EPA 625/1-81, Oct. 1981.
18. U.S. Environmental Protection Agency, *Design Manual—Onsite Wastewater Treatment and Disposal Systems,* U.S. Environmental Protection Agency, EPA 625/1-80-012, Oct. 1980.

Chapter

8

Preapplication Treatment and Storage

The level of preapplication treatment needed prior to any of the land treatment processes should be an engineering decision that recognizes the sequence of components as an integrated approach. A rational approach would be to start with the final effluent or percolate quality requirements, then determine what contribution the land treatment processes can provide, and then adopt a level of preapplication treatment for those constituents that will not be removed or reduced to an acceptable concentration by the land treatment process. The method of preapplication treatment should then be selected as the simplest and most cost-effective system possible. Unfortunately, some regulatory agencies still arbitrarily specify both the level and the method of preapplication treatment.

EPA Guidance

The level of preapplication treatment required should also be based on either the degree of public access to the site or the type and end use of the crop grown. The guidelines for preapplication treatment developed by the U.S. Environmental Protection Agency are summarized in Table 8.1. The level of treatment required increases as the degree of public access increases and when the end use of the crop involves direct human consumption. The bacterial standards are based on water quality

TABLE 8.1 Guidelines for Assessing the Level of Preapplication Treatment[1]

I.	Slow Rate Systems
A.	Primary treatment—acceptable for isolated locations with restricted public access and when limited to crops not for direct human consumption
B.	Biological treatment by lagoon or in-plant processes plus control of fecal coliform count to less than 1000 MPN/100 mL—acceptable for controlled agricultural irrigation except for human food crops to be eaten raw
C.	Biological treatment by lagoons or in-plant processes with additional BOD or TSS removal as needed for aesthetics plus disinfection to log mean of 200 MPN/100 mL (EPA fecal coliform criteria for bathing waters)—acceptable for application in public access areas such as parks and golf courses
II.	Rapid Infiltration Systems
A.	Primary treatment—acceptable for isolated locations with restricted public access
B.	Biological treatment by lagoons or in-plant processes—acceptable for urban locations with controlled public access
III.	Overland Flow Systems
A.	Screening or comminution—acceptable for isolated sites with no public access
B.	Screening or comminution plus aeration to control odors during storage or application—acceptable for urban locations with no public access

requirements for irrigation with surface water and on bathing water quality limits for the recreational case.[1]

Another reason for preapplication treatment is to reduce the level of total suspended solids (TSS) in the wastewater. High levels of TSS can clog sprinklers, valves, and other equipment, resulting in increased operation and maintenance (O&M) costs. High concentrations of TSS or algae may clog the infiltration surfaces and reduce the hydraulic capacity of rapid infiltration (RI) systems. Algae can also pose a problem in overland flow (OF) systems, where some microalgae will be removed inadequately.

Types of Preapplication Treatment

Preapplication treatment operations and processes can include fine screening, primary treatment, lagoons or ponds, constructed wetlands, biological treatment, and disinfection. Removal efficiencies and design criteria for these treatment operations and processes are documented in Ref. 2. Because ponds and constructed wetlands are often compatible with land treatment systems, the efficiencies of these preapplication treatment methods are described in the following.

Constituent Removals in Ponds

Effluent from any conventional wastewater treatment process can be applied successfully to the land. In many cases, however, a pond or lagoon will be the most cost-effective choice. Ponds are often used with land treatment for flow equalization, for emergency storage, and where there are seasonal constraints on the operation of land treatment systems. In cases where storage is needed, it will usually be most cost-effective to combine the treatment and storage functions in a multiple-cell pond system. Where odor control or high-strength wastes are a factor, the initial cell may be aerated followed by one or more deep storage cells. In remote locations an anaerobic primary cell designed for solids removal and retention may be possible, followed by the storage cells. The treatment occurring in the storage cells will be similar to that in a facultative pond. Basic design criteria for conventional pond systems are available from a number of sources.[2–5]

The pond unit can be specifically designed for the removal of a particular wastewater constituent. More typically the detention time in the pond component is established by the storage requirements for the system. The removal of various constituents that will occur within that detention time can then be calculated. If additional removal is required, the cost-effectiveness of providing more detention time in the pond can be compared to alternative removal processes. The removal of nitrogen in the pond unit is particularly important because, as discussed in earlier chapters, nitrogen is often the limiting design parameter (LDP) for slow rate systems. Any reduction of nitrogen in the pond unit directly impacts on the design of the land treatment component.

BOD and TSS removal in ponds

As indicated in Chap. 3, BOD is usually not the LDP for design of the land treatment component in any of the processes. However, many regulatory agencies specify a BOD requirement for the wastewater to be applied, so it may be necessary to estimate the removal that will occur in the pond components. There may be a combination of an aerated or anaerobic cell followed by the storage pond.

Aerated ponds. The BOD removal that will occur in aerated cells can be estimated with.

$$\frac{C_n}{C_0} = 1/\left(1 + k_c t/n\right)^n \tag{8.1}$$

where C_n = effluent BOD from cell n, mg/L
C_0 = influent BOD to system, mg/L
k_c = reaction rate constant (see Table 8.2) at 20°C
t = total hydraulic resident time, days
n = number of cells

The reaction rate k_c is dependent on the water temperature, as shown in Eq. (8.2):

$$k_{cT} = k_{20}\,\theta^{(T-20)} \tag{8.2}$$

where k_{cT} = reaction rate at temperature T
k_{20} = reaction rate at 20°C (see Table 8.2)
θ = 1.036
T = temperature of pond water, °C

The temperature of the pond can be estimated with the following equation:

$$T_w = \frac{AfT_a + QT_i}{Af + Q} \tag{8.3}$$

where T_w = pond temperature, °C
T_a = ambient air temperature, °C
A = surface area of pond, m^2

TABLE 8.2 Reaction Rates for Aerated Ponds[5]

Type of aeration	k at 20°C
Complete mix	2.5
Partial mix	0.276

f = proportionality factor (= 0.5)
Q = wastewater flow rate, m^3/day

The selection of an apparent reaction rate value from Table 8.2 depends on the aeration intensity to be used. The "complete mix" value assumes high-intensity aeration (about 100 hp/million gal) sufficient to maintain the solids in suspension. The "partial mix" value assumes that there is sufficient air supplied to satisfy the oxygen demand (about 10 hp/million gal) but that solids deposition will occur.

The suspended solids in the effluent from a complete mix aerated cell will be nearly the average concentration in the cell. The suspended solids in the partial mix pond effluent will be lower, depending on the detention time. For a detention time of 1 day, assume the suspended solids are similar to primary effluent (60 to 80 mg/L).

Facultative ponds. The BOD removal that will occur in a facultative cell can be estimated using Eq. (8.4).

$$\frac{C_n}{C_0} = e^{-k_p t} \tag{8.4}$$

where C_n = effluent BOD, mg/L
C_0 = influent BOD, mg/L
k_p = plug flow apparent reaction rate constant (see Table 8.3)
t = detention time, days

The apparent rate constant for plug flow also varies with temperature with a theta value of 1.09.

TABLE 8.3 Variation of Plug Flow Apparent Rate Constant with Organic Loading Rate for Facultative Ponds[6]

Organic loading rate, kg/(ha·day)*	k_p, per day
22	0.045
45	0.071
67	0.083
90	0.096
112	0.129

*kg/(ha·day) × 0.8928 = lb/(acre·day)

The TSS concentrations from facultative cells depend on the temperature and detention time. Algae concentrations can reach 120 to 150 mg/L or more in warm temperatures and may be as low as 40 to 60 mg/L in cooler temperatures.[23]

Anaerobic ponds. Anaerobic ponds are rarely used with municipal wastewaters unless there is a large industrial waste component. The ponds are typically 10 to 15 ft (3 to 4.5 m) deep. BOD loading rates may be as high as 450 lb/(ac·day) [500 kg/(ha·day)], detention times range from 20 to 50 days, depending on the climate, and a BOD conversion of about 70 percent is typical. Effluent TSS values range from 80 to 160 mg/L.

A primary anaerobic cell is used at a number of municipal pond systems in rural areas of the western provinces of Canada.[7] The anaerobic cells are also designed for solids removal and retention and are typically followed by one or more long-detention-time facultative cells. Anaerobic cells are usually designed for up to 10 days' detention time, with depths ranging from 10 to 20 ft (3 to 6 m). Effluent from these cells is comparable to primary effluent. Detectable odors have been noted to at least 1000 ft (305 m) around these systems, so a remote location or other odor control is needed.

Nitrogen removal in ponds

The loss of nitrogen from ponds and water bodies has been recognized, and predictive models are available.[8] The removal of nitrogen in a pond is dependent on pH, temperature, and detention time, and under ideal conditions up to 95 percent has been observed. Volatilization of the ammonia fraction is believed to be the major pathway responsible for long-term permanent losses.

Because nitrogen is often the LDP for land treatment design, it is essential to determine the losses that will occur in any preliminary pond units for treatment or storage. This may influence the basic feasibility of a particular process or control the amount of land needed.

The equations presented below can be used for facultative ponds and for storage ponds. The nitrogen losses in short-detention-time aerated ponds can usually be neglected. The procedure is based on total nitrogen in the system because numerous transformations from one form of nitrogen to another are likely during the long detention time.

The first design equation is

$$\frac{N_e}{N_0} = \exp \{ -k_{nt} [t + 60.6 (\mathrm{pH} - 6.6)] \} \tag{8.5}$$

where N_e = effluent total N, mg/L
N_0 = influent total N, mg/L
k_{nt} = temperature-dependent reaction rate, per day (= 0.0064 at 20°C)
t = detention time, days
pH = median pH in pond during time t

The temperature adjustment can be made using Eq. (8.2), using a theta value of 1.039.

The second design equation is presented below:[25]

$$N_e = N_0 \frac{1}{1 + t\,(0.000576T - 0.00028) \exp [(1.08 - 0.042T)(\mathrm{pH} - 6.6)]} \tag{8.6}$$

terms are the same as for Eq. (8.5).

Example 8.1: Nitrogen Removal in Facultative Ponds

Conditions N_0 = 40 mg/L, detention time = 50 days, pH = 8, temperature = 15°. Determine the effluent nitrogen concentration using Eq. (8.5).

Solution

1. Convert k from 20 to 15°C.

$$k = 0.0064(1.039)^{15-20}$$

$$k = 0.0064(0.826)$$

$$k = 0.00529 \text{ per day}$$

2. Calculate effluent nitrogen concentration using Eq. (8.5).

$$N_e = 40 \exp \{-0.00529 [50 + 60.6(8 - 6.6)]\}$$

$$= 19.6 \text{ mg/L}$$

Application of Eq. (8.5) requires information on the wastewater nitrogen concentration, the detention time, pH, and temperature conditions to be expected. In a typical case the nitrogen concentration will vary from month to month, so actual long-term data are desirable for design. A first approximation for typical municipal wastewater can be obtained with:

	Total nitrogen, mg/L
Weak wastewater (BOD ≈ 120)	20
Medium wastewater (BOD ≈ 220)	35
Strong wastewater (BOD ≈ 350)	60

For the first iteration, the detention time should be determined based on (1) any BOD removal required, or (2) the storage time needed. If additional nitrogen removal is necessary, then the cost-effectiveness of providing more detention time can be compared to other alternatives.

Equation (8.5) is based on plug flow kinetics and is valid when a pond is discharging, and the detention time is then the total detention time in the system. A value of one-half the detention time should be used for the filling and storage (nondischarge) periods for storage ponds.

The pH is controlled by the algae interactions with the carbonate buffering system in the pond. If possible, pH values should be obtained from an operating pond in the vicinity. The median pH values for four facultative ponds in the United States are given in Table 8.4. A rough estimate of the pH to be expected can be obtained with

$$pH = 7.3 \exp [0.005 (Alk)] \tag{8.7}$$

where pH = median pH in bulk liquid
Alk = alkalinity of influent (as $CaCO_3$), mg/L

TABLE 8.4 Typical pH and Alkalinity Values in Facultative Ponds[9–12]

Location	Annual median pH	Annual average alkalinity, mg/L
Peterborough, N.H.	7.1	85
Eudora, Kan.	8.4	284
Kilmichael, Miss.	8.2	116
Corinne, Utah	9.4	557

Phosphorus removal in ponds

Phosphorus removal in ponds is limited. Chemical addition using alum or ferric chloride has been used to reduce phosphorus to below 1 mg/L.[3] Application of chemicals can be on a batch or continuous-feed basis. For controlled-release ponds the batch process is appropriate. The state of Minnesota has 11 facultative pond systems that use the addition of liquid alum directly into secondary cells via motorboat to meet a spring and fall discharge limitation of 1 mg/L.[13]

For continuous-flow applications, a mixing chamber is often used between the last two ponds or between the last pond and a clarifier. In Michigan, both aerated ponds and facultative ponds have been used with continuous-flow applications. Influent phosphorus concentrations for 21 treatment facilities ranged from 0.5 to 15 mg/L with an average of 4.1 mg/L, and the effluent target is 1 mg/L.[13]

Pathogen removal in ponds

The design of systems that include a pond component should evaluate the bacteria and virus reductions that will occur in the pond. In some cases the reductions that will occur in a pond will produce acceptable levels so an extra disinfection step will not be required. At Muskegon, Mich., for example, the fecal coliforms in the storage pond effluents were consistently below required levels, so that chlorination was terminated.[14] The effluent in this case is applied to corn, with poultry feed a major use of the harvested corn. Water-quality changes through the storage pond at Muskegon, Mich.,[15] and in a pilot-scale pond in Israel[16] are summarized in Table 8.5.

Removal of bacteria and virus in ponds is strongly dependent on temperature and detention time. Virus removal in model ponds is illustrated in Fig. 8.1.[17] Similar results were observed at operational facultative ponds in the southwest, southeast, and north central United States.[18] In summer months, virus removal exceeded 99 percent in the first two cells of these systems. The overall removal on a year-round basis exceeded 95 percent. Removal of fecal coliforms was even higher.

Results very similar to those in Fig. 8.1 have been demonstrated for fecal coliforms in facultative ponds in Utah.[19] An equation was developed, based on Chick's law, which describes

TABLE 8.5 Changes of Microorganism Concentrations During Storage[14]

Location	Input concentration, count/100 mL	Output concentration, count/100 mL
Muskegon County, Mich. (winter):		
Fecal coliform	1×10^6	1×10^3
Haifa, Israel (winter, 73 days):		
Total coliform	2.3×10^7	1.84×10^4
Fecal coliform	1.1×10^6	2.4×10^3
Fecal streptococcus	1.1×10^6	5.0×10^2
Enterovirus	1.1×10^3	0
Haifa, Israel (summer, 35 days):		
Total coliform	1.4×10^7	2.3×10^4
Fecal coliform	3.5×10^6	2.4×10^4
Fecal streptococcus	6.0×10^5	3.7×10^3
Enterovirus	200	0

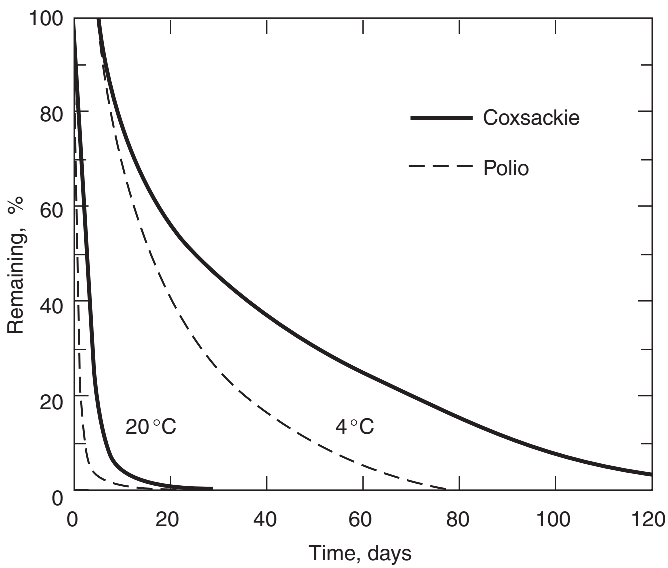


Figure 8.1 Virus removal in ponds. (*After Ref. 17.*)

the die-off of fecal coliforms in a pond system as a function of time and temperature:

$$t = \frac{\ln (C_i/C_f)}{k_{fc}} \tag{8.8}$$

where t = actual detention time, days
C_i = influent fecal coliforms, count/100 mL
C_f = final fecal coliforms, count/100 mL
k_{fc} = rate constant; use 0.5 for temperature of 20°C
θ = theta value for Eq. (8.2) (= 1.072)

Removal of fecal coliform with time is shown in Fig. 8.2. Temperature and detention times to achieve final concentrations of 200 counts/100 mL for irrigation standards and 1000/100 mL for recreation water standards are shown in Fig. 8.2. The detention time used in the equation is the actual detention time as measured by dye studies. In the ponds used for model development the actual detention time ranged from 25 to 89 percent of the theoretical design detention time due to short-circuiting. The geometric mean was 46 percent. If the actual detention time in the pond system is not known, it is suggested that this factor be applied when using the equation to estimate fecal coliform die-off to ensure a conservative prediction.

Metals and trace organic removal in ponds

Removal of metals in the pond component will be comparable to that achieved in primary treatment unless a high-intensity,

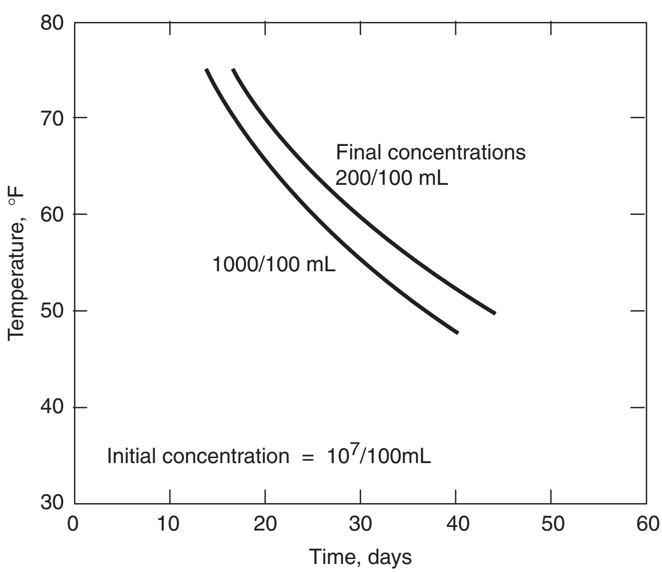


Figure 8.2 Fecal coliform removal in ponds—detention time vs. liquid temperature.

complete-mix aeration cell is used. In that case removals will be comparable to activated sludge. The removal of trace organics, particularly the volatile type, is very effective in ponds. At the Muskegon County, Mich., system, for example, there were 56 organic compounds in the wastewater entering the ponds. Of these 56 compounds only 17 were present, and at low concentrations, in the effluent leaving the ponds.[20]

Constituent Removals in Constructed Wetlands

Constructed wetlands have been used to remove BOD, TSS, nitrate-nitrogen, and metals, among other constituents, from wastewater.[2,3,24] Constructed wetlands can be free water surface (FWS) or subsurface flow (SF). Free water surface constructed wetlands are best suited to preapplication treatment, especially for flows above 0.1 mgd (387 m^3/day).

Area for BOD removal

The field area needed for a constructed wetland can be calculated using Eq. (8.9).

$$A = \frac{Q\,(\ln C_0 - \ln C_e)}{K\,(y)\,(\eta)} \tag{8.9}$$

where A = field area, acres
Q = average flow, acre · ft/day (3.07 × flow, mgd)
C_0 = influent BOD, mg/L
C_e = effluent BOD, mg/L
K = apparent removal rate constant (= 0.678 per day for FWS wetlands at 20°C; = 1.104 per day for SF wetlands at 20°C)
y = water depth, ft
η = porosity (= 0.75 to 0.85 for FWS wetlands; = 0.28 to 0.45 for SF wetlands)

The average flow should be the annual average flow into the wetlands plus the effluent flow divided by 2. The apparent K factor is temperature-dependent, and Eq. (8.2) can be used for different water temperatures, with the theta factor being 1.06. The porosity of FWS wetlands depends on the density of the vegetation, with 0.75 being appropriate for high densities and 0.85 being appropriate for moderate densities. Where open water area is interspersed with vegetated zones the porosity will be 0.8 to 0.9. For SF constructed wetlands the porosity depends on the particle size of the gravel used. Coarse sand and gravelly sand has a porosity of 0.28 to 0.35. Fine gravel, widely used in SF systems, has a porosity of 0.35 to 0.38. Medium to coarse gravel has a porosity of 0.36 to 0.45.[3]

Area for nitrate removal

For effluents containing nitrate, constructed wetlands can be used for nitrate removal. Constructed wetlands are not very efficient at nitrification, particularly in cold water, however, denitrification progresses relatively fast. Equation (8.8) can be used to predict nitrate reduction by using a K of 1.0 and a theta of 1.15. For water temperatures of 1°C or less, assume that denitrification effectively ceases.

Design of Storage Ponds

For SR and OF systems, adequate storage must be provided when climatic conditions require operations to be curtailed or hydraulic loading rates to be reduced. Most RI systems are operated year-round, even in areas that experience cold winter weather. Rapid infiltration systems may require cold weather storage during periods when the temperature of the wastewater to be applied is near freezing and the ambient air temperature at the site is below freezing. Generally, the problem occurs only when ponds are used for preapplication treatment. Land treatment systems also may need storage for flow equalization, system backup and reliability, and system management, including crop harvesting (SR and OF) and spreading basin maintenance (RI). Reserve application areas can be used instead of storage for these system management requirements.

During the planning process, Fig. 6.2 may be used to obtain a preliminary estimate of storage needs for SR and OF systems. This figure was developed from data collected and analyzed by the National Climatic Center in Asheville, N.C. The data were used to develop computer programs that estimate site-specific wastewater storage requirements based on climate, which, in turn, were used to plot Fig. 6.2. The map is based on the number of freezing days per year corresponding to a 20-year return period. If application rates are reduced during cold weather, additional storage may be required. Should there be a need for more detailed data, the design engineer should contact:

National Climatic Data Center
151 Patton Avenue, Room 120
Asheville, N.C. 28801-5001
(828)-271-4800
FAX (828)-271-4876
Email: orders@ncdc.noaa.gov

Any communications should refer to computer programs EPA-1, 2, and 3. Each of these programs costs $300 for an initial computer run plus $11 per order for processing (1999). The factors involved with each program are summarized in Table 8.6. The storage days are calculated for recurrence intervals of 2, 4, 10, and 20 years. The sections of the United States for which each program is applicable are shown in Fig. 8.3.

Storage days required for crop management activities (harvesting, planting, cultivating, etc.) must be added to the computer estimated storage days due to weather, to obtain the total storage days required each month. The estimated required storage volume is then calculated by multiplying the number of storage days in each month times the average daily flow for the corresponding month.

An alternative for preliminary planning of OF and SR systems is to assume 25°F (−3.9°C) as the minimum temperature at which a system will operate successfully. Then, the required storage volume is estimated from the average cold weather flow

TABLE 8.6 Summary of Computer Programs for Determining Storage from Climatic Variables

EPA program	Applicability	Variables	Remarks
EPA-1	Cold climates	Mean temperature, rainfall, snow depth	Uses freeze index
EPA-2	Wet climates	Rainfall	Storage to avoid surface runoff
EPA-3	Moderate climates	Maximum and minimum temperature, rainfall, snow depth	Variation of EPA-1 for more temperate regions

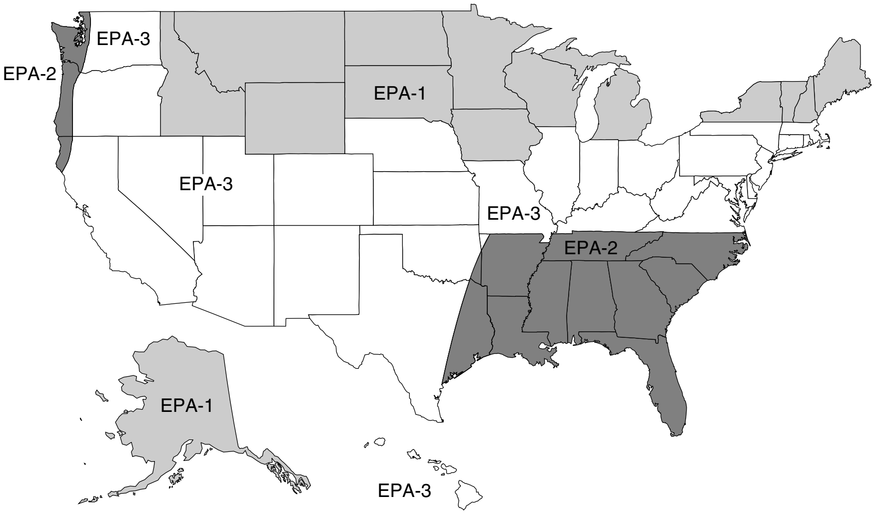


Figure 8.3 Applicable zones in the United States for application of U.S. Environmental Protection Agency storage programs. (*After Ref. 11.*)

and the number of days in which the mean temperature is less than 25°F (−3.9°C).

Storage calculation method

The required storage volume should be determined by conducting a monthly water balance, which must include the net precipitation or evaporation on the pond. This method requires an iterative solution with some assumed initial conditions because the pond area is not known. It is usually convenient to assume a depth for the initial calculation. A water balance for each month can be calculated with the general relationship

$$S = (P - E) + Q - W - I \tag{8.10}$$

where S = storage volume need for the month
P = volume of precipitation falling into the pond during the month
E = volume of water lost by evaporation during the month
Q = volume of wastewater entering the pond during the month
W = volume of wastewater leaving the pond during the month

I = volume of water lost by seepage from the pond during the month

Precipitation and evaporation volumes can be estimated from the climatological data. Compile all available monthly and annual data for the closest climatic station to the proposed land treatment site. Using the annual data, calculate the 10 percent chance of exceeding values for both precipitation and evaporation. Apportion these annual values according to the average percent rainfall and evaporation for each month. To convert these data from water depth to volume, the surface area of the pond must be known. One method of calculating the surface area is to

1. Estimate the number of storage days required using EPA-1, 2, or 3.
2. Multiply the number of storage days by the average daily design flow to obtain a volume of storage.
3. Assume a depth of water in the pond and calculate the surface area by dividing the volume of storage by the depth. A depth of 10 ft is usually reasonable for a first estimate.

It may be necessary to adjust the surface area once the actual storage volume is determined. However, adjusting the surface area requires a recalculation of the precipitation and evaporation volumes. The other alternative is to change the water depth. The latter method is preferred because P and E volumes then remain unchanged. The volume of wastewater entering the pond per month can be calculated by multiplying the average daily design flow by the number of days in the month.

The volume of wastewater leaving the pond can be calculated by multiplying the depth of wastewater applied by the field area. The depth of wastewater applied can be determined from the planned irrigation schedule. Field area (in acres) can be determined from the relationship

$$F = \frac{Q + P - E}{L_w} \tag{8.11}$$

where F = field area, acres
Q = volume of wastewater entering the pond, (acre · ft) /year

P = volume of precipitation falling onto the pond, (acre · ft) /year

E = volume of evaporation from the pond, (acre · ft) /year

L_w = wastewater loading on application site, ft/year

The volume of water lost by seepage is difficult to estimate over the design life of the system. State standards for allowable seepage rates from ponds vary from 0.062 to 0.25 in/day. These standards are becoming more stringent, and essentially impervious linings may be required in the future. Therefore, for a conservative design, assume seepage losses to be negligible. A typical water balance is shown in Table 8.7.

As shown in the final column of the table, the maximum storage required is 5274 acre·ft during the month of April. If the surface area is maintained at the assumed 430 acres, the depth of the pond would have to be 12.3 ft. If the assumed 10-ft depth is retained, then the actual surface area will be larger than 430 acres and another iteration of the calculations will be needed to account for the additional precipitation or evaporation.

Storage for overland flow

Storage facilities may be required at an OF system for any of the following reasons:

1. Storage of water during the winter due to reduced hydraulic loading rates or system shutdown
2. Storage of stormwater runoff to meet mass discharge limitations
3. Equalization of incoming flows to permit constant application rates

In general, OF systems must be shut down for the winter when effluent quality requirements cannot be met due to cold temperature even at reduced application rates or when ice begins to form on the slope. The duration of the shutdown period and, consequently, the required storage period will, of course, vary with the local climate and the required effluent quality. In studies at Hanover, N.H., a storage period of 112 days, including acclimation, was estimated to be required when treating primary effluent to BOD and TSS limits of 30 mg/L. This estimate was

TABLE 8.7 Monthly Water Balance on a Storage Pond

Month	$P^a - E$, in	$P - E$, acre·ft[b]	Q^c, acre·ft	W^d, in	W^e, acre·ft	S, acre·ft	Cumulative storage, acre·ft
Nov.	4.0	143	920	1	103	960	960
Dec.	4.2	151	950	0	0	1,101	2,061
Jan.	4.3	154	950	0	0	1,104	3,165
Feb.	3.5	125	860	0	0	985	4,150
Mar.	4.8	172	950	1	103	1,019	5,169
Apr.	3.2	115	920	9	930	105	5,274[f]
May.	0.7	25	950	15	1,550	−575	4,699
June	−1.3	−47	920	20	2,067	−1,194	3,505
July	−1.6	−57	950	24	2,480	−1,587	1,918
Aug.	−0.3	−11	950	20	2,067	−1,128	790
Sept.	0.9	32	920	16	1,653	−701	89
Oct.	2.7	98	950	11	1,137	−89	0
Annual	25.1	900	11,190	117	12,090	—	—

[a]From climatic data for area. Assumes evaporation equal to evapotranspiration.
[b]Based on a storage pond area of 430 acres. Estimated 140 days of storage at 10 mgd, depth 10 ft.
[c]Based on an average daily design flow of 10 mgd.
[d]Determined from operational schedule of land application site.
[e]Based on a land treatment area of 1240 acres.
[f]Peak storage value.

Preapplication Treatment and Storage

reasonably close to the 130 days of storage that were predicted using the EPA-1 computer program with a limiting 32°F mean temperature. For design purposes, the EPA-1 or EPA-3 programs may be used to estimate conservatively the winter storage requirements for OF.

In areas of the country below the 40-day storage contour (on Fig. 6.2), OF systems generally can be operated year-round. However, winter temperature data at the proposed OF site should be compared with those at existing systems that operate year-round to determine if all-year operation is feasible.

Storage is required at those OF sites where winter loading rates are reduced below the average design rate. The required storage volume can be calculated using Eq. (8.12).

$$V = (Q_w)\,(D_w) - (A_s)\,(L_{ww})\,(D_{aw})\,(7.48/10^6) \qquad (8.12)$$

where V = storage volume, Mgal

Q_w = average daily flow during winter, mgd

D_w = number of days in the winter period

A_s = slope area, ft^2

L_{ww} = hydraulic loading rate during winter, ft/day

D_{aw} = number of operating days in winter period

The duration of the reduced loading period at existing systems generally has been about 90 days.

Stormwater runoff from the overland slopes must be considered because OF is a surface discharging system. In many cases, the permits may allow direct discharge of stormwater but may have limitations on the mass of certain constituents that may be present. In such cases, stormwater runoff may need to be stored and discharged at a later time when mass discharge limits would not be exceeded. A procedure for estimating storage requirements for stormwater runoff is outlined below.

1. Determine the maximum monthly mass discharge allowed by the permit for each regulated constituent.
2. Determine expected runoff concentrations of regulated constituents under normal operation (no precipitation).
3. Estimate monthly runoff volumes from the system under normal operation by subtracting estimated monthly ET and percolation losses from design hydraulic loading.
4. Estimate the monthly mass discharge under normal operation by multiplying the values from steps 2 and 3.

5. Calculate the allowable mass discharge of regulated constituents resulting from storm runoff by subtracting the estimated monthly mass discharge in step 5 from the permit value in step 1.

6. Assuming that storm runoff contains the same concentration of constituents as runoff during normal operation, calculate the volume of storm runoff required to produce a mass discharge equal to the value of step 5.

7. Estimate runoff as a fraction of rainfall for the particular site soil conditions. Consult the local NRCS office for guidance.

8. Calculate the total rainfall required to produce a mass discharge equal to the value in step 5 by dividing the value in step 6 by the value in step 7.

9. Determine for each month a probability distribution for rainfall amounts and the probability that the rainfall amount in step 8 will be exceeded.

10. In consultation with regulatory officials, determine what probability is an acceptable risk before storm runoff storage is required and use this value (P_d) for design.

11. Storage must be provided for those months in which total rainfall probability exceeds the design value P_d determined in step 10.

12. Determine the change in storage volume each month by subtracting the allowable runoff volume in step 6 from the runoff volume expected from rainfall having an occurrence probability of P_d. In months when the expected storm runoff exceeds the allowable storm runoff, the difference will be added to storage. In months when allowable runoff exceeds expected runoff, water is discharged from storage.

13. Determine cumulative storage at the end of each month by adding the change in storage during 1 month to the accumulated quantity from the previous month. The computation should begin at the start of the wettest period. Cumulative storage cannot be less than zero.

14. The required storage volume is the largest value of cumulative storage. The storage volume must be adjusted for net gain or loss due to precipitation and evaporation.

If stored storm runoff does not meet the discharge permit concentration limits for regulated constituents, then the stored water must be reapplied to the OF system. The amount of stored storm runoff is expected to be small relative to the total volume of wastewater applied, and therefore increases in slope area should not be necessary. The additional water volume can be accommodated by increasing the application period as necessary.

From a process control standpoint, it is desirable to operate an OF system at a constant application rate and application period. For systems that do not have storage facilities for other reasons, small equalizing basins can be used to even out flow variations that occur in municipal wastewater systems. A storage capacity of 1 day flow should be sufficient to equalize flow in most cases. The surface area of basins should be minimized to reduce intercepted precipitation. However, an additional $^1/_2$ day of storage can be considered to hold intercepted precipitation in wet climates.

For systems providing only screening or primary sedimentation as preapplication treatment, aeration should be provided to keep the storage basin contents mixed and the surface zone aerobic. The added cost of aeration, in most cases, will be offset by savings resulting from reduced pump sizes and peak power demands. The designer should analyze the cost-effectiveness of this approach for the system in question.

Operation of Storage Ponds

The scheduling of inputs or withdrawals from storage ponds will depend on the overall process and the treatment functions expected for the pond unit. Storage units in an RI system are typically only for emergency conditions and should be used accordingly. These ponds should remain dry during routine operations and then be drained as rapidly as possible after the emergency is resolved. In some cases a separate pond is not provided in RI systems but extra freeboard is constructed into one or more of the infiltration basins.

Storage ponds for OF systems may be bypassed in many cases during the late spring and summer months to avoid performance problems caused by algae. The storage pond contents are then gradually blended with the main wastewater stream so that the pond is drawn down to the specified level at the start of the next storage period. In areas with noncontinuous algal blooms, the pond discharges should be coordinated with periods of low algae concentration.

Operation of storage ponds for SR systems will depend on whether or not any treatment function has been assigned to the pond. If a specified level of nitrogen or fecal coliform removal is expected, then the incoming wastewater should continue to flow into the pond and the withdrawals should be sufficient to reach the required pond level at the end of the application season. When these factors are not a concern, or when it is desired to maximize the nitrogen application to the land, the main wastewater stream should bypass the storage and be applied directly. Regular withdrawals over the season can then draw down the pond. Algae in the pond effluent are not a concern for type 1 SR systems, so special schedules for this purpose are generally not required.

For type 2 SR systems with urban irrigation, steps may be needed to minimize algae in the storage ponds. These steps can include prestorage treatment in constructed wetlands, poststorage treatment by constructed wetlands, dissolved air flotation (DAF), or filtration, or reservoir management that may include mixing, aeration, or selective depth removal of the highest-quality water.

Physical Design and Construction

Most agricultural storage ponds are constructed earthen impoundments. The design of reservoirs for storage conforms to the principles of small dam design. Depending on the magnitude of the project, state regulations may govern the design. In California, for example, a reservoir will be subject to state regulation depending on the size and depth. Regulatory review can be avoided if (1) the depth is 6 ft (1.8 m) or less and the capacity is 1500 acre·ft or less, or (2) the depth is less than 13 ft (3.9 m) and the capacity is less than 50 acre·ft. Design criteria and information sources are included in the U.S. Bureau of Reclamation publication, *Design of Small Dams.*[21] In many cases, it will be necessary that a competent soils engineer be consulted for proper soils analyses and structural design of foundations and embankments.

In addition to storage volume, the principal design parameters are depth and area. The design depth and area depend on the function of the pond and the topography at the pond site. If the storage pond is also to serve as a facultative pond, then a minimum water depth of at least 1.5 to 3 ft (0.45 to 0.9 m) should be maintained in the pond when the stored volume is at a minimum. The area must also be sufficient to meet the BOD pond loading criteria for the local climate, or aeration must be used to reduce area requirements.

The maximum depth depends on whether the reservoir is constructed with embankments on level ground or is constructed by damming a natural water course or ravine. Maximum depths of embankments typically range from 9 to 18 ft (2.7 to 5.4 m). Other design considerations include wind fetch and the need for riprap and lining. These aspects of design are covered in standard engineering references, and assistance is also available from the local NRCS offices and publications.[22]

References

1. Thomas, R. E., and S. C. Reed, "EPA Policy on Land Treatment and the Clean Water Act of 1977," *Journal WPCF,* **52:**452 (1980).
2. Crites, R. W., and G. Tchobanoglous, *Small and Decentralized Wastewater Management Systems,* McGraw-Hill, New York, 1998.
3. Reed, S. C., R. W. Crites, and E. J. Middlebrooks, *Natural Systems for Waste Management and Treatment,* 2d ed., McGraw Hill, New York, 1995.
4. U.S. Environmental Protection Agency, *Design Manual—Municipal Wastewater Stabilization Ponds,* EPA-625/1-83-015, Cincinnati, Ohio, 1983.
5. Middlebrooks, E. J., et al., *Wastewater Stabilization Lagoon Design, Performance and Upgrading,* Macmillan, New York, 1982.
6. Neel, J. K., J. H. McDermott, and C. A. Monday, "Experimental Lagooning of Raw Sewage," *Journal WPCF,* 33(6):603–641 (1961).
7. Higo, T. T., *A Study of the Operation of Sewage Ponds in the Province of Alberta,* Department of Public Health, Government of Alberta, 1966.
8. Reed, S. C., "Nitrogen Removal in Wastewater Ponds," *CRREL Report* 84-13, Cold Regions Research and Engineering Laboratory, Hanover, N.H., 1984.
9. Reynolds, J. H., et al., "Performance Evaluation of an Existing Seven Cell Lagoon System," U.S. Environmental Protection Agency, EPA 600/2-77-086, Cincinnati, Ohio, 1977.
10. McKinney, R. E., "Performance Evaluation of an Existing Lagoon System at Eudora, Kan.," U.S. Environmental Protection Agency, EPA-600/2-77-167, Cincinnati, Ohio, 1977.
11. Hill, D. O., and A. Shindala, "Performance Evaluation of Kilmichael Lagoon," U.S. Environmental Protection Agency, EPA-600/2-77-109, Cincinnati, Ohio, 1977.
12. Bowen, S. P., "Performance Evaluation of Existing Lagoons, Peterborough, N.H.," U.S. Environmental Protection Agency, EPA-600/2-77-085, Cincinnati, Ohio, 1977.
13. Surampalli, R. Y., et al., "Phosphorus Removal in Ponds," *Proceedings of the 2nd International Association of Water Quality International Specialist Conference, Oakland, Calif.,* 1993.
14. Reed, S. C., "Health Aspects of Land Treatment," U.S. GPO 1979-657-093/7086, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1979.
15. U.S. Environmental Protection Agency, "Is Muskegon County's Solution, Your Solution?" U.S. Environmental Protection Agency, Region V, Chicago, Ill., 1976.
16. Kott, Y., "Lagooned Secondary Effluents as Water Source for Extended Agricultural Purposes," *Water Research,* **12**(12):1101–1106 (1978).
17. Sagik, B. P., "The Survival of Human Enteric Viruses in Holding Ponds," *Contract Report* DAMD 17-75-C-5062, U.S. Army Medical Research and Development Command, Ft. Detrick, Md., 1978.
18. Bausam, H. T. et al., "Enteric Virus Removal in Wastewater Lagoon Systems," U.S. Environmental Protection Agency HERL, *Report* IAG 79-0-X0728, Cincinnati, Ohio, 1980.

19. Bowles, D. S., E. J. Middlebrooks, and J. H. Reynolds, "Coliform Decay Rates in Waste Stabilization Ponds," *Journal WPCF,* **51:**87–99 (1979).
20. U.S. Environmental Protection Agency, "Preliminary Survey of Toxic Pollutants at the Muskegon Wastewater Management System," USEPA, ORD, Washington, D.C., 1977.
21. U.S. Department of the Interior, *Design of Small Dams,* 2d ed., Bureau of Reclamation. GPO, Washington, D.C., 1973.
22. U.S. Department of Agriculture, SCS, *Ponds—Planning, Design, Construction, Agricultural Handbook,* 590, GPO, Washington, D.C., 1983.
23. Stowell, R., "A Study of the Screening of Algae from Stabilization Ponds," Masters Thesis, Department of Civil Engineering, University of California, Davis, 1976.
24. Reed, S. C., "Wetland Systems," Chap. 9 in *Natural Systems for Wastewater Treatment: WEF Manual of Practice,* 2d ed., Water Environment Federation, Alexandria, Va., 1999.
25. Pano, A., and E. J. Middlebrooks, "Ammonia Nitrogen Removal in Facultative Wastewater Stabilization Ponds," *Journal WPCF,* **54**(4):344–351, 1982.

Chapter

9

Transmission and Distribution Systems

Transmission of wastewater from the point of collection to the land treatment site involves either a pumping station and force-main or a gravity pipeline. The wastewater at the site must then be applied using either a surface or sprinkler distribution system.

Pumping Stations

Different types of pumping stations are used for transmission, distribution, and tailwater pumping. Transmission pumping of either raw or treated wastewater usually involves a conventional wastewater pumping station.

Distribution pumping of treated wastewater can involve either a conventional wastewater pumping station (Fig. 9.1) or a structure built into a treatment and storage pond. Tailwater pumping is used with surface distribution systems and may also be used with some sprinkler distribution systems.

Transmission pumping

Transmission pumping stations can be located within the wastewater collection system or can be located at the preapplication treatment site if the land application site is remote from the preapplication treatment site. Pumps are usually centrifugal nonclog or vertical turbine.

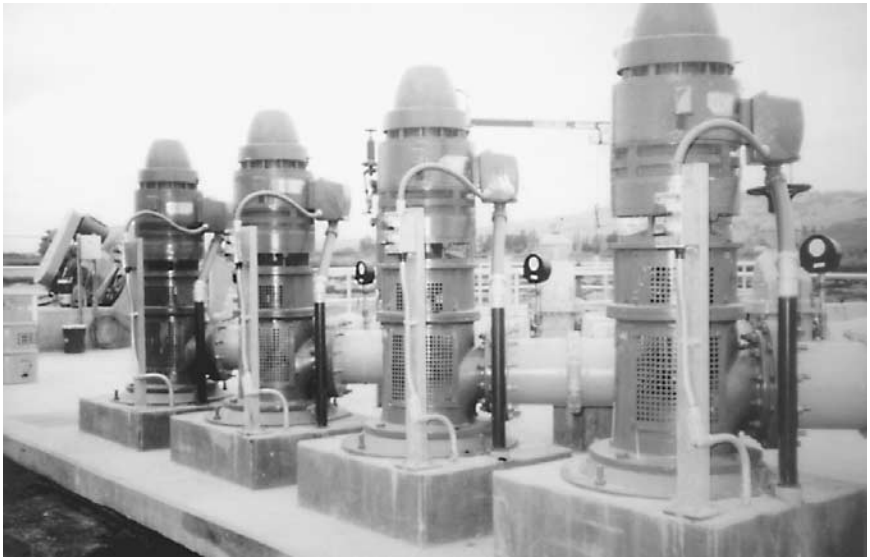


Figure 9.1 Typical outdoor wastewater pumping station.

The number of pumps to be installed depends on the magnitude of the flow and the range of flows expected. Typically the pumps should have capacity equal to the maximum expected inflow with at least one pump out of service.

In pumping stations with capacities of 1 mgd or less usually only two pumps are installed. Each pump should be capable of pumping the maximum inflow. Pumps should be selected with head-capacity characteristics that correspond as nearly as possible to the flow and head requirements of the overall system.[1]

The horsepower required for pumping can be estimated using Eq. (9.1).

$$\text{hp} = \frac{QH}{3960e} \tag{9.1}$$

where hp = horsepower required
Q = flow, gal/min
H = total head, ft
3960 = conversion factor
e = pumping system efficiency

Efficiencies range from about 40 to 50 percent when pumping raw wastewater up to a range of 65 to 80 percent when pumping primary or secondary effluent.

Distribution pumping

Distribution pumping stations can be located next to preapplication treatment facilities, or they can be built into the dikes of treatment and storage ponds (see Fig. 9.2). Depending on the method of distribution, the pumps may discharge under pressure. Peak flows depend on the operation plan and the variation in application rates throughout the operating season. For example, if the land application site is to receive wastewater for only 8 h/day, the pumps must be able to discharge at least three times the average daily flow rate (24/8 = 3).

The basis of the pump design is the total head (static plus friction) and the peak flow requirements. Flow requirements are determined based on the hours of operation per day or per week and the system capacity (see next section). Details of pumping station design are available in standard references.[1,2]

Figure 9.2 Distribution pumps in the side of a storage pond dike.

Tailwater pumping

Most surface distribution systems will produce some runoff, which is referred to as tailwater. When partially treated wastewater is applied, tailwater must be contained within the treatment site and reapplied. Thus, a tailwater return system is an integral part of an SR system using surface distribution methods. A typical tailwater return system consists of a sump or reservoir, a pump(s), and return pipeline (see Fig. 9.3).

The simplest and most flexible type of system is a storage reservoir system in which all or a portion of the tailwater flow from a given application is stored and either transferred to a main reservoir for later application or reapplied from the tailwater reservoir to other portions of the field. Tailwater return systems should be designed to distribute collected water to all parts of the field, not consistently to the same area. If all the tailwater is stored, pumping can be continuous and can commence at the convenience of the operator. Pumps can be any convenient size, but a minimum capacity of 25 percent of the distribution system capacity is recommended. If a portion of the

Figure 9.3 Typical tailwater pumping station.

tailwater flow is stored, the reservoir capacity can be reduced but pumping must begin during tailwater collection.

Cycling pump systems and continuous pumping systems can be designed to minimize the storage volume requirements, but these systems are much less flexible than storage systems. The designer is directed to Ref. 3 for design procedures.

The principal design variables for tailwater return systems are the volume of tailwater and the duration of tailwater flow. The expected values of these parameters for a well-operated system depend on the infiltration rate of the soil. Guidelines for estimating tailwater volume, the duration of tailwater flow, and suggested maximum design tailwater volume are presented in Table 9.1.

Runoff of applied wastewater from sites with sprinkler distribution systems should not occur because the design application rate of the sprinkler system is less than the infiltration rate of the soil-vegetation surface. However, some runoff from systems on steep (10 to 30 percent) hillsides should be anticipated. In these cases, runoff can be temporarily stored behind small check dams located in natural drainage courses. The stored runoff can be reapplied with portable sprinkling equipment.

Forcemains

Forcemains are pressurized pipelines that transmit the wastewater from the pumping station to the application site or storage

TABLE 9.1 Recommended Design Factors for Tailwater Return Systems[3]

Permeability		Texture range	Maximum duration of tailwater flow, % of application time	Estimated tailwater volume, % of application volume	Suggested maximum design tailwater volume, % of application volume
Class	Rate, in/h				
Very slow to slow	0.06–0.2	Clay to clay loam	33	15	30
Slow to moderate	0.02–0.6	Clay loam to silt loam	33	25	50
Moderate to moderately rapid	0.6–6	Silt loams to sandy loams	75	35	70

pond. The considerations in forcemain design are velocity and friction loss. Velocities should be in the range of 3 to 5 ft/s to keep any solids in suspension without developing excessive friction losses. Optimum velocities and pipe sizes depend on the cost of energy and the cost of pipe (see Chap. 15).

Forcemains are usually buried. Pipe materials are usually asbestos cement (AC), ductile iron, or plastic. Under some conditions reinforced concrete pipe (RCP) may also be used.

Distribution Systems

Design of the distribution system involves two steps: (1) selection of the type of distribution system, and (2) detailed design of system components. The two major types of distribution systems are surface and sprinkler systems. Only basic design principles for each type of distribution system are presented in this book, and the designer is referred to several standard agricultural engineering references for further design details.[4–6]

Surface distribution

With surface distribution systems, water is applied to the ground surface at one end of a field and allowed to spread over the field by gravity. Conditions favoring the selection of a surface distribution system include the following:

1. Capital is not available for the initial investment required for more sophisticated systems.
2. Surface topography of land requires little additional preparation to make uniform grades for surface distribution.

The principal limitations or disadvantages of surface systems include the following:

1. Land leveling costs may be excessive on uneven terrain.
2. Uniform distribution cannot be achieved with highly permeable soils.
3. Runoff control and a return system must be provided when applying wastewater.
4. Periodic maintenance of leveled surfaced is required to maintain uniform grades.

The two general types of surface distribution are the ridge and furrow and the graded border systems. Variations of these two types of methods can be found in standard references.[3–5]

Sprinkler distribution

Sprinkler distribution uses a rotating nozzle as opposed to spray distribution, which refers to a fixed nozzle orifice. Most nozzles used in land treatment systems are of the sprinkler type.

Sprinkler distribution systems simulate rainfall by creating a rotating jet of water that breaks up into small droplets that fall to the field surface. The advantages and disadvantages of sprinkler distribution systems relative to surface distribution systems are summarized in Table 9.2.

In this book, sprinkler systems are classified according to their movement during and between applications because this characteristic determines the procedure for design. There are three major categories of sprinkler systems based on movement: (1) solid set, (2) move-stop, and (3) continuous move. A summary of the various types of sprinkler systems under each category is given in Table 9.3 along with respective operating characteristics.

Design considerations

Design parameters that are common to all distribution systems are defined as follows.

Depth of wastewater applied. The depth of applied wastewater per application is determined using Eq. (9.2).

TABLE 9.2 Advantages and Disadvantages of Sprinkler Distribution

Advantages	Disadvantages
Feasible for porous soils, shallow profiles, rolling terrain, easily eroded soils, small flows, frequent applications	High capital and energy costs
	Traffic problems in clay soils
	Wind influences distribution and draft
Positive control of all water	Nozzle clogging
Minimal interference with cultivation	
No tailwater	

TABLE 9.3 Sprinkler System Characteristics

Type	Typical application rate, in/h	Labor required per application, h/acre	Nozzle pressure range, lb/in^2	Size of single system, acres	Maximum grade, %
Solid set					
Permanent	0.05–2.0	0.008–0.016	30–100	No limit	40
Portable	0.05–2.0	0.03–0.04	30–60	No limit	40
Move-stop					
Hand-move	0.01–2.0	0.08–0.24	30–60	2–40	20
End tow	0.01–2.0	0.03–0.06	30–60	20–40	5 –10
Side roll	0.1–2.0	0.016–0.048	30–60	20–80	5–10
Stationary gun	0.25–2.0	0.03–0.06	50–100	20–40	20
Continuous move					
Traveling gun	0.25–1.0	0.016–0.048	50–100	40–100	20–30
Center pivot	0.20–1.0	0.008–0.024	15–60	40–160	15–20
Linear move	0.20–1.0	0.008–0.024	15–60	40–320	15–20

$$D = \frac{L_w}{F} \tag{9.2}$$

where D = depth of wastewater applied, in
L_w = monthly hydraulic loading, in
F = frequency of applications, applications/month

Application frequency. The application frequency is defined as the number of applications per month or per week. The application frequency to use for design is a judgment decision to be made by the designer considering (1) the objectives of the system, (2) the water needs or tolerance of the crop, (3) the moisture-retention properties of the soil, (4) the labor requirement of the distribution system, and (5) the capital cost of the distribution system. Some general guidelines for determining an appropriate application frequency are presented here, but consultation with a local farm adviser is recommended.

Except for the water-tolerant forage grasses, most crops, including forest crops, require a drying period between applications to allow aeration of the root zone to achieve optimum growth and nutrient uptake. Thus, more frequent applications are appropriate as the evapotranspiration (ET) rate and the soil permeability increase. In practice, application frequencies range from once every 3 or 4 days for sandy soils to about once every

2 weeks for heavy clay soils. An application frequency of once per week is commonly used.

The operating and capital costs of distribution systems can affect the selection of application frequency. With distribution systems that must be moved between applications (move-stop systems), it is usually desirable to minimize labor and operating costs by minimizing the number of moves and therefore the frequency of application. On the other hand, capital costs of the distribution system are directly related to the flow capacity of the system. Thus, the capital cost may be reduced by increasing the application frequency to reduce system capacity.

Application rate. Application rate is the rate at which water is applied to the field by the distribution system. In general, the application rate should be matched to the infiltration rate of the soil or vegetated surface to prevent excessive runoff and tailwater return requirements. Specific guidelines relating application rates to infiltration properties are discussed under the different types of distribution systems.

Application period. The application period is the time necessary to apply the desired depth of water D. Application periods vary according to the type of distribution system but in general are selected to be convenient to the operator and compatible with regular working hours. For most distribution systems application periods are less than 24 h.

Application zone. In most systems, wastewater is not applied to the entire field area during the application period. Rather, the field area is divided into application plots or zones and wastewater is applied to only one zone at a time.

Application is rotated among the zones such that the entire field area receives wastewater within the time interval specified by the application frequency. Application zone area can be computed with the following:

$$A_a = \frac{A_w}{N_a} \tag{9.3}$$

where A_a = application zone area
A_w = field area
N_a = number of application zones

The number of application zones is equal to the number of applications that can be made during the time interval between successive applications on the same zone as specified by the application frequency.

For example, if the application period is 11 h, effectively two applications can be made each operating day. If the application frequency is once per week and the system is operated 7 days per week, there are 7 operating days between successive applications on the same zone and the number of application zones is

$$N_a = \text{(2 applications/day) (7 operating days)}$$
$$= 14$$

If the field area is 35 acres, the application zone is

$$A_a = \frac{35}{14}$$

$$= 2.5 \text{ acres}$$

System capacity. Whatever type of distribution system is selected, the maximum flow capacity of the system must be determined so that components such as pipelines and pumping stations can be properly sized. For systems with a constant application rate throughout the application period, the flow capacity of the system can be computed using the following formula:

$$Q = \frac{CA_aD}{t_a} \tag{9.4}$$

where Q = discharge capacity, gal/min
C = constant, 453
A_a = application area, acres
D = depth of water applied, in
t_a = application period, h

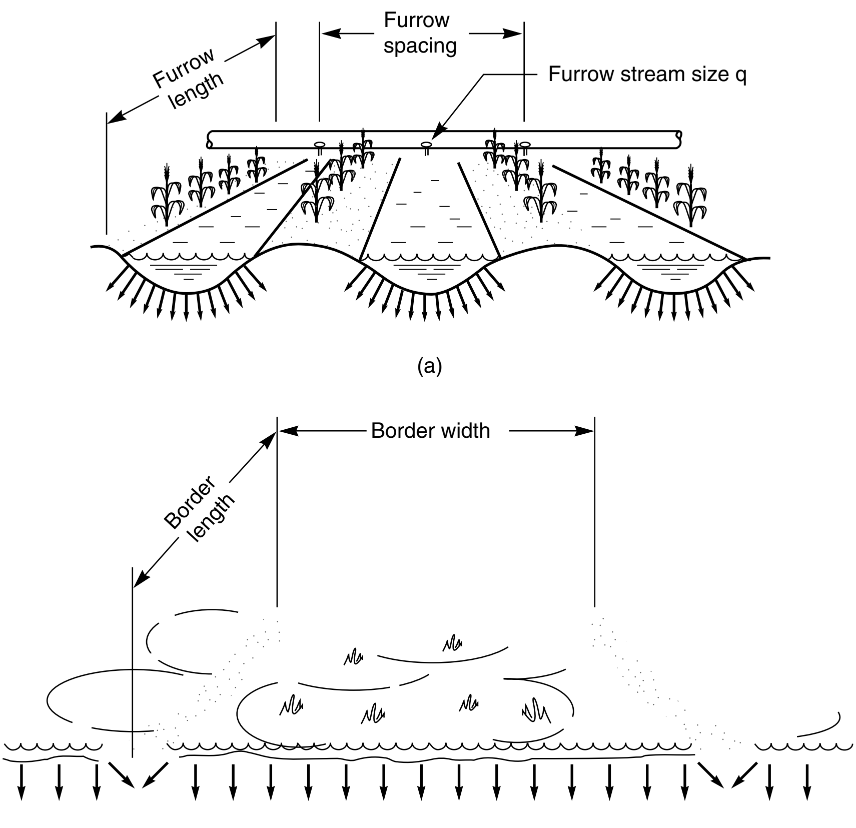
Surface Distribution

Ridge and furrow and graded border distribution are usually associated with slow rate systems. For overland flow, surface application can be used with either gated aluminum pipe or bubbling orifices. For rapid infiltration, the common method of application is basin flooding.

Ridge and furrow distribution

The design procedure for ridge and furrow systems is empirical and is based on past experience with good irrigation systems and field evaluation of operating systems. For more detailed design procedures, the designer is referred to Refs. 4 and 5.

The design variables for furrow systems include furrow grade, spacing, length, and stream size (flow rate) (Fig. 9.4*a*). The furrow grade will depend on the site topography. A grade of 2 percent is recommended maximum for straight furrows. Furrows



(a)

(b)

Figure 9.4 Typical surface distribution methods. (*a*) Ridge and furrow; (*b*) graded border.

can be oriented diagonally across fields to reduce grades. Contour furrows or corrugations can be used with grades in the range of 2 to 10 percent.

The furrow spacing depends on the water intake characteristics of the soil. The principal objective in selecting furrow spacing is to make sure that the lateral movement of the water between adjacent furrows will wet the entire root zone before it percolates beyond the root zone. Suggested furrow spacings based on different soil and subsoil conditions are given in Table 9.4.

The length of the furrow should be as long as will permit reasonable uniformity of application, because labor requirements and capital costs increase as furrows become shorter. Suggested maximum furrow lengths for different grades, soils, and depths of water applied are given in Table 9.5.

The furrow stream size or application rate is expressed as a flow rate per furrow. The optimum stream size is usually deter-

TABLE 9.4 Optimum Furrow Spacing[6]

Soil condition	Optimum spacing, in
Coarse sands—uniform profile	12
Coarse sands—over compact subsoils	18
Fine sands to sandy loams—uniform	24
Fine sands to sandy loams—over more compact subsoils	30
Medium sandy-silt loam—uniform	36
Medium sandy-silt loam—over more compact subsoils	40
Silty clay loam—uniform	48
Very heavy clay soils—uniform	36

TABLE 9.5 Suggested Maximum Lengths of Furrows

	Average depth of wastewater applied* in											
Furrow grade,	Clays				Loams				Sands			
%	3	6	9	12	2	4	6	8	2	3	4	5
0.05	1000	1300	1300	1300	400	900	1300	1300	200	300	500	600
0.2	1200	1540	1740	2030	720	1200	1540	1740	400	600	800	1000
0.5	1300	1640	1840	2460	920	1200	1540	1740	400	600	800	1000
1.0	920	1300	1640	1970	820	980	1200	1540	300	500	700	800
2.0	720	890	1100	1300	590	820	980	1100	200	300	500	600

*From Eq. (9.2).

mined by trial and adjustment in the field after the system has been installed.[5] The most uniform distribution (highest application efficiency) generally can be achieved by starting the application with the largest stream size that can be safely carried in the furrow. Once the stream has reached the end of the furrow, the application rate can be reduced or cut back to reduce the quantity of runoff that must be handled. As a general rule, it is desirable to have the stream size large enough to reach the end of the furrow within one-fifth of the total application period. This practice will result in an application efficiency of greater than 90 percent for most soils if tailwater is returned.

The application period is the time needed to infiltrate the desired depth of water plus the time required for the stream to advance to the end of the furrow. The time required for infiltration depends on the water intake characteristics of the furrow. There is no standard method for estimating the furrow intake rate. The recommended approach is to determine furrow intake rates and infiltration times by field trials as described in Ref. 5.

Design of supply pumps and transmission systems should be based on providing the maximum allowable stream size, which is generally limited by erosion considerations when grades are greater than 0.3 percent. The maximum nonerosive stream size can be estimated from the equation

$$q_e = \frac{C}{G} \tag{9.5}$$

where q_e = maximum unit stream size, gal/min
C = constant, 10
G = grade, percent

For grades less than 0.3 percent, the maximum allowable stream size is governed by the flow capacity of the furrow, estimated as follows:

$$q_c = CF_a \tag{9.6}$$

where q_c = furrow flow capacity, gal/min
C = constant, 74
F_a = cross-sectional area of furrow, ft^2

For wastewater distribution, pipelines are generally used. If buried pipelines are used to convey water, vertical riser pipes with valves are usually spaced at frequent intervals to release water into temporary ditches equipped with siphon tubes or into hydrants connected to gated surface pipe (Fig. 9.5).

The spacing of the risers is governed either by the head loss in the gated pipe or by widths of border strips when graded border and furrow methods are alternated on the same field. The valves used in risers are alfalfa valves (mounted on top of the riser) or orchard valves (mounted inside the riser). Valves must be sized to deliver the design flow rate.

Gated surface pipe may be aluminum, plastic, or rubber. Outlets along the pipe are spaced to match furrow spacings. The pipe and hydrants are portable so that they may be moved for each irrigation. The hydrants are mounted on valved risers, which are spaced along the buried pipeline that supplies the wastewater. Operating handles extend through the hydrants to control the alfalfa or orchard valves located in the risers. Control of flow into each furrow is accomplished with slide gates or screw-adjustable orifices at each outlet. Slide gates are recommended for use with wastewater. Gated outlet capacities vary with the available head at the gate, the velocity of flow passing the gate, and the gate opening. Gate openings are adjusted in the field to achieve the desired stream size.

Graded border distribution

The design variables for graded border distribution are:

1. Grade of the border strip
2. Width of the border strip
3. Length of the border strip
4. Unit stream size

Graded border distribution can be used on grades up to about 7 percent. Terracing of graded borders can be used for grades up to 20 percent.

The widths of border strips are often selected for compatibility with farm implements, but they also depend to a certain extent upon grade and soil type, which affect the uniformity of distribution across the strip. A guide for estimating strip widths is presented in Tables 9.6 and 9.7.

Figure 9.5 Typical gated pipe distribution unit.

TABLE 9.6 Design Guidelines for Graded Borders for Deep-Rooted Crops[4]

Soil type and infiltration rate, in/h	Grade, %	Unit flow per foot of strip width, gal/min	Average depth of water applied, in	Border strip, ft	
				Width	Length
Sand					
>1.0	0.2–0.4	50–70	4	40–100	200–300
	0.4–0.6	40–50	4	30–40	200–300
	0.6–1.0	25–40	4	20–30	250
Loamy sand					
0.75–1.0	0.2–0.4	30–50	5	40–100	250–500
	0.4–0.6	25–40	5	25–40	250–500
	0.6–1.0	13–25	5	25	250
Sandy loam					
0.5–0.75	0.2–0.4	25–35	6	40–100	300–800
	0.4–0.6	18–30	6	20–40	300–600
	0.6–1.0	9–18	6	20	300
Clay loam					
0.25–0.5	0.2–0.4	13–18	7	40–100	600–1000
	0.4–0.6	9–13	7	20–40	300–600
	0.6–1.0	5–9	7	20	300
Clay					
0.10–0.25	0.2–0.3	9–18	8	40–100	1200

TABLE 9.7 Design Guidelines for Graded Borders for Shallow-Rooted Crops[4]

Soil profile	Grade, %	Unit flow per foot of strip width, gal/min	Average depth of water applied, in	Border strip, ft	
				Width	Length
Clay loam, 24 in deep over permeable subsoil	0.15–0.6	25–35	2–4	15–60	300–600
	0.6–1.5	18–30	2–4	15–20	300–600
	1.5–4.0	9–18	2–4	15–20	300–600
Clay, 24 in deep over permeable subsoil	0.15–0.6	13–18	4–6	15–60	600–1000
	0.6–1.5	9–13	4–6	15–20	600–1000
	1.5–4.0	5–9	4–6	15–20	600
Loam, 6 to 18 in deep over hardpan	1.0–4.0	5–20	1–3	15–20	300–1000

Border strips should be as long as practical to minimize capital and operating costs. However, extremely long runs are not practical owing to time requirements for patrolling and difficulties in determining stream size adjustments. Lengths in excess of 1300 ft are not recommended. In general, border strips should not be laid out across two or more soil types with different intake characteristics or water-holding capacities, and border strips should not extend across slope grades that differ substantially. The appropriate length for a given site depends on the grade, the allowable stream size, the depth of water applied, the intake characteristics of the soil, and the configuration of the site boundaries. For preliminary design, the length of the border may be estimated using Tables 9.6 and 9.7.

The application rate or unit stream size for graded border irrigation is expressed as a flow rate per unit width of border strip, feet. The stream size must be such that the desired volume of water is applied to the strip in a time equal to or slightly less than the time necessary for the water to infiltrate the soil surface. When the desired volume of water has been delivered onto the strip, the stream is turned off. Shutoff normally occurs when the stream has advanced about 75 percent of the length of the strip. The objective is to have sufficient water remaining on the border after shutoff to apply the desired water depth to the remaining length of border with very little runoff.

Use of a proper stream size is necessary to achieve uniform and efficient application. Too rapid a stream results in inadequate application at the upper end of the strip or in excessive surface runoff at the lower end. If the stream is too small, the lower end of the strip receives inadequate water or the upper end has excessive deep percolation. Actually achieving uniform distribution with minimal runoff requires a good deal of skill and experience on the part of the operator. The range of stream sizes given in Tables 9.6 and 9.7 for various soil and crop conditions may be used for preliminary design. Procedures given in Ref. 7 may be used to obtain a more accurate estimate of stream size.

The application period necessary to apply the desired depth of water may be determined from the following equation:

$$t_a = \frac{LD}{Cq} \tag{9.7}$$

where t_a = application period, h
L = border strip length, ft
D = depth of applied water, in
C = constant, 96.3
q = unit stream size, gal/ [min · (ft of width)]

The conveyance and application devices used for border distribution are basically the same as described for ridge and furrow distribution. Open ditches with several evenly spaced siphon tubes are often used to supply the required stream size to a border strip. When buried pipe is used for conveyance, vertical risers with valves are usually spaced at intervals equal to the width of the border strip and are located midway in the border strip. With this arrangement, one valve supplies each strip. Water is discharged from the valve directly to the ground surface, as indicated in Fig. 9.6, and is distributed across the width of the strip by gravity flow. For border strip widths greater than 30 ft (9 m), at least two outlets per strip are necessary to achieve good distribution across the strip. Hydrants and gated pipe can be used with border systems. Use of gated pipe provides much more uniform distribution at the head of border strips and allows the flexibility of easily changing to ridge and furrow distribution if crop changes are desired.

Figure 9.6 Typical discharge valve for border strip application.

Example 9.1: Establish Preliminary Design Criteria for a Graded Border System

Conditions Deep clay loam soil, finished grade G: 0.3 percent, maximum monthly hydraulic loading L_w: 12 in, application frequency F: 3 times per month, field area, A_w: 120 acres, crop: pasture.

Solution

1. Calculate the depth of wastewater to be applied.

$$D = \frac{L_w}{F}$$

$$= \frac{12 \text{ in}}{3}$$

$$= 4 \text{ in}$$

2. Select border width and length from Table 9.7 for design conditions for shallow-rooted crops.

$$\text{Width} = 40 \text{ ft}$$

$$\text{Length} = 600 \text{ ft}$$

3. Select unit flow per width of strip, gal/min from Table 9.7.

$$q = 30 \text{ gal/[min·(ft of width)]}$$

4. Calculate the period of application t_a using Eq. (9.7).

$$t_a = \frac{LD}{96.3\,q}$$

$$= \frac{(600 \text{ ft})(4)}{(96.3)(30)}$$

$$= 0.83 \text{ h}$$

5. Determine number of applications per day assuming a 12 h/day operating period.

$$\text{Number of applications} = \frac{12 \text{ h/day}}{0.83 \text{ h/application}}$$

$$= 14.5 \text{ applications/day}$$

Use 15 applications/day

6. Determine the number of application zones.

$$\text{Application cycle is 10 days } \frac{(30 \text{ days/month})}{3 \text{ cycles/month}}$$

$$\text{Application zones} = (10 \text{ days})(15 \text{ applications/day})$$

$$= 150$$

7. Calculate the area per zone A_a.

$$A_a = \frac{A_w}{\text{number of zones}}$$

$$= \frac{120 \text{ acres}}{150 \text{ zones}}$$

$$= 0.8 \text{ acre}$$

8. Determine the number of border strips per application zone.

$$\text{Number of borders} = \frac{A_a}{(L)(W)}$$

$$= \frac{(0.8 \text{ acre})(43{,}560 \text{ ft}^2\text{/acre}}{(600)(40)}$$

$$= 1.45 \ \ (\text{use } 2)$$

9. Determine system flow capacity Q.

$$\begin{aligned} Q &= (2 \text{ borders})(W)(q) \\ &= (2)(40 \text{ ft})[30 \text{ gal/(min)(ft)}] \\ &= 2400 \text{ gal/min} \end{aligned}$$

The system must be capable of supplying 2400 gal/min during the maximum month.

Surface distribution for overland flow

Municipal wastewater can be surface applied to overland flow slopes, but industrial wastewater should usually be sprinkler applied. Surface distribution methods include gated aluminum pipe commonly used for agricultural irrigation, and slotted or perforated plastic pipe. Commercially available gated pipe can have gate spaces ranging from 2 to 4 ft (0.6 to 1.2 m), and gates can be placed on one or both sides of the pipe. A 2-ft (0.6-m) spacing is recommended to provide operating flexibility. Slide gates rather than screw-adjustable orifices are recommended for wastewater distribution. Gates can be adjusted manually to achieve reasonably uniform distribution along the pipe. However, the pipe should be operated under low pressure, 2 to 5 lb/in^2, to achieve good uniformity at the application rates recommended in Chap. 11, especially with long pipe lengths. Pipe lengths up to 1700 ft have been used, but shorter lengths are recommended. For pipe lengths greater than 300 ft, in-line valves should be provided along the pipe to allow additional flow control and isolation of pipe segments for separate operation.

Slotted or perforated plastic pipe have fixed openings at intervals ranging from 1 to 4 ft. These systems operate under gravity or very low pressure, and the pipe must be level to achieve uniform distribution. Consequently, such methods should be considered only for small systems having relatively short pipe lengths that can be easily leveled. The advantages and disadvantages of surface and sprinkler systems are compared in Chap. 11.

Surface distribution for rapid infiltration

Although sprinklers may be used, wastewater distribution for rapid infiltration is usually by surface spreading. This distribution technique employs gravity flow from piping systems or ditches to flood the application area. To ensure uniform basin application, basin surfaces should be reasonably flat.

Overflow weirs may be used to regulate basin water depth. Water that flows over the weirs is either collected and conveyed to holding ponds for recirculation or distributed to other infiltration basins. If each basin is to receive equal flow, the distribution piping channels should be sized so that hydraulic losses between outlets to basins are insignificant. Design standards for distribution systems and for flow control and measurement techniques are published by the American Society of Agricultural Engineers (ASAE). Outlets used at currently operating systems include valved risers for underground piping systems and turnout gates from distribution ditches.

Basin layout and dimensions are controlled by topography, distribution system hydraulics, and loading rate. The number of basins is also affected by the selected loading cycle. As a minimum, the system should have enough basins so that at least one basin can be loaded at all times, unless storage is provided.

The number of basins also depends on the total area required for infiltration. Optimum basin size can range from 0.5 to 5 acres (0.2 to 2 ha) for small to medium-sized systems to 5 to 20 acres (2 to 8 ha) for large systems. For a 62-acre (24-ha) system, if the selected loading cycle is 1 day of wastewater application alternated with 10 days of drying, a typical design would include 22 basins of 2.8 acres each. Using 22 basins, 2 basins would be flooded at a time and there would be ample time for basin maintenance before each flooding period.

At many sites, topography makes equal-sized basins impractical. Instead, basin size is limited to what will fit into areas having suitable slope and soil type. Relatively uniform loading rates and loading cycles can be maintained if multiple basins are constructed. However, some sites will require that loading rates or cycles vary with individual basins.

In flat areas, basins should be adjoining and should be square or rectangular to maximize land use. In areas where groundwater mounding is a potential problem, less mounding occurs when long, narrow basins with their length normal to the prevailing groundwater flow are used than when square or round basins are constructed. Basins should be at least 12 in (300 mm) deeper than the maximum design wastewater depth, in case initial infiltration is slower than expected and for emergencies. Basin walls are normally compacted soil with slopes ranging from 1:1 to 1:2 (vertical distance to horizontal distance). In areas that experience severe winds or heavy rains, basin walls should be planted with grass or covered with riprap to prevent erosion.

If basin maintenance will be conducted from within the basins, entry ramps should be provided. These ramps are formed of compacted soil at grades of 10 to 20 percent and are from 10 to 12 ft (3 to 3.6 m) wide. Basin surface area for these ramps and for wall slopes should not be considered as part of the necessary infiltration area.

Sprinkler Distribution

Sprinkler distribution is common to SR systems, is generally used with industrial OF systems, and can be used with RI systems. Forest SR, OF, and many agricultural SR systems use solid set (stationary) sprinkler distribution, whereas move-stop and continuous move sprinklers are restricted to SR systems.

For all SR sprinkler systems the design application rate (inches per hour) should be less than the infiltration rate of the surface soil to avoid surface runoff. For final design, the application rate should be based on field infiltration rates determined from previous experience with similar soils and crops or from direct field measurements.

Solid set systems

Solid set sprinkler systems remain in one position during the application season. The system consists of a grid of mainline and lateral pipes covering the field to be irrigated. Impact sprinklers are mounted on riser pipes extending vertically from the laterals. Riser heights are determined by crop heights and spray angle. Sprinklers are spaced at prescribed equal intervals along each lateral pipe, usually 40 to 100 ft (12 to 30 m). A system is called fully permanent or stationary when all lines and sprinklers are permanently located. Permanent systems usually have buried main and lateral lines to minimize interference with farming operations. Solid set systems are called fully portable when portable surface pipe is used for main and lateral lines. Portable solid set systems can be used in situations where the surface pipe will not interfere with farming operations and when it is desirable to remove the pipe from the field during periods of winter storage. When the mainline is permanently located and the lateral lines are portable surface pipe, the system is called semipermanent or semiportable.

The primary advantages of solid set systems are low labor requirements and maintenance costs, and adaptability to all types of terrain, field shapes, and crops. They are also the most adaptable systems for climate control requirements. The major disadvantages are high installation costs and obstruction of farming equipment by fixed risers.

Application rate. For solid set systems, the application rate is expressed as a function of the sprinkler discharge capacity, the spacing of the sprinklers along the lateral, and the spacing of the laterals along the main according to the following equation:

$$R = \frac{q_s C}{S_s S_L} \tag{9.8}$$

where R = application rate, in/h
q_s = sprinkler discharge rate, gal/min
C = constant = 96.3
S_s = sprinkler spacing along lateral, ft
S_L = lateral spacing along main, ft

TABLE 9.8 Recommended Spacing of Sprinklers[8]

Average wind speed, mi/h	Spacing, % of wetted diameter
0–7	40 (between sprinklers) 65 (between laterals)
7–10	40 (between sprinklers) 60 (between laterals)
>10	30 (between sprinklers) 50 (between laterals)

Detailed procedures for sprinkler selection and spacing determination to achieve the desired application rate are given in Refs. 8 to 10.

Sprinkler selection and spacing determination. Sprinkler selection and spacing determination involves an iterative process. The usual procedure is to select a sprinkler and lateral spacing, then determine the sprinkler discharge capacity required to provide the design application rate at the selected spacing. The required sprinkler discharge capacity may be calculated using Eq. 9.8.

Manufacturers' sprinkler performance data are then reviewed to determine the nozzle sizes, operating pressures, and wetted diameters of sprinklers operating at the desired discharge rate. The wetted diameters are then checked with the assumed spacings for conformance with spacing criteria. Recommended spacings are based on a percentage of the wetted diameter and vary with the wind conditions. Recommended spacing criteria are given in Table 9.8.

The sprinkler and nozzle size should be selected to operate within the pressure range recommended by the manufacturer. Operating pressures that are too low cause large drops which are concentrated in a ring a certain distance away from the sprinkler, whereas high pressures result in fine drops which fall near the sprinkler. Sprinklers with low design operating pressures are desirable from an energy-conservation standpoint.

Lateral design. Lateral design consists of selecting lateral sizes to deliver the total flow requirement of the lateral with friction losses limited to a predetermined amount. A general practice is to limit all hydraulic losses (static and dynamic) in a lateral to 20 percent of the operating pressure of the sprinklers. This will result in sprinkler discharge variations of about 10 percent along the lateral. Since flow is being discharged from a number of

TABLE 9.9 Pipe Friction Loss Factors to Obtain Actual Loss in a Line with Multiple Outlets[6]

Numbers of outlets	Value of F
1	1.000
2	0.634
3	0.528
4	0.480
5	0.451
6	0.433
7	0.419
8	0.410
9	0.402
10	0.396
15	0.379
20	0.370
25	0.365
30	0.362
40	0.357
50	0.355
100	0.350

sprinklers, the effect of multiple outlets on friction loss in the lateral must be considered. A simplified approach is to multiply the friction loss in the entire lateral at full flow (discharge at the distal end) by a factor based on the number of outlets. The factors for selected numbers of outlets are presented in Table 9.9. For long lateral lines, capital costs may be reduced by using two or more lateral sizes that will satisfy the head loss requirements.

The following guidelines should be used when laying out lateral lines:

1. Where possible, run the lateral lines across the predominant land slope and provide equal lateral lengths on both sides of the main line.
2. Avoid running laterals uphill where possible. If this cannot be avoided, the lateral length must be shortened to allow for the loss in static head.
3. Lateral lines may be run down slopes from a main line on a ridge, provided the slope is relatively uniform and not too steep. With this arrangement, static head is gained with distance downhill, allowing longer or smaller lateral lines to be used compared to level ground systems.
4. Lateral lines should run as nearly as possible at right angles to the prevailing wind direction. This arrangement

allows the sprinklers rather than laterals to be spaced more closely together to account for wind distortion and reduces the amount of pipe required.

Example 9.2: Establish Preliminary Design Criteria for Solid Set Sprinkler System

Conditions Infiltration rate: 0.6 in/h, depth of wastewater applied D: 2 in, crop: forage grass, applications zone area A_a: 10 acres, average wind speed: 5 mi/h.

Solution

1. Determine design application rate R. Assume an 8-h application period.

$$R = \frac{D}{t_a} = \frac{2\text{ in}}{8\text{ h}}$$

$$= 0.25\text{ in/h }(<0.6\text{ in/h})$$

2. Select sprinkler and lateral spacings.

$$\text{Use } S_s = 60\text{ ft}$$

$$S_L = 60\text{ ft}$$

3. Calculate required sprinkler discharge using Eq. (9.8).

$$q_s = \frac{RS_sS_L}{96.3} = \frac{(0.25)(60)(60)}{96.3}$$

$$= 9.3\text{ gal/min}$$

4. Select sprinkler nozzle size, pressure, and wetted diameter to provide necessary discharge. Use a $^{7}/_{32}$-in nozzle at 50 lb/in^2 pressure.

$$\text{Wetted diameter} = 125\text{ ft}$$

5. Check selected spacing against criteria in Table 9.8 for the average wind speed.

$$\text{Sprinkler spacing } S_s = \frac{60}{125}$$

$$= 48\% > 40\% \quad (\textit{too large})$$

$$\text{Lateral spacing } S_L = \frac{60}{125}$$

$$= 48\% < 65\% \quad (\text{O.K.})$$

6. Change sprinkler spacing to 50 ft (O.K. at 40 percent), and lateral spacing to 80 ft (O.K. at 64 percent). Recalculate q_s = 10.4 gal/min. The same nozzle is satisfactory if the pressure is increased to 55 lb/in^2 (379 kPa). Wetted diameter is 127 ft.
7. Determine system flow capacity Q.

$$Q = A_a R$$

$$= (10 \text{ acres})\left(\frac{0.25 \text{ in}}{\text{h}}\right)\left(\frac{27{,}154 \text{ gal}}{\text{acre}\cdot\text{in}}\right)\left(\frac{1 \text{ h}}{60 \text{ min}}\right)$$

$$= 1131 \text{ gal/min}$$

Solid set forest systems

Solid set irrigation systems are the most commonly used systems in forests. Buried systems are less susceptible to damage from ice and snow and do not interfere with forest management activities (thinning, harvesting, and regeneration). Solid set sprinkler systems for forest crops have some special design requirements. Spacing of sprinkler heads must be closer and operating pressures lower in forests than in other vegetation systems because of the interference from tree trunks and leaves and possible damage to bark. A 60-ft (18-m) spacing between sprinklers and an 80-ft (24-m) spacing between laterals has proved to be an acceptable spacing for forested areas. This spacing, with sprinkler overlap, provides good wastewater distribution at a reasonable cost. Operating pressures at the nozzle should not exceed 55 lb/in^2 (379 kPa), although pressures up to 85 lb/in^2 (586 kPa) may be used with mature or thick-barked hardwood species. The sprinkler risers should be high enough to raise the sprinkler above most of the understory vegetation, but generally not exceeding 5 ft (1.5 m). Low-trajectory sprinklers should be used so that water is not thrown into the tree canopies, particularly in the winter when ice buildup on pines and other evergreen trees can cause the trees to be broken or uprooted.

A number of different methods of applying wastewater during subfreezing temperatures in the winter have been attempted. These range from various modifications of rotating and nonrotating sprinklers to furrow and subterranean applications. General practice is to use low-trajectory, single-nozzle impact-type sprinklers or low-trajectory, double-nozzle hydraulic-driven sprinklers. A spray nozzle used at West Dover, Vt., is shown in Fig. 9.7.

Installation of a buried solid set irrigation system in existing forests must be done with care to avoid excessive damage to the trees or soil. Alternatively, solid set systems can be placed on the surface if adequate line drainage is provided (see Fig. 9.8). For buried systems, sufficient vegetation must be removed during construction to ensure ease of installation while minimizing site disturbance so that site productivity is not decreased or erosion hazard increased. A 10-ft-wide path cleared for each lateral meets these objectives. Following construction, the disturbed area must be mulched or seeded to restore infiltration and prevent erosion. During operation of the land treatment system, a 5-ft (1.5-m) radius should be kept clear around each sprinkler. This practice allows better distribution and more convenient observation of sprinkler operation. Spray distribution patterns will still not meet agricultural standards, but this is not as important in forests because the roots are quite extensive.

Solid set overland flow systems

Sprinkler distribution systems recommended for OF systems are discussed in Chap. 11. High-pressure, 50 to 80 lb/in^2 (345 to 550 kPa), impact sprinklers have been used successfully with food-processing wastewaters containing suspended solids concentration $>$500 mg/L. The position of the impact sprinkler on the slope is also discussed in Chap. 11.

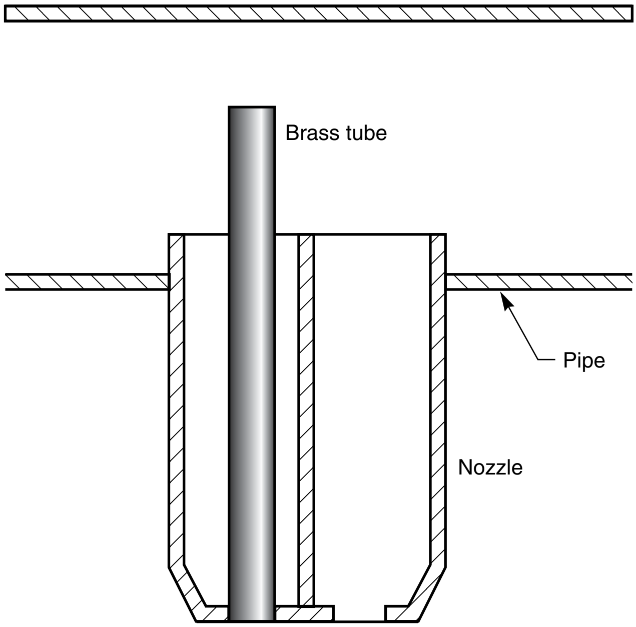


Figure 9.7 Nozzle adaptation for winter spraying. The brass tube drains quickly when the pipe flow is stopped. The other orifice drains more slowly and may freeze. Discharge will start immediately out of the brass tube at the start of the next cycle. Heat from the moving fluid then melts any ice in the other side.

The spacing of the sprinkler along the slope depends on the design application rate and must be determined in conjunction with the sprinkler discharge capacity and the spray diameter. The relationship between OF application rate and sprinkler spacing and discharge capacity is given by the following equation:

$$R = \frac{q}{S_s} \tag{9.9}$$

where R = OF application rate, gal/ [min · (ft of slope width)]
q = sprinkler discharge rate, gal/min
S_s = sprinkler spacing, ft

The sprinkler spacing should allow for some overlap of sprinkler diameters. A spacing of about 80 percent of the wetted diameter should be adequate for OF. Using the design OF application rate and the above criteria for overlap, a sprinkler can be selected from a manufacturer's catalog.

Figure 9.8 Forest solid set sprinkler irrigation at Clayton County, Ga.

Move-stop sprinkler systems

With move-stop systems, sprinklers (or a single sprinkler) are operated at a fixed position in the field during application. After the desired amount of water has been applied, the system is turned off and the sprinklers (or sprinkler) are moved to another position in the field for the next application. Multiple-sprinkler move-stop systems include portable hand-move systems, end tow systems, and side-wheel roll (also known as side-roll or wheel-line) systems. Single-sprinkler move-stop systems include stationary gun systems.

Portable hand-moved systems. Portable hand-moved systems consist of a network of surface aluminum lateral pipes connected to a main line which may be portable or permanent. The major advantages of these systems include low capital costs and adaptability to most field conditions and climates. They may also be removed from the fields to avoid interference with farm machinery. The principal disadvantage is the high labor requirement to operate the system.

End tow systems. End tow systems are multiple-sprinkler laterals mounted on skids or wheel assemblies to allow a tractor to pull the lateral intact from one position along the main to the next. The pipe and sprinkler design considerations are identical to those for portable pipe systems with the exception that pipe joints are stronger than those of hand-moved systems to accommodate the pulling requirements.

The primary advantages of an end tow system are lower labor requirements than those of hand-moved systems, relatively low system costs, and the capability to be readily removed from the field to allow farm implements to operate. Disadvantages include crop restrictions to movement of laterals and cautious operation to avoid crop and equipment damage.

Side-wheel roll. Side-wheel roll or wheel-move systems are basically lateral lines of sprinklers suspended on a series of wheels. The lateral line is aluminum pipe, typically 4 to 5 in (100 to 125 mm) in diameter and up to 1320 ft (406 m) long. The wheels are aluminum and are 5 to 7 ft (1.5 to 2.1 m) in diameter (see Fig. 9.9). The end of the lateral is connected by flexible hose to hydrants located along the main line. The unit is stationary during application and is moved between applications by an integral engine powered drive unit located at the center of the lateral.

Figure 9.9 Side-wheel roll sprinkler system.

The principal advantages of side-wheel roll systems are relatively low labor requirements and overall cost, and freedom from interference with farm implements. Disadvantages include restrictions to crop height and field shape, and misalignment of the lateral caused by uneven terrain.

Stationary gun systems. Stationary gun systems are wheel-mounted or skid-mounted single-sprinkler units, which are moved manually between hydrants located along the laterals. The advantages of a stationary gun are similar to those of portable pipe systems with respect to capital costs and versatility. In addition, the larger nozzle of the gun-type sprinkler is relatively free from clogging. The drawbacks to this system are similar to those for portable pipe systems in that labor requirements are high owing to frequent sprinkler moves. Power requirements are relatively high because of high pressures at the nozzle, and windy conditions adversely affect distribution of the fine droplets created by the higher pressures.

Design procedures. The design procedures regarding application rate, sprinkler selection, sprinkler and lateral spacing, and lateral design for move-stop systems are basically the same as those described for solid set sprinkler systems. An additional design variable for move-stop systems is the number of units required to cover a given area. The minimum required number of units is a function of the area covered by each unit, the application frequency, and the period of application. More than the minimum number of units can be provided to reduce the number of moves required to cover a given area. The decision to provide additional units must be based on the relative costs of equipment and labor.

Continuous move systems

Continuous move sprinkler systems are self-propelled and move continuously during the application period. The three types of continuous move systems are (1) traveling gun, (2) center pivot, and (3) linear move.

Traveling gun systems. Traveling gun systems are self-propelled, single-large-gun sprinkler units that are connected to the supply source by a hose 2.5 to 5 in (63 to 127 mm) in diameter. Two types of travelers are available, the hose drag type and the reel type. The hose drag traveler is driven by a hydraulic or gas-driven winch located within the unit, or a gas-driven winch located at the end of the run. In both cases, a cable anchored at the end of the run guides the unit in a straight path during the application. The flexible rubber hose is dragged behind the unit. The reel-type traveler (see Fig. 9.10) consists of a sprinkler gun cart attached to a take-up reel by a semirigid polyethylene hose. The gun is pulled toward the take-up reel as the hose is slowly wound around the hydraulic-powered reel. Variable-speed drives are used to control travel speeds. Typical lengths of run range between 660 and 1320 ft (201 and 403 m), and spacings between travel lanes range between 165 and 330 ft (50 and 100 m). After application on a lane is complete, the unit shuts off automatically. Some units also shut off the water supply automatically. The unit must be moved by tractor to the beginning of the next lane.

The more important advantages of a traveling gun system are low labor requirements and relatively clog-free nozzles. They may also be adapted to fields of somewhat irregular shape and topography. Disadvantages are high power requirements, hose travel lanes required for hose drag units for most crops, and drifting of sprays in windy conditions.

Figure 9.10 Reel-type traveling gun sprinkler.

In addition to the application rate and depth of application, the principal design parameters for traveling guns are the sprinkler capacity, spacing between travel lanes, and travel speed. The minimum application rate of most traveling gun sprinklers is about 0.23 in/h (5.8 mm/h), which is higher than the infiltration rate of the less permeable soils. Therefore, the use of traveling guns on soils of low permeability without a mature cover crop is not recommended. The relationship between sprinkler capacity, lane spacing, travel speed, and depth of application is given by the following equation:

$$D = \frac{q_s C}{(S_t)(S_p)} \tag{9.10}$$

where D = depth of water applied, in
q_s = sprinkler capacity, gal/min
S_t = space between travel lanes, ft
S_p = travel speed, ft/min
C = conversion constant, 1.60

The typical design procedure is as follows:

1. Select a convenient application period, hours per day, allowing at least 1 h between applications to move the gun.
2. Estimate the area to be irrigated by a single unit. This value should not exceed 80 acres (32 ha).
3. Calculate the sprinkler discharge capacity using Eq. (9.11).

$$q_s = \frac{(435)(D)(A)}{Ct} \tag{9.11}$$

where q_s = sprinkler discharge capacity, gal/min
D = depth of wastewater applied per application, in
A = area irrigated per unit, acres
C = cycle time between applications, days
t = operating period, h/day

4. Select a sprinkler size and operating pressure from manufacturer's performance tables that will provide the estimated discharge capacity.

5. Calculate the application rate using Eq. (9.12).

$$R = \frac{96.3\,Q}{\pi r^2} \tag{9.12}$$

where R = application rate, in/h
Q = sprinkler capacity, gal/min
r = sprinkler wetted radius, ft

6. Compute the lane spacing as a percentage of the wetted diameter against spacing criteria in Table 9.10.

7. Adjust sprinkler selection and lane spacing as necessary to be compatible with soil intake rate.

8. Calculate the travel speed using Eq. (9.10) as rearranged:

$$S_p = \frac{1.6q_s}{DS_t}$$

9. Calculate the area covered by a single unit.

$$A = \frac{S_t\,\text{(travel distance, ft/day) (cycle, days)}}{43{,}560\ \text{ft}^2\text{/acre}}$$

10. Determine the total number of units required.

$$\text{Units required} = \frac{\text{field area}}{\text{unit area}}$$

11. Determine the system capacity Q.

$$Q = (q_s)\,\text{(number of units)}$$

Example 9.3: Establish Preliminary Design Criteria for Reel-Type Traveling Gun System

Conditions Loam soil, infiltration rate: 0.4 in/h, depth of wastewater applied D: 3 in, field area: 100 acres, application cycle: every 10 days, average wind speed: 5 mi/h.

Solution

1. Select a 15 h/day application period.
2. Estimate 25 acres/unit.
3. Calculate the sprinkler discharge capacity.

$$q_s = \frac{(435)(3)(25)}{(10)(15)}$$

$$= 217.5 \text{ gal/min}$$

4. Select a sprinkler with a 230 gal/min capacity and a wetted diameter of 340 ft.
5. Calculate the application rate.

$$R = \frac{96.3(230)}{\pi\,(170)^2}$$

$$= 0.24 \text{ in/h } (<0.4 \text{ in/h, O.K.})$$

6. Lane spacing should be less than 70 to 75 percent of wetted diameter.

$$S_t = 0.7(340)$$

$$= 238 \text{ ft}$$

Use 240 ft.

7. Calculate the travel speed.

$$S_p = \frac{(1.6)(230)}{(3)(240)}$$

$$= 0.5 \text{ ft/min}$$

8. Calculate the area covered by a single unit.

$$A = \frac{(240)(0.5)(15 \text{ h})(60 \text{ min/h})(10 \text{ days})}{43{,}560}$$

$$= 24.8 \text{ acres}$$

9. Calculate the number of units required.

$$\text{Units required} = \frac{100 \text{ acres}}{24.8 \text{ acres/unit}}$$

$$= 4.03$$

Use 4 units.

10. Calculate the system capacity Q.

$$Q = (q_s)(\text{number of units})$$
$$= (230 \text{ gal/min})(4)$$
$$= 920 \text{ gal/min}$$

Center pivot systems. Center pivot systems consist of a lateral with multiple sprinklers or spray nozzles that are mounted on self-propelled, continuously moving tower units (see Fig. 9.11) rotating about a fixed pivot in the center of the field. Sprinklers on the lateral may be high-pressure impact sprinklers; however, the trend is toward use of low-pressure spray nozzles to reduce energy requirements. Water is supplied by a buried main to the pivot, where power is also furnished. The lateral is usually constructed of 6- to 8-in (150-to 200-mm) steel pipe 200 to 2600 ft (60 to 780 m) in length. A typical system with a 1288-ft (393-m) lateral covers a 160-acre (64-ha) parcel. The circular pattern reduces coverage to about 130 acres (52 ha), although systems with traveling end sprinklers or high-pressure corner guns are available to irrigate the corners.

The tower units are driven electrically or hydraulically and may be spaced from 80 to 250 ft (24 to 76 m) apart. The lateral is supported between the towers by cables or trusses. Control of the travel speed is achieved by varying the running time of the tower motors.

An important limitation of the center pivot system is the required variation in sprinkler application rates along the length of the pivot lateral. Because the area circumscribed by a given length of pivot lateral increases with distance from the pivot point (as does the ground speed of the unit), the application rate provided by the sprinklers along the lateral must

TABLE 9.10 Recommended Maximum Lane Spacing for Traveling Gun Sprinklers

Wind speed, mi/h	Lane spacing, % of wetted diameter
0	80
0–5	70–75
5–10	60–65
>10	50–55

Figure 9.11 Center pivot sprinkler unit.

increase with distance from the center to provide a uniform depth of application. Increasing the application rates can be accomplished by decreasing the spacing of the sprinklers along the lateral and increasing the sprinkler discharge capacity. The resulting application rates at the outer end of the pivot lateral can be unacceptable for many soils.

Application rates approaching 1.0 in/h (25 mm/h) may be necessary at a distance of 1300 ft (393 m). The designer should be particularly aware of this limitation at sites where soil permeabilities vary within the pivot circle. Areas of slower permeability can be flooded, causing crop damage and traction problems for the drive wheels. This particular problem has been encountered at the Muskegon project.

Wastewater application rates along a center pivot are determined by nozzle sizes and pressures, sprinkler spacing, length of lateral, and type of sprinkler. The application rate is not affected by rotational speed of the center pivot. Rotational speed affects only the duration of application and the total depth of wastewater applied.

The flow capacity of a center pivot system is given by Eq. (9.13).

$$Q = 1890\ CA \tag{9.13}$$

where Q = flow capacity, gal/min
C = wastewater application, in/day
A = area of application, acres

Since the water application rate pattern of a center pivot lateral is elliptical, the maximum application rate is given by Eq. (9.14).[11]

$$R = \frac{122.5\ Q}{r_1 r_2} \tag{9.14}$$

where R = maximum application rate of the last sprinklers, in/h
Q = center pivot capacity, gal/min
r_1 = wetted radius of the center pivot lateral, ft
r_2 = wetted radius of the last few sprinklers, ft

A variety of sprinkler spacing packages are available from the manufacturers along with variable sizing of sprinkler nozzle sizes. The selection of the sprinkler package should take into account the soil infiltration rate, wind conditions, potential for soil compaction, and pressure requirements.

A limitation of center pivots is mobility under certain soil conditions. Some clay soils can build up on wheels and eventually cause the unit to stop. Drive wheels can lose traction on slick (silty) soils and can sink into soft soils and become stuck. As a result, high-flotation tires are used and low tire pressures are recommended according to the data in Table 9.11.

Linear move systems. Linear move systems are constructed and driven in a similar manner to center pivot systems, except that the unit moves continuously in a linear path rather than a circular path. Complete coverage of rectangular fields can thus be achieved while retaining all the advantages of a continuous move system. Water can be supplied to the unit through a flexible hose that is pulled along with the unit, or it can be pumped from an open center ditch constructed down the length of the linear path. Slopes greater than 5 percent restrict the use of center ditches. Manufacturers should be consulted for design details.

TABLE 9.11 Recommended Soil Contact Pressure for Center Pivots

Percent fines	Pounds per square inch
20	25
40	16
50	12

Note: To illustrate the use of this table, if 20% of the soil fines pass through a 200-mesh screen, the contact pressure of the supporting structure to the ground should be no more than 25 lb/in2. If this is exceeded, one can expect wheel tracking problems to occur.

References

1. ”Design of Wastewater and Stormwater Pumping Stations, Water Pollution Control Federation,” *Manual of Practice* FD-4, 1981.
2. *Hydraulic Institute Standards,* Hydraulic Institute, Cleveland, Ohio, 1983.
3. Hart, W. E., *Irrigation System Design,* Colorado State University, Department of Agricultural Engineering, Ft. Collins, Colo., Nov. 10, 1975.
4. Booher, L. J., “Surface Irrigation,” *FAO Agricultural Development Paper* 94, Food and Agricultural Organization of the United Nations, Rome, 1974.
5. Merriam, J. L., and J. Keller, *Irrigation System Evaluation: A Guide for Management,* Utah State University, Logan, Utah, 1978.
6. McCulloch, A. W., et al., *Lockwood-Ames Irrigation Handbook,* Lockwood Corporation, Gering, Neb., 1973.
7. ”Border Irrigation, Irrigation,” Chap. 4 in *SCS National Engineering Handbook,* Sec. 15, U.S. Department of Agriculture, Soil Conservation Service, Aug., 1974.
8. Fry, A. W., and A. S. Gray, *Sprinkler Irrigation Handbook,* 10th ed., Rain Bird Sprinkler Manufacturing Corporation, Glendora, Calif., 1971.
9. ”Sprinkler Irrigation, Irrigation,” Chap. 11 in *SCS National Engineering Handbook,* Sec. 15, U.S. Department of Agriculture, Soil Conservation Service, July 1968.
10. Pair, C. H., et al., *Irrigation,* 5th ed., Irrigation Association, Silver Spring, Md., 1983.
11. Dillon, R. C., E. A. Hiler, and G. Vittetoe, “Center-Pivot Sprinkler Design Based on Intake Characteristics,” *ASAE Trans.,* **15:**996–1001 (1972).
12. Burt, C. M., *The Surface Irrigation Manual,* Waterman Industries, Inc., Exeter, Calif., 1995.

Chapter

10

Process Design—Slow Rate Systems

System Types

Slow rate (SR) land treatment involves the controlled application of wastewater to a vegetated land surface. There are two basic types of SR systems:

Type 1. Optimum hydraulic loading, i.e., apply the maximum amount of water to the least possible land area; a "treatment" system.

Type 2. Optimum irrigation potential, i.e., apply the least amount of water that will sustain the crop or vegetation; an irrigation or water reuse system with treatment being of secondary importance.

Many of the system components (vegetation, preapplication treatment, transmission, distribution, etc.) may be identical for both types. The land area used, however, and the operational procedures will not be the same, so it is necessary to develop a unique design approach for each case.

In general, industrial operations with easily degraded wastes and municipalities in the humid parts of the country will seek to minimize land and distribution system costs, and will implement type 1 systems, in general. In the arid parts of the world, where the water itself has a significant economic value, it is often cost-effective to design a type 2 system.

Type 1 systems are based on the limiting design parameter (LDP) concept defined in Chaps. 2 and 3. The LDP for typical municipal wastewater and many industrial wastewaters will be either the hydraulic capacity of the soil or the nitrogen loading rate. For other industrial wastewaters the LDP may be metals, solids, organics, or other constituents as discussed in Chap. 3.

The design of type 2 irrigation systems is based on the water needs of the crop to be grown and is similar to standard irrigation system design. However, it is necessary to check to ensure that an LDP is not being exceeded. The LDP, in this case, will usually apply to any effects on the quantity or quality of the crop to be grown, or to nitrogen impacts on the groundwater. In general, the application rates for type 2 irrigation are usually much lower than the ability of the soil to transmit water, so the hydraulic capacity of the soil is not typically a constraint.

Maximum Hydraulic Loading Rate

In all cases the maximum hydraulic loading rate, as controlled by soil permeability, should be determined to establish the capacity of the soil profile to transmit water and to determine if this factor is the LDP for design. The hydraulic design loading rate is the volume of wastewater applied per unit area of land over at least one loading cycle and is commonly expressed in inches per day, inches per week, or feet per year.

The general site water balance, with runoff of applied wastewater assumed to be zero, is given by

$$L_w = \mathrm{ET} - P_r + P_w \tag{10.1}$$

where L_w = wastewater hydraulic loading rate
ET = evapotranspiration rate
P_r = precipitation rate
P_w = design percolation rate

Common units of depth (inches or feet) and time (days, weeks, or years) are needed in Eq. (10.1). An annual basis is often used in preliminary screening, but a monthly basis should be used for final design.

Example 10.1: Determine Minimum Land Area Based on Hydraulic Loading Criteria

Conditions A community has a wastewater flow of 200,000 gal/day. For preliminary screening purposes, determine the minimum land area to accept the flow in an SR system if ET = 3 ft/year; P_r = 4 ft/year; P_w = 5 ft/year.

Solution

1. Convert flow from gal/day to acre·ft/year

$$Q = \frac{(200{,}000 \text{ gal/day})}{10^6 \text{ Mgal/gal}} \times 3.069 \text{ acre·ft/Mgal} \times 365 \text{ days/year}$$

$$= 224 \text{ acre·ft/year}$$

2. Calculate the hydraulic loading rate, using Eq. (10.1).

$$\begin{aligned} L_w &= \text{ET} - P_r + P_w \\ &= 3 - 4 + 5 \\ &= 4 \text{ ft/year} \end{aligned}$$

3. Calculate the minimum land area.

$$\begin{aligned} A &= Q/L_w \\ &= 224 \text{ acre·ft/4 ft/year} \\ &= 56 \text{ acres} \end{aligned}$$

Design percolation rate

The design percolation rate in Eq. (10.1) is a function of the soil permeability and the type of system being designed. If a type 1 system is being designed, the design percolation rate P_w is a function of the limiting permeability or hydraulic conductivity in the soil profile. If a type 2 system is being designed, then the P_w is the amount of water required to leach salts out of the root zone so plant growth will not be inhibited. Both of these approaches are described in detail below.

Type 1 Systems—Permeability Limiting. The design P_w is taken as a conservative percentage of the limiting hydraulic conductivity, as determined by field tests using the procedures described in Chap. 7. The top 5 to 8 ft (1.5 to 2.4 m) of the soil profile is the depth of concern. If the soil permeability measurements are variable over the site, a weighted average, based on soil type, should be determined. The annual rate of P_w can be estimated using Fig. 4.6. The values in Fig. 4.6 range from 4 to 10 percent of the clean water permeability of the soil. The P_w on a daily basis can also be estimated using Eq. (10.2).

$$P_w \text{ (daily)} = (K, \text{ in/h}) \text{ (24 h/day) (0.04 to 0.10)} \qquad (10.2)$$

where K = limiting saturated hydraulic conductivity of the site, in/h

The percentage to be used in the calculation is a judgment decision by the design engineer. If the soils are relatively uniform and permeable ($K \geq 2$ in/h), the upper 10 percent limit would be appropriate. If the soils are slowly permeable or variable in their permeability, the lower value of 4 percent in Eq. (10.2) would be appropriate.

The monthly value of the design percolation rate depends on crop management, precipitation, and freezing conditions. The monthly P_w is then

$$P_w \text{ (month)} = P_w \text{ (daily) (operating days per month)} \qquad (10.3)$$

The number of operating days in a particular month may depend on:

- *Crop management.* Downtime must be allowed for harvesting, planting, and cultivation as applicable.
- *Precipitation.* Downtime for precipitation is already factored into the water balance computation. No further adjustments are necessary.
- *Freezing temperature.* Subfreezing temperatures may cause soil frost that reduces infiltration rates. Operation is usually stopped when this occurs. The most conservative approach to adjusting the monthly percolation rate for freezing conditions is to allow no operation for days during the month when the mean temperature is less than 32°F (0°C). A less conservative, but acceptable, approach is to use a lower minimum temperature. The recommended lowest mean temperature for operation is 25°F (−4°C). Data sources and procedures for determining the number of subfreezing days during a month are discussed in

Chaps. 6 and 8. Nonoperating days due to freezing conditions may also be estimated using the EPA-1 computer program without precipitation constraints. For forested sites, operation can often continue during subfreezing conditions.

- *Seasonal crops.* When a single annual crop is grown, wastewater is not normally applied during the winter season, although applications may occur after harvest and before the next planting.

Procedures for determining the storage days needed based on climatic factors are presented in Chap. 8. The additional agronomic factors listed above can be determined from local experience in the area once the type of crop is tentatively identified. It is necessary to select the general type of vegetation at an early stage of design so that the crop uptake of nitrogen or other constituents can be estimated.

Type 2 systems—optimize irrigation potential. The design wastewater percolation rate P_w in this case is usually zero in the wet months when the natural precipitation exceeds ET. In the dry months, P_w is equal to the leaching requirement (LR) which is that volume of water or percentage of the hydraulic loading rate needed to leach or flush accumulated salts out of the root zone. Irrigation results in evapotranspiration of the water molecules and retention of the dissolved salts in the root zone. The leaching requirement, on an annual basis (expressed as a percentage), is determined by.

$$\mathrm{LR} = \frac{P_w}{L_w + (P_r - \mathrm{ET})} \tag{10.4}$$

where LR = leaching requirement, percent (other terms defined previously).

The LR is dependent on the salinity of the irrigation water and the salt tolerance of the crop grown, as detailed in Chap. 3 [Eq. (3.5)].[1] Figure 10.1 can be used to determine the LR for a variety of crops such that no adverse effects on crop yield are experienced. As shown in Fig. 10.1, the LR ranges from 2 percent for nonsensitive crops and low-salinity waters to over 30 percent for high-salinity waters and sensitive crops.

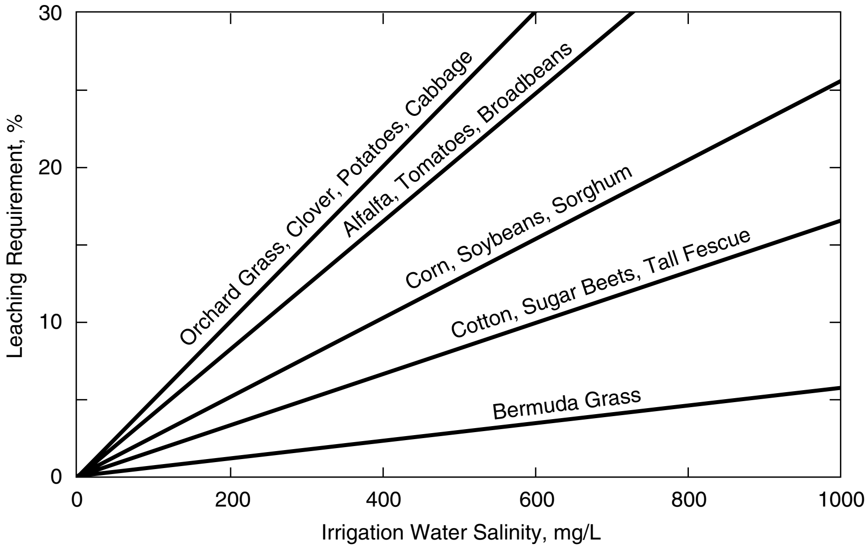


Figure 10.1 Leaching requirement vs. salinity for various crops. (*After Ref. 1.*)

In arid climates there is typically no excess P_r available for deep percolation in the dry months, so

$$P_w = \frac{\text{LR}\,(\text{ET} - P_r)}{100} \tag{10.5}$$

Substitution into the original water balance equation (10.1), for periods when $(\text{ET} - P_r) \leq 0$, yields

$$L_w = (\text{ET} - P_r)\left(1 + \frac{\text{LR}}{100}\right) \tag{10.6}$$

A further modification is necessary to account for water losses to percolation and evaporation in the conveyance and distribution systems. This overall efficiency ranges from about 65 to over 85 percent.[2] The final water balance equation for the irrigation case (type 2 system) is

$$L_w = (\text{ET} - P_r)\left(1 + \frac{\text{LR}}{100}\right)\left(\frac{100}{E_s}\right) \tag{10.7}$$

where E_s = efficiency of distribution system, percent (65 to 75 percent for surface systems); (70 to 85 percent for sprinklers) (other terms defined previously) .

Design precipitation rate

An estimate on an annual basis is suitable for preliminary calculations during site planning. Monthly values are needed for final design. These values should be based on a 5-year return period frequency analysis for monthly precipitation. These values are then distributed monthly based on the ratio of average monthly to average annual precipitation.

Design evapotranspiration rate

The design ET rate is a critical component in the water balance for both crop production and water quality concerns. In the latter case, a high water loss due to ET will tend to increase the concentration of constituents in the remaining percolate. The potential ET is defined as the water loss that could occur from a vegetated field (typically grass-covered) with soil water readily available to the plants and with the plants in a vigorous growth stage. See Chap. 5 for discussion and procedures for estimating ET for a particular crop.

A preliminary estimate of ET can also be obtained with Holdridge's method:[3]

$$ET_p = 1.07\,T_m - 34.24 \tag{10.8}$$

where ET_p = potential evapotranspiration, in/month
T_m = mean monthly air temperature, °F

In humid regions these estimates of ET_p are usually sufficient for design when perennial full-cover crops are to be used.

Hydraulic Loading Rate Based on the LDP

In many cases the constituent LDP for municipal effluents will be nitrogen, based on protection of drinking water aquifers at the project boundary. Industrial wastes may have one of the other constituents discussed in Chap. 3 as the LDP. The calculation procedure is derived below in terms of nitrogen, but the same approach is valid for other constituents by substitution of the appropriate boundary conditions. The mass balance for wastewater nitrogen on the site is given by

$$L_n = U + D + 2.7\,C_p\,P_w \tag{10.9}$$

where L_n = mass loading of nitrogen, lb/ (acre · year)
U = crop uptake, lb/ (acre · year)
D = nitrogen losses from denitrification, volatilization, etc., lb/ (acre · year)
C_p = percolate nitrogen concentration, mg/L
P_w = percolate flow, ft/year

The site losses D are a function of the amount of nitrogen applied:

$$D = f(L_n)$$

Substituting for D in Eq. (10.9) yields

$$L = U + f(L) + C_p P_w \tag{10.10}$$

Solving for P_w,

$$P_w = \frac{(1-f)\, L_n - U}{2.7\, C_p} \tag{10.11}$$

The water balance on the site is given by

$$L_{wn} = ET - P_r + P_w \tag{10.12}$$

where L_{wn} = hydraulic loading controlled by nitrogen as the LDP, ft/year

The amount of nitrogen in the annual hydraulic loading L_{wn} is

$$L_n = 2.7\, C_n L_{wn} \tag{10.13}$$

where C_n = concentration of nitrogen in the applied wastewater, mg/L

Rearranging Eq. (10.12) and solving for P_w,

$$P_w = L_{wn} + (P_r - \mathrm{ET}) \tag{10.14}$$

Setting Eqs. (10.11) and (10.14) equal to each other,

$$L_{wn} + (P_r - \mathrm{ET}) = \frac{(1 - f)\,(L_n) - U}{2.7\, C_p}$$

Then substitute Eq. (10.13) on the right side for L_n:

$$L_{wn} + (P_r - \mathrm{ET}) = \frac{(1 - f)(2.7\,C_n)(L_{wn}) - U}{2.7\,C_p}$$

Finally, combine terms and solve for L_{wn}:

$$L_{wn} = \frac{C_p\,(P_r - \mathrm{ET}) + 0.37U}{(1 - f)\,C_n - C_p} \tag{10.15}$$

(Note: the coefficient 0.37 is based on the use of feet; for inches the coefficient is 4.4; for meters the coefficient is 0.1).

Equation (10.15) can be used to determine the hydraulic loading allowed for a particular wastewater and a specified combination of site factors (P_r, ET, and U) and regulatory requirements (C_p). The regulatory constraint when nitrogen is the LDP is the nitrate concentration in the groundwater at the project boundary. To ensure a conservative design, the C_n and C_p values in the equation are taken as the total nitrogen present, not just the nitrate fraction because it is possible that other forms of nitrogen may eventually be oxidized to nitrate in the soil profile. The C_n value may be nitrate-nitrogen or total inorganic nitrogen in some cases.[10] The equation is also very conservative because it is based on the concentration C_p in the percolate prior to any mixing or dispersion in the groundwater. It will be advantageous for large projects, particularly in arid climates, to determine the degree of mixing, dispersion, and dilution that will occur between the application point and the project boundary. In that case, C_p would be equal to 10 mg/L nitrate-nitrogen at the project boundary. An allowable percolate nitrogen can then be determined and Eq. (10.15) solved for the allowable hydraulic loading.

The f factor ranges from 10 to 80 percent, depending on wastewater characteristics and application methods. For food-processing wastewater with a high BOD:N ratio (≥ 5), an f value of 0.8 can be realized. The f value for primary effluent will be about 0.25 while the f value for secondary effluent will be 0.15 to 0.2. Highly oxidized tertiary effluent would have an f value of 0.1.

Design modification for supplemental nitrogen

In some cases, supplemental nitrogen in addition to that contained in the wastewater is also applied to the site. This could be in the form of commercial fertilizer, manure, or biosolids. In the Nitrogen section in Chap. 3 these sources are discussed and calculation methods are presented for determining the nitrogen concentration of manure or biosolids. If supplemental nitrogen from any source is to be added, then Eq. (10.15) must be modified accordingly:

$$L_{wn} = \frac{C_p\,(P_r - \mathrm{ET}) + 0.37\,(U - S)}{(1 - f)\,(C_n) - C_p} \tag{10.16}$$

where S = supplemental nitrogen, lb/ (acre · year)

Example 10.2: Determine Allowable Hydraulic Loading If Nitrogen Is the LDP

Conditions

U = 500 lb/(acre·year) (coastal bermudagrass, from Chap. 5)

$P_r - \mathrm{ET}$ = −1.0 ft/year (a dry climate)

C_n = 50 mg/L total nitrogen (a strong wastewater)

f = 0.20 (assume lagoon effluent)

C_p = 10 mg/L (required by the state)

$S = 0$

Solution

1. $L_{wn} = \dfrac{C_p\,(P_r - \mathrm{ET}) + 0.37U}{(1 - f)(C_n) - C_p}$

$= \dfrac{(10)(-1) + 0.37(500)}{(0.8)(50) - 10}$

$= 5.8$ ft/year

2. The calculation for final design would be repeated on a monthly basis to ensure that sufficient water is applied in the dry months and the percolate nitrogen requirement is satisfied.
3. Maintaining a percolate nitrogen concentration of 10 mg/L or less in arid climates is difficult because of the concentrating effects of the higher ET losses. Repeating this example for more arid conditions demonstrates the concern:

Assume:

$$P_r - \mathrm{ET} = -5 \text{ ft/year}$$

Then

$$L_{wn} = \frac{(10)(-5) + (0.37)(500)}{(0.8)(50) - 10}$$

$$= 4.5 \text{ ft/year}$$

4. This is the maximum amount of wastewater that could be applied and still maintain a percolate nitrogen concentration of 10 mg/L. However, the crop in this example needs at least 5 ft/year of water to survive. Supplemental irrigation water with no nitrogen will be required to make up the deficit.
5. Equations (10.15) and (10.16) are valid only for positive values of P_w. In arid climates the leaching requirement (LR) may control design, and it may be necessary to use low-nitrogen water sources for this purpose.
6. In step 3 above the water deficit was 5 ft/year. Assuming the LR for the crop and the wastewater is 10 percent, the hydraulic loading rate would be

$$L_w = (5)(1.10) = 5.5 \text{ ft/year}$$

To maintain the specified C_p at 10 mg/L only 4.5 ft of this could be wastewater; the remainder would have to come from other sources.

LDP for constituents other than nitrogen

The basic approach described above for nitrogen is valid for any other constituent. For example, assume that a small industry involved with galvanized metal products is interested in land treatment for its zinc-laden wastewater. The mass balance for this case is given by a modification of Eq. (10.9):

$$L_{zn} = U + D + \text{SA} + 2.7\, C_p\, P_w$$

where L_{zn} = mass loading of zinc, lb/ (acre · year)
U = crop uptake, lb/ (acre · year) (see Ref. 6 for typical values)
D = site losses, assume = 0 for nonvolatile constituents
SA = soil profile accumulation, lb/ (acre · year) . Example: assume a soil CEC of 15 and a recommended lifetime limit of 1000 lb/acre (see Table 3.10) .
C_p = allowable concentration in percolate, mg/L (5 mg/L for zinc)
P_w = volume or flow of percolate, ft/year

Use Eq. (10.13), with zinc specified as the parameter of concern:

$$L_{zn} = 2.7\, C_{zn}\, L_{wzn}$$

Then combine Eqs. (10.13) and (10.17) and rearrange terms as before to determine the L_w limited by zinc:

$$L_{wzn} = \frac{C_p\,(P_r - \mathrm{ET}) + 0.37U + 0.37\mathrm{SA}}{C_{zn} - C_p} \tag{10.17}$$

In theory, this is the allowable annual waste loading to maintain the specified 5 mg/L, C_p in the percolate. In fact, since zinc and other metals are strongly adsorbed by the soil profile there may be no zinc found in the percolate until the assimilative capacity of the soil profile is reached. In such cases the limiting hydraulic loading should be based on only the crop removal and the soil profile accumulation:

$$L_{wzn} = \frac{U + \mathrm{SA}}{2.7\, C_{zn}} \tag{10.18}$$

Chapter 3 should be consulted to determine the anticipated responses for the constituent of concern to ensure that all factors are included in the mass balance equation. In general, the form of the hydraulic loading equation will be similar to either Eq. (10.16) or Eq. (10.18).

Monthly Water Balance and Hydraulic Loading Rate for Final Design

The allowable hydraulic loading based on the LDP should be compared to the maximum possible hydraulic loading based on soil permeability. The lowest of these two values then controls the design. A monthly water balance is then prepared to determine the specific monthly hydraulic loadings for design. A typical water balance is illustrated in Table 10.1 for a site in an arid climate. The soil has a permeability of 0.2 in/h.

$$\text{Maximum } P_w = (K)\,(24 \text{ h/day})\,(0.05)\,(30 \text{ days/month})$$
$$= 7.2 \text{ in/month}$$

TABLE 10.1 Typical Water Balance to Determine Maximum Hydraulic Loading, in/month

Month	ET	P_r	ET − P_r	P_w	L_w
Jan.	0.9	1.0	−0.1	2.4	2.3
Feb.	2.0	1.1	0.9	2.4	3.3
Mar.	3.8	1.1	2.7	6.5	9.2
Apr.	5.2	0.8	4.4	7.2	11.6
May	7.0	0.2	6.8	7.2	14.0
Jun	8.6	0.1	8.5	7.2	15.7
Jul	9.4	0.0	9.4	7.2	16.6
Aug.	8.7	0.0	8.7	7.2	15.9
Sep.	5.8	0.1	5.7	7.2	12.9
Oct.	4.3	0.3	4.0	7.2	11.2
Nov.	2.0	0.5	1.5	6.2	7.7
Dec.	1.0	1.0	0.0	5.6	5.6
Annual	58.7	6.2	52.5	73.5	126

The operating time for each month and the monthly percolation rate are as follows:

April to October = 30 days each, so P_w = 7.2 in/month

November = 28 days, so P_w = 6.2 in/month

December = 23 days, so P_w = 5.6 in/month

January and February = 10 days each, so P_w = 2.4 in/month

March = 27 days, so P_w = 6.5 in/month

The values in Table 10.1 would be for a type 1 system where the intent is to maximize the hydraulic loading. A type 2 irrigation system would be designed to make up the water deficit (ET−P_r) plus a leaching requirement. Assuming a 15 percent LR for this case would give

$$L_w = (\text{ET} - P_r)\left(1 + \frac{\text{LR}}{100}\right)$$

$$= 52.5\ (1.15)$$

$$= 60.4 \text{ in/year}$$

The monthly L_w values would then be calculated in the same way. If the climate is humid, there will be more negative values in the net ET column. For a type 2 system, when the net ET (ET−P_r) is negative, then zero is placed in the column for L_w.

If the L_w that is based on soil permeability is less than the L_{wn} (based on nitrogen or other constituent), then the L_w based on soil permeability becomes the basis for design. If nitrogen or some other constituent controls, additional calculations are necessary.

Example 10.3: Establish the Design Hydraulic Loading

Conditions Type 1 system, assume wastewater nitrogen $C_n = 25$ mg/L, crop uptake $U = 300$ lb/(acre · year), $C_p = 10$ mg/L; $f = 0.2$.

For the arid climate, use annual $(\text{ET} - P_r) = 52.5$ in/year (Table 10.1)

For the humid climate, use annual $(\text{ET} - P_r) = -19.7$ in/year

From Table 10.1, $P_w = 73.5$ in/year

Find the design hydraulic loading rate for both conditions.

Solution

1. Arid climate conditions:

$$\begin{aligned} L_w &= \text{ET} - P_r + P_w \\ &= 52.5 + 73.5 \\ &= 126 \text{ in/year} \\ &= 10.5 \text{ ft/year} \end{aligned}$$

$$\begin{aligned} L_{wn} &= \frac{C_p\,(P_r - \text{ET}) + 0.37U}{(1 - f)\,(C_n) - C_p} \\ &= \frac{(10)\,(-52.5/12) + 0.37\,(300)}{(0.8)(25) - 10} \\ &= 6.7 \text{ ft/year} \end{aligned}$$

L_{wn} is less than $L_{w,}$ so L_{wn} controls for design.

2. Humid climate conditions:

$$\begin{aligned} L_w &= -19.7 + 73.5 \\ &= 53.8 \text{ in/year} \\ &= 4.5 \text{ ft/year} \end{aligned}$$

$$\begin{aligned} L_{wn} &= \frac{(10)(19.7/12) + (0.37)(300)}{(0.8)(25) - 10} \\ &= 12.8 \text{ ft/year} \end{aligned}$$

The loading rate that is based on soil permeability controls, so $L_W = 4.5$ ft/year.

If crop uptake or supplemental nitrogen are factors in the equation, it is necessary to determine a monthly increment for each component. The application for supplemental fertilizer is often determined by local agronomic practice. In some cases, as shown in Fig. 5.3, a monthly value for crop uptake U can be determined. In other cases, when only the annual crop uptake is known, the monthly value of U can be estimated by distributing the monthly crop uptake in proportion to the ratio of the monthly ET to the growing season ET.

If the L_w based on soil permeability controls the design, then the monthly and annual values have already been determined by the preliminary water balance, as shown in Table 10.1. If the L_{wn} (or some other constituent) controls the design, it is necessary to use Eq. (10.16) modified for the particular constituent. These monthly values are then compared to the previously calculated L_w values, and the lower of the two is used as the design hydraulic loading for a particular month.

Nitrogen loading is more likely to govern the design hydraulic loading rate for systems in arid climates than in humid climates. The reason for this is that the net positive ET rate in arid climates causes an increase in the concentration of the nitrogen level in the percolating water.

For systems in arid climates, it is possible that the design monthly hydraulic loading rates based on nitrogen limits will be less than the irrigation requirements of the crop. The designer should compare the design L_w with the irrigation requirement to determine if this situation exists. If it does exist, the designer has three options available:

1. Reduce the concentration of nitrogen applied through preapplication treatment. See Chap. 8 for natural treatment systems and Ref. 10 for biological nitrogen removal.
2. Demonstrate that sufficient mixing and dilution will occur with the existing groundwater flow to allow higher values of percolate nitrogen concentration to be used in Eq. (10.16).
3. Select a different crop with a higher nitrogen uptake rate U.

Land Area Determination

The land area required for wastewater treatment is based on the design hydraulic loading rate L_{wD}. The surface area that actually receives the wastewater is called the field area and is determined by

$$A_F = \frac{(C)(Q) + V_s}{L_{wD}} \tag{10.19}$$

where A_F = field area, acres
C = conversion factor = 3.069 (acre · ft) /Mgal
Q = average annual wastewater flow, Mgal/year
L_{wD} = design annual hydraulic loading rate, ft/year
V_s = net loss or gain of water in storage pond as a result of precipitation, evaporation, or seepage, (acre · ft) /year [see Eq. (8.10)]

An iterative approach to the calculations is necessary because there is an interrelationship between the storage area required and the hydraulic loading on the field area. The first calculation is made without considering the V_s factor to determine an approximate land area. The procedure is defined as follows:

1. Determine the preliminary field area $A_F = CQ/L_{wD}$.
2. Use monthly L_{wD} values and A_F to determine monthly volumetric applications:

   $$W = (L_{wD})(A_F) .$$

   where W = monthly storage pond withdrawal, (acre · ft) (see Chap. 8, Table 8.6) .
3. Assume a storage pond depth and tabulate a monthly water balance for the storage pond volume (see Table 8.6).
4. Determine the net precipitation or net evaporation and seepage for the assumed pond depth and area. This is V_s in Eq. (10.19). Use a positive sign for net precipitation and a negative sign for net evaporation and seepage.
5. Solve Eq. (10.19) for A_F, including the V_s factor.
6. Repeat steps 2 through 4 to develop a balance. Adjust the assumed area or depth of the storage pond as necessary.

Example 10.4: Field Area Determination

Conditions Determine the preliminary field area for a flow of 0.6 Mgal/day if the annual loading rate is 6.7 ft/year.

Solution

1. Q = (0.6 Mgal/day) (365 days/year)
   = 219 Mgal/year
2. Preliminary $A_F = CQ/L_{wD} = \dfrac{(3.069)(219)}{6.7} = 100.3$ acres

The total land area required includes not only the field area but land for roads, buffer zones, storage ponds, administration and maintenance buildings, and unusable portions of the site. An allowance of about 15 to 20 percent is often made for these factors in preliminary design. If significant winter storage is expected, the area for the storage and preapplication treatment system should be estimated separately. The final design must include an exact determination for each of these requirements.

Buffer zone requirements

The objectives of buffer zones around land treatment sites are to control public access and in some cases improve project aesthetics. There are no universally accepted criteria for determining the width of buffer zones around SR treatment systems. In practice, the widths of buffer zones range from zero for remote systems to 200 ft or more for systems using sprinklers near populated areas. In many states, the width of buffer zones is prescribed by regulatory agencies, and the designer should determine if such requirements exist.

The requirements for buffer zones in forest SR systems are generally less than those of other vegetation systems because forests reduce wind speeds and, therefore, the potential movement of aerosols. Forests also provide a visual screen for the public. A minimum buffer zone width of 50 ft should be sufficient to meet all objectives if the zone contains trees with a dense leaf canopy.

Storage requirements

A detailed discussion and calculation procedures for storage are presented in Chap. 8. When storage is a component in an SR system, it may be advantageous not to bypass the pond in the application season to allow reductions in coliforms and nitrogen to occur as described in Chap. 8. Algal production in storage ponds should not affect SR operations.

Crop selection

The type of crop selected will directly influence the land area required if crop uptake is a critical factor in determining the design hydraulic loading. In most cases, crop selection will be one of the first design decisions in SR design. See Chap. 5 for discussion of crop-selection procedures.

Distribution system

It is necessary for type 2 irrigation systems to decide on the method of distribution that will be used, at an early stage of design. The system efficiency [see Eq. (10.7)] is a significant factor in determining the L_w and the amount of land that can be irrigated. An early decision on distribution method is less critical for type 1 treatment system.

Application Scheduling

A regular, routine application schedule is usually adopted for type 1 treatment systems for operational convenience. Sprinklers with an application rate of 0.2 to 0.3 in/h are often employed in SR systems. This will not usually exceed the intake rate of most soils, so surface runoff is avoided. It is then typical to operate the sprinkler unit continuously for a sufficient number of hours to achieve the design weekly loading. The application is then repeated 7 days later. Operation can be manual, automated with time switches, or some combination.

The scheduling of a type 2 irrigation system is dependent on the climate and the crop to be grown. The purpose is to maintain sufficient moisture in the root zone to sustain plant growth. The water available for plant use is defined as the difference between the field capacity and the wilting point (see Chap. 4).

The usual range of the deficit that is allowed ranges from 30 to 50 percent of the available water in the root zone, depending on the crop type and the stage of growth (see Chap. 4, Table 4.2). An irrigation is scheduled when the soil moisture reaches the predetermined deficit. This can be measured using tensiometers or estimated manually (see Table 4.2). Tensiometers can be used in a completely automated system to start up, shut down, and shift applications from field to field. The amount of water to be applied in each irrigation can be determined with

$$I_T = I_D \left(1 + \frac{\text{LR}}{100}\right)\left(\frac{100}{E_a}\right) \tag{10.20}$$

where I_T = total depth of water to be applied during an irrigation, in

I_D = soil moisture deficit to be replaced, in

LR = leaching requirement, percent

E_a = application efficiency, percent [see Eq. (10.7) for typical values]

Example 10.5: Determine Design Hydraulic Loading and Field Area

Conditions The site is in north central United States. Flow is 0.5 Mgal/day. Industrial wastewater characteristics: BOD = 900 mg/L, TSS = 400 mg/L, total N = 60 mg/L, total P = 20 mg/L, K = 9 mg/L.

Available site has 250 acres with silt loam soil (K = 0.5 in/h), and depth to groundwater of 30 ft. EPA climate programs indicate 130 days of storage needed. There is a residential area next to the site. (P_r − ET) = 2 in/year for the area. Type 1 treatment system proposed.

Solution

1. Preliminary design assumes perennial grass [U = 280 lb/(acre·year)] and application with sprinklers. Because 130 days of storage is required, use a three-cell lagoon for preapplication treatment and storage. Design in accordance with Chap. 8:

First cell: Aerated, 10 ft deep, 12 h detention time

$$\text{Surface area} = \frac{(500{,}000)(12)}{(12)(7.48)(10)} = 3342 \text{ ft}^2$$

Net precipitation on cell:

$$V_s = \frac{2.0}{12(3342)} = 557 \text{ ft}^3\text{/year}$$

Second and third cells: nonaerated, variable depth (12 ft max), 130 days of storage capacity.

$$\text{Total surface area} = \frac{(500{,}000)(130 \text{ days})}{(7.48)(12)} = 724{,}000 \text{ ft}^2 = 16.6 \text{ acres}$$

Area of each cell = 16.6/3 = 5.5 acres

Volume of 2 in net precipitation = 2/12(16.6 acres) = 2.76 acre·ft
Storage period = 130 days, discharge period = 365 − 130 = 235 days = 33.6 weeks/year

Average weekly discharge =

$$\frac{(0.5\ \text{Mgal/day})[3.069\ \text{acre·ft/Mgal}](365) + 2.76}{33.6\ \text{weeks/year}}$$

$$= 16.75\ \text{(acre·ft)/week}$$

2. Determine nitrogen removal in the pond system.
   a. During filling and storage period: water temperature = 8°C, pH = 7.5, average detention time = 130 days/2 = 65 days, $k_T = (0.0064)(1.039)^{(8\text{-}20)} = 0.004$
   Use Eq. (8.5) to determine nitrogen removal

$$\text{Effluent N} = (60)e^{-0.004[65 + 60.6(7.5 - 6.6)]}$$
$$= 37.2\ \text{mg/L}$$

   b. During discharge period, assuming plug flow conditions, it will take about 83 days to empty the stored water (temperature = 15°C, pH = 8.5, $k_T = (0.0064)\,(1.039)^{(15\text{-}20)} = 0.0053$). So the average pond effluent N during first 83 days of discharge is

$$\text{Effluent N} = (37.2)\ e^{-0.0053\ [83 + 60.6(8.5 - 6.6)]}$$
$$\text{Effluent N} = 13.0\ \text{mg/L total N}$$

   Average pond effluent N during final 152 days of discharge (temperature = 10°C, pH = 8.0, $k_T = 0.0064\ (1.039)^{(10\text{-}20)} = 0.0044$):

$$\text{Effluent N} = (60)\ e^{-0.0044\ [130 + 60.6(8.0 - 6.6)]}$$
$$= 23.3\ \text{mg/L total N}$$

   Average effluent N during total discharge period;

$$\text{Effluent N} = \frac{(13)(83) + (23.3)(152)}{235}$$
$$= 19.7\ \text{mg/L}$$

3. Determine L_w based on soil permeability. Use Eq. (10.2) with a 4 percent safety factor to determine the design percolation rate:

$$P_w = (k)(24)(0.04)$$
$$= (0.5)(24)(0.04)$$
$$= 0.48\ \text{in/day}$$

$$\text{Annual } P_w = (0.48 \text{ in/day})(235 \text{ days/year}) = 112.8 \text{ in/year}$$
$$= 9.4 \text{ ft/year}$$

Use Eq. (10.1) to determine the hydraulic loading:

$$L_w = {}^2/_{12} + 9.4$$
$$= 9.6 \text{ ft/year}$$

4. Determine L_{wn} based on nitrogen loading using Eq. (10.15):

$$L_{wn} = \frac{(C_p)(P_r - \text{ET}) + 0.37\,(U - S)}{(1 - f)(C_n) - C_p}$$

C_n = 19.7 mg/L (see step 2)

C_p = 10 mg/L (regulatory agency)

f = 0.25

S = 0

U = 280 lb/(acre·year)

$$L_{wn} = \frac{(10)({}^2/_{12}) + 0.37\,(280)}{(0.75)(19.7) - 10}$$

$$= 22.0 \text{ ft/year}$$

5. Determine the design hydraulic loading L_{wD}

L_w = 9.6 ft/year (from step 3)

L_{wn} = 22.0 ft/year (from step 4)

$L_{wD} = L_w$ = 9.6 ft/year

6. Determine the field area. Using Eq. (10.19):

$$A_f = \frac{CQ + V}{L_{wD}}$$

$$= \frac{3.069(0.5)(365) + 2.76}{9.6}$$

$$= 58.6 \text{ acres}$$

7. Check nutrient requirements for perennial grass.

Nitrogen: 280 lb/(acre·year) required, surplus available in wastewater.

Phosphorus: 35 lb/(acre·year) required, surplus available in wastewater

Potassium: Use Eq. (5.2).

$$K_f = 0.9\, U - K_{ww}$$

$$K_{ww} = 2.7\ (9\ \text{mg/L})(9.6\ \text{ft/year}) = 233\ \text{lb/(acre·year)}$$

$$K_f = (0.9)(280) - 233 = 19\ \text{lb/(acre·year)}$$

A supplemental potassium fertilization with 19 lb/acre will be needed each growing season to maintain crop growth. Soil sampling should be conducted to verify potassium levels are sufficient for plant growth.

8. Determine sprinkler system layout and schedule.

From step 1 the weekly flow is 16.75 (acre·ft)/week

From step 6: Field area = 58.6 acres

Weekly hydraulic loading = 16.75(12 in/ft)/58.6 acres = 3.4 in/week

Soil intake rate = 0.5 in/h

Divide the 58.6 acres into 7 fields of 8.4 acres each

Use sprinklers with an application rate of 0.4 in/h

$$\text{Sprinkler operation} = \frac{(3.4\ \text{in/week})}{(0.4\ \text{in/h})} = 8.5\ \text{h/week}$$

Operate the sprinklers on one field per day in rotation. See Chap. 9 for details on sprinkler spacing and design.

Toxic and Hazardous Wastes

In 1983 there were about 200 land treatment sites receiving toxic or hazardous wastes.[8,9] Most of these were industrial operations with the majority (over 100) at petroleum refineries. Typically, the wastes are applied to the soil surface and mixed with the topsoil layer. When surface conditions permit, grass is then planted. The design waste loading and the number of repetitions are dependent on the factors discussed in Chap. 3. The number of repetitions may range from a single application of inorganic wastes to a number of periodic applications for organic materials such as solvents and oily wastes.

A treatment demonstration using the specific toxic or hazardous waste material with the expected site soils and operating conditions is essential for these types of waste and is required by the 1983 EPA regulations. This demonstration will define the treatability of a particular waste, the loading rate, and the loading cycle for design. Other requirements for the final operational site include:

Process Design—Slow Rate Systems 259

1. A 5-ft depth of unsaturated soil to function as the "treatment zone."
2. A 3-ft interval between the bottom of the treatment zone and the seasonally high groundwater table.
3. Surface runoff and runon controls designed for a 25-year storm. The runoff system must be able to collect and control a volume equal to the 24-h, 25-year storm.
4. The groundwater must be monitored upgradient and downgradient from the application site.
5. The soil and the soil moisture immediately beneath the treatment zone must be monitored routinely.
6. The designer should contact the EPA regional office for any additional requirements (see also "Soil Treatment Systems" in Chap. 17).

References

1. U.S. DOI, *Drainage Manual,* U.S. GPO, No. 024-003-00117-1, Washington, D.C., 1978.
2. Asano, T., and G. Pettygrove, *Irrigation with Reclaimed Municipal Wastewater—A Guidance Manual,* California State Water Resources Control Board, Sacramento, Calif., 1984.
3. Holdridge, L. R., "The Determination of Atmospheric Water Movements," *Ecology,* **43:**1–9 (1962).
4. Flach, K. W., "Land Resources," in *Recycling Municipal Sludges and Effluents on Land,* Champaign, Ill., 1973.
5. California State Department of Water Resources, "Vegetated Water Use in California," *California SDWR Bulletin* 113-3, 1975.
6. Reed, S. C. et al., "Wastewater Management by Disposal on the Land," U.S.A. CRREL SR 171, U.S.A. CRREL, Hanover, N.H., 1972.
7. U.S. Environmental Protection Agency, *Process Design Manual, Land Application of Sewage Sludge and Domestic Septage,* EPA/625/R-95/001, Washington, D.C., 1995.
8. Morrison, A., "Land Treatment of Hazardous Waste," *ASCE Civil Engineering,* 53(5):33–38 (1983).
9. U.S. Environmental Protection Agency, *Hazardous Waste Land Treatment,* SW-874, OSW, U.S. EPA, Washington, D.C., 1983.
10. Giggey, M. D., R. W. Crites, and K. A. Brantner, "Spray Irrigation of Treated Septage on Reed Canarygrass," *Journal WPCF,* **61**(3):333–342 (1989).

Chapter

11

Process Design—Overland Flow Systems

System Concept and Components

Overland flow (OF) is defined as the controlled application of wastewater onto grass-covered, uniformly graded, gentle slopes, with relatively impermeable surface soils. The process was first applied in the United States for industrial wastewaters in Napoleon, Ohio,[1] and Paris, Tex.[2] As described in Chap. 13, there are many OF systems used to treat industrial wastewater, especially food processing. Early application of the process for municipal wastewaters occurred in England,[3] where it was termed "grass filtration" and in Melbourne, Australia.[4] Many of these OF systems have been in continuous and successful operation since the late 19th century. Research efforts by EPA[5] and the U.S. Army Corps of Engineers[6,7] and the performance of operational systems[8–10] led to modeling efforts and the development of rational design criteria.[11–13]

Site characteristics

Overland flow is best suited for use at sites having surface soils that are slowly permeable (clays) or that have a restrictive layer, such as a hardpan or claypan at depths of 1 to 2 ft (0.3 to 0.6 m). Overland flow can also be used on moderately permeable soils if the subsurface layer is compacted.

Overland flow may be used at sites with grades between 1 and 12 percent. Slopes can be constructed on level terrain by creating a 2 percent slope. Grades steeper than 10 percent should be terraced (slopes of 2 to 8 percent builtup, followed by a steep drop and another terrace) so that erosion from heavy rainfall is minimized. For the desired slope range of 2 to 8 percent, the actual slope does not affect the treatment performance.[15] The slope must be graded so that it is smooth and of nearly constant grade. Site grades less than 2 percent may require special measures to avoid ponding of water on the slope. The potential for short-circuiting and erosion is high for slopes greater than 8 percent.

System configuration

The general system layout should match as closely as possible the natural topography at the site to minimize expensive earthwork. The total field area for treatment is determined by methods described in this chapter. Individual slopes are laid out on a topographic map of the site until the needed field area is satisfied. The individual slopes must be connected with a network of ditches for collection of treated runoff and stormwater runoff for conveyance to the final system discharge point.

The choice of the system layout is also influenced by the type of wastewater distribution. High-solids-content wastewaters typically are applied using high-pressure sprinklers to ensure uniform distribution of the solids on the treatment slope. Low-pressure systems involving gated pipe or sprinklers have been used successfully for screened, primary, secondary, or pond effluents. The various possibilities for both high- and low-pressure types are illustrated in Fig. 11.1. Chapter 9 contains design details on both types of distribution systems.

Most of the early industrial systems were of the type shown in Fig. 11.1*a* or *b,* with the sprinklers for type *b* located at the one-third point down the slope so that all the wastewater applied is contained on the treatment surface. Empirical criteria were developed through trial-and-error experience, so that slope lengths from 100 to 150 ft (30 to 45 m) in length would provide adequate treatment for most wastewaters. If, for example, a sprinkler with a 100-ft- (30-m-) diameter wetted circle is located at the one-third point on a 150-ft- (45-m)-long slope, the "average" travel distance for all the applied

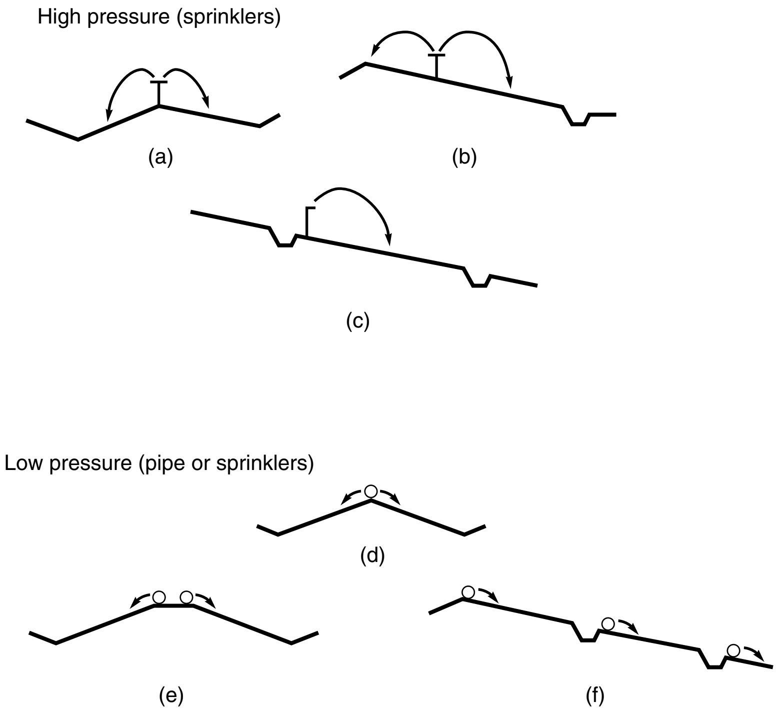


Figure 11.1 Distribution alternatives for overland flow. (*After Ref. 15.*)

wastewater would then be 100 ft (30 m). If the solids content permits the use of low-pressure systems (less than 100 mg/L typically), a slotted or gated pipe at the top of a 100-ft (30-m) slope should therefore provide the same degree of treatment as the 150-ft (45-m) slope with the pressure sprinklers at the one-third point. Low-pressure systems are not suitable for high-solids-content wastewater because deposition of the solids will occur in the immediate vicinity of the application point, resulting in excess accumulation and either maintenance requirements or the production of odors. The city of Davis recently replaced their gated pipe distribution with a low-pressure spray distribution to allow better solids distribution of the primary effluent to be applied.

Performance standards and system capabilities

Most OF systems have an outlet to surface water for the treated runoff and therefore require discharge permits. In the majority of the cases the permit will limit BOD and TSS, and that is the basis for the design approach presented in this chapter. If the permit contains other requirements (i.e., nitrification of ammonium, phosphorus removal, etc.) then Chap. 3 should be consulted to determine the limiting design parameter (LDP) for the system. The design procedure in these cases is a multistep procedure:

1. Determine the slope length, loading rates, etc., for BOD removal.
2. Determine the slope length and loading rate for other parameters.
3. Select the parameter that results in the lowest application rate as the LDP.

The effluent quality from properly designed OF systems can consistently produce effluents with 10 mg/L BOD and 15 mg/L TSS.[23] OF systems can be designed to nitrify to 1 mg/L of ammonium-nitrogen and can produce effluent total nitrogen concentrations of 5 mg/L.[23] In concept, the system can be thought of as a plug-flow, attached-growth biological reactor with a vegetated surface.[21] The near-surface soil and surface deposits and the grass stems and roots provide a matrix for the microbial components that result in the bulk of the treatment. The grass also serves as a sink for nutrients as well as water removal by evapotranspiration.

Vegetation on the treatment slopes is essential to regulate the flow and minimize erosion, short-circuiting, and channeling. The choice of vegetation is more limited for OF systems as compared to SR systems because perennial, water-tolerant grasses are the only feasible possibility for OF systems, as described in Chap. 5. Reed canarygrass, tall fescue, and other similar grasses can withstand daily saturation and flourish under frequently anaerobic conditions.

In some respects the OF process offers more flexibility and control of effluent quality than RI and SR systems do. For most RI or SR systems there is no access to the wastewater once it is applied to the soil. All of the responses and constraints have to be anticipated and programmed into the design because there will be limited opportunities to control the responses once the system is operational. In contrast, most of the wastewater is continuously accessible in an OF system, and this permits greater flexibility in operational adjustments. Because BOD is often the LDP for municipal systems, the engineer, using the procedures in this chapter, can optimize the slope length required for a particular combination of wastewater quality and discharge requirements.

Design Procedures

The design approaches to be used for BOD, nitrogen, phosphorus, and other LDP constituents are described below. In addition, the physical design is included because the system must ensure uniform sheet flow of applied wastewater and have the capacity to convey stormwater runoff.

BOD

Laboratory and field research at the University of California at Davis[12–14] has resulted in the development and validation of a rational design procedure for OF when BOD is the limiting design parameter. The design model, based on first-order, plug-flow kinetics, can be described with the following equation:

$$\frac{C_z - R}{C_0} = A \exp\left(\frac{-kz}{q^n}\right) \tag{11.1}$$

where C_z = BOD_5 concentration of runoff at a distance z downslope, mg/L
R = background BOD_5 concentration, typically 5 mg/L
C_0 = BOD_5 concentration of applied wastewater, mg/L
A = empirically determined coefficient dependent on the value of q
k = empirically determined exponent (less than 1)
z = distance downslope, ft or m
q = application rate, gal/ (min · ft) or m^3/ (h · m)
n = empirically derived exponent

The equation is presented graphically in Fig. 11.2 for primary effluent. It has been validated for screened raw wastewater and primary effluent, as shown in Table 11.1. The equation has not been validated for industrial wastewater with BOD values of 400 mg/L or more. Although the 5 mg/L of BOD is called residual or background, it is more likely that it represents decaying organic matter from the slope rather than a component of the influent BOD.[25] For facultative pond effluent, the application rate should not exceed 0.12 gal/(min·ft) [0.10 $m^3/(h \cdot m)$].

Application rate. The application rate has been shown to have a direct effect on the removal of BOD.[12] The removal of BOD for various application rates and different types of wastewater is

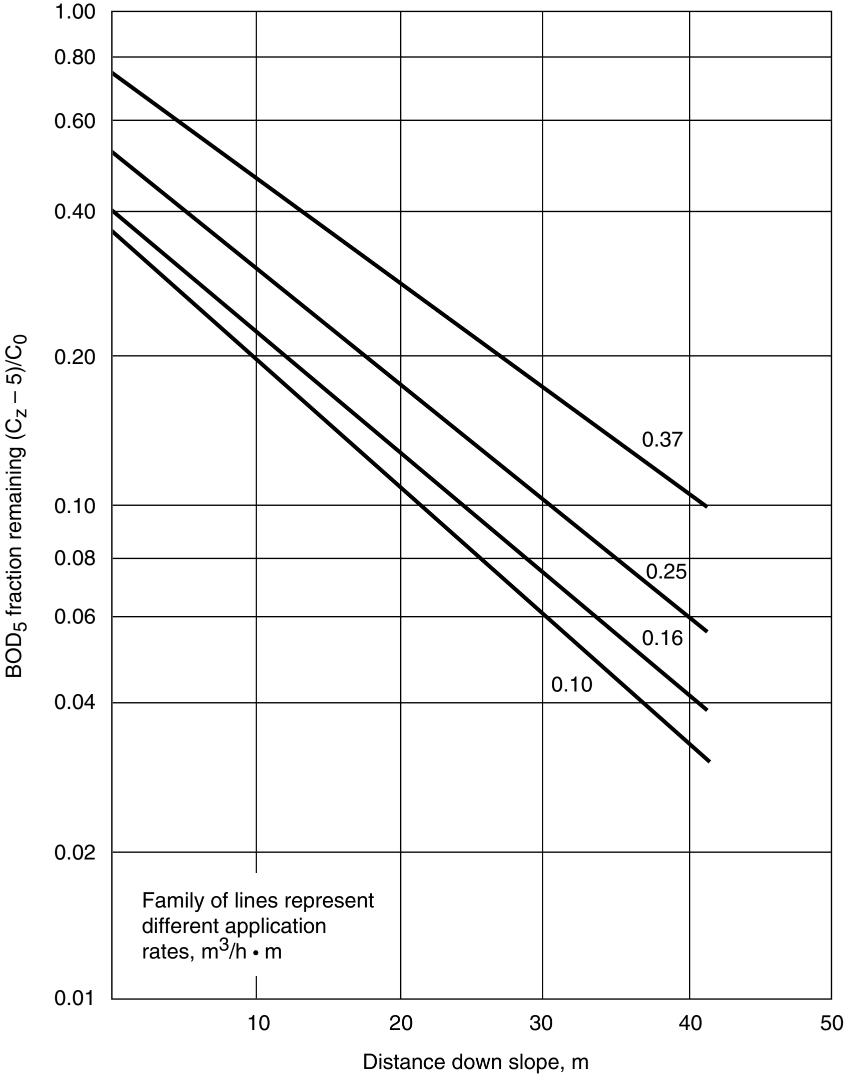


Figure 11.2 BOD fraction remaining vs. distance downslope for different application rates with primary effluent.

TABLE 11.1 Comparison of Actual and Predicted OF Effluent BOD Concentrations Using Primary and Raw Wastewater[13]

Location	Applied wastewater	Application rate, $m^3/(h \cdot m)$	Slope length, m	BOD concentration, mg/L	
				Actual	Predicted
Hanover, N.H.	Primary	0.25	30.5	17	16.3
	Primary	0.37	30.5	19	17.5
	Primary	0.12	30.5	8.5	9.7
Ada, Okla.	Primary	0.10	36	8	8.2
	Raw	0.13	36	10	9.9
Easley, S.C.	Raw	0.21	53.4	23	9.6

TABLE 11.2 BOD Removal for Overland Flow Systems[24]

Location	Wastewater type	Application rate,* gal/(ft·min)	Slope length, ft	BOD concentration, mg/L	
				Influent	Effluent
Ada, Okla.	Raw wastewater	0.10	120	150	8
	Primary effluent	0.13	120	70	8
	Secondary effluent	0.27	120	18	5
Easley, S.C.	Raw wastewater	0.29	180	200	23
	Pond effluent	0.31	150	28	15
Hanover, N.H.	Primary effluent	0.17	100	72	9
	Secondary effluent	0.10	100	45	5
Melbourne, Australia	Primary effluent	0.32	820	507	12

*Application rate is average flow, gal/min, divided by the width of the slope, ft.

presented in Table 11.2. A range of suggested application rates is presented in Table 11.3 for different climates and levels of required removal.[24,25]

Slope length. Slope lengths in OF practice have ranged typically from 100 to 200 ft (30 to 60 m). The longer the slope has been, the greater has been the removal of BOD, TSS, and nitrogen. The recommended slope length depends on the method of application. For gated pipe or spray heads where the wastewater is applied at the top of the slope, a slope length of 120 to 150 ft (36 to 45 m) is recommended. For high-pressure sprinkler application, the slope should be between 150 and 200 ft (45 and 61 m). The minimum slope length for sprinkler application should be the wetted diameter of the sprinkler plus about 65 to 70 ft (19 to 21 m).[24]

TABLE 11.3 Application Rates Suggested for Overland Flow Design,[25] gal/(min·ft)

Preapplication treatment	Stringent requirements and cold climates*	Moderate requirements and climates†	Least stringent requirements and warm climates‡
Screening/ primary	0.09–0.13	0.21–0.33	0.34–0.50
Aerated cell (1-day detention)	0.10–0.13	0.21–0.44	0.44–0.54
Secondary	0.21–0.27	0.27–0.44	0.44–0.54

*Stringent requirements: BOD = 10 mg/L, TSS = 15 mg/L.
†Moderate requirements: BOD and TSS ≤ 20 mg/L.
‡Least stringent requirements: BOD and TSS ≤ 30 mg/L.

Hydraulic loading rate. The hydraulic loading rate, expressed in inches per day (in/day) or inches per week (in/week), is the principal design parameter in the *EPA Design Manual*.[18] Selecting the application rate, however, and calculating the hydraulic loading rate has a more rational basis. The relationship between the application rate and the hydraulic loading rate is presented in Eq. (11.2).

$$L = \frac{qPF}{Z} \tag{11.2}$$

where L = wastewater hydraulic loading rate, in/day (m/day)
q = application rate per unit width of slope, gal/ (min · ft) [m³/ (h · m)]
P = application period, h/day
F = conversion factor, 96.3 (min · ft² · in) /h · gal (1 h/h)
Z = slope length, ft (m)

Hydraulic loading rates have generally ranged from 0.8 to 4 in/day (20 to 100 mm/day).

Application period. Application periods usually range from 6 to 12 h/day for 5 to 7 days/week. For municipal wastewater an 8 h/day application period is typical. For industrial wastewaters the application period can be as short as 4 h/day. Occasionally, municipal OF systems can operate 24 h/day for relatively short periods. The ability to nitrify is impaired with an application schedule beyond 12 h on and 12 h off.[20] The typical 8 h on and 16 h off schedule allows the total field area to be divided into three subareas and for the system to operate 24 h/day when required.

Organic loading rates. Organic loading rates for OF are typically less than 90 lb/(acre·day) (100 kg/(ha·day). The oxygen transfer efficiency through the thin water film (usually 0.2 in or 5 mm) limits the aerobic treatment capacity of the OF process to the above rates. The organic loading rate can be calculated using Eq. (11.3).

$$L_{\mathrm{BOD}} = 0.225\,(L_w)\,(C_0) \tag{11.3}$$

where L_{BOD} = BOD loading rate, lb/ (acre · day) [kg/ (ha · day)]
0.225 = conversion factor (0.1 in SI units)
L_w = hydraulic loading rate, in/day (mm/day)
C_0 = influent BOD_5 concentration, mg/L

When the BOD of the applied wastewater exceeds about 800 mg/L, the treatment efficiency becomes impaired by the oxygen transfer efficiency. Effluent recycle has been used to reduce the concentration to around 500 mg/L and achieve 97 percent BOD removal at a BOD loading rate of 50 lb/(acre·day) [(56 kg/(ha·day)].[26]

Example 11.1: Application Rate for OF

Conditions Determine the application rate, slope length, and hydraulic loading rate for the removal of 250 mg/L BOD down to 20 mg/L. Assume an application period of 8 h/day.

Solution

1. Compute the required removal ratio.

$$\frac{C_z - 5}{C_0} = \frac{20 - 5}{250} = 0.06$$

2. Using Fig. 11.2, select the longest slope length where the removal ratio is 0.06. Select the 0.25 curve, at 0.06 BOD fraction, the slope length is 40 m (130 ft).

3. The application rate of 0.25 $m^3/(h \cdot m)$, or 0.33 gal/(min·ft).

4. Calculate the hydraulic loading rate using Eq. (11.2).

$$L = \frac{qPF}{Z}$$

$$= \frac{(0.33)(8)(96.3)}{130} = 1.96 \text{ in/day}$$

Total suspended solids

With the exception of algae, wastewater solids will not be the LDP for overland flow design. Suspended and colloidal solids are effectively removed because of the low velocity and the shallow depth of flow on the treatment slope. Maintenance of a thick grass cover and elimination of channel flow are essential for solids removal. The removal of suspended matter is relatively unaffected by cold weather[18] or other process loading parameters.

When lagoons or storage ponds are used in overland flow systems the presence of algae in the wastewater may result in high suspended solids in the final effluent because of the inability to remove some types of algae.[16] Many small-diameter, free-floating species of algae and diatoms have little or no tendency to aggregate and are particularly difficult to remove. Examples are the green algae *Chamdomonas* and *Chlorella* and the diatoms *Anomoeoneis.* In contrast, the green algae *Protococcus* has a "sticky" surface and is effectively removed on the OF slope. Because control of algal species in the lagoons or ponds is not a practical possibility, it is necessary to bypass or isolate the ponds with the algal blooms. Once the algal bloom periods have passed, the affected pond cell can be returned to service.

If overland flow is otherwise best suited to a site with an existing pond system, design and operational procedures are available to improve algae removal. The application rate should not exceed 0.12 gal/(min·ft) [0.10 $m^3/(h \cdot m)$] for such systems, and a nondischarge mode of operation can be used during algae blooms. In the nondischarge mode, short application periods (15 to 30 min) are followed by 1- to 2-h rest and dry periods. The OF systems at Heavener, Okla., and Sumrall, Mich., operate in this manner during algae blooms.[24]

Nitrogen

The removal of nitrogen by OF systems depends on nitrification and denitrification and crop uptake. Nitrification and denitrification, which accounts for most of the nitrogen removal,[25] depends on adequate detention time, temperature, and BOD/nitrogen ratios. Denitrification appears to be most effective when screened raw or primary effluent is applied, because of the high BOD/nitrogen ratio. Soil temperatures below 4°C (39°F) will limit the nitrification reaction.

Up to 90 percent removal of ammonium was reported at application rates of 0.13 gal/(min·ft) [0.10 m^3/(h·m)] at the OF system at Davis, Calif.[20] Slope lengths of 150 to 200 ft (45 to 60 m) may be required to achieve this level of ammonia removal.

At Garland, Tex., nitrification studies were conducted with secondary effluent to determine if a 2 mg/L summer limit for ammonia and a 5 mg/L winter limit could be attained. Removal data for the two periods are presented in Table 11.4 for different application rates.[22] Winter air temperatures ranged from 3 to 21°C (26 to 70°F). The recommended application rate for Garland was 0.56 gal/(min·ft) [0.43 m^3/(h·m)] for a slope length of 200 ft (60 m) with sprinkler application.[22]

Land Area Requirements

The field area for OF depends on the flow, the application rate, the slope length, and the period of application. If there is no seasonal storage, the field area can be calculated using Eq. (11.4).

$$A = \frac{QZ}{qPF} \tag{11.4}$$

TABLE 11.4 Ammonia Concentrations (in mg/L) in Overland Flow Systems at Garland, Tex.[22]

Months	Application rate, m^3/(h·m)	Length downslope, m		
		46	61	91
Summer	0.57	1.51	0.40	0.12
Mar.–Oct.	0.43	0.65	0.27	0.11
	0.33	0.14	0.03	0.03
Winter	0.57	2.70	1.83	0.90
Nov.–Feb.	0.43	1.29	0.39	0.03
	0.33	0.73	0.28	0.14

*Note: Summer-applied ammonia nitrogen = 16.0 mg/L; winter-applied ammonia nitrogen = 14.1 mg/L.

where A = field area, acres (ha)
Q = wastewater flow rate, gal/min (m^3/day)
Z = slope length, ft (m)
q = application rate, gal/ (min · ft) [m^3/ (h · m)]
P = period of application h/day
F = conversion factor, 726 in U.S. units (10,000 in SI units)

If wastewater storage is a project requirement, the field area is determined using Eq. (11.5).

$$A = \frac{365Q + V_s}{DL_w F} \tag{11.5}$$

where A = field area, acres (ha)
Q = wastewater flow, ft^3/day (m^3/day)
V_s = net loss or gain in storage volume due to precipitation, evaporation, and seepage, ft^3/year (m^3/year)
D = number of operating days per year
L_w = hydraulic loading rate, in/day (cm/day)
F = conversion factor, 3630 (100)

Example 11.2: Land Area Requirement for OF

Conditions Determine the field area for an overland flow system with a flow of municipal wastewater of 0.5 mgd. The primary effluent has 130 mg/L of BOD and an effluent requirement of 15 mg/L. The cold winters require 60 days of storage. Assume a gain in storage of 3000 ft^3/year.

Solution

1. Compute the required removal ratio.

$$\frac{C_z - 5}{C_0} = \frac{15 - 5}{130} = 0.077$$

2. Using Fig. 11.2, enter the graph at a BOD remaining fraction of 0.077 and proceed to the maximum application rate, or 0.25 m^3/(h·m) [0.325 gal/(min·ft)].

3. Select a slope length of 35 m (115 ft) from the intersection of the 0.25 curve for application rate and the remaining BOD fraction.

4. Using a safety factor of 1.25 compute the design application rate q.

$$q = \frac{0.325}{1.25} = 0.26 \text{ gal/(min·ft)}$$

5. Calculate the hydraulic loading rate.

$$L_w = \frac{qP}{Z} = \frac{(0.26)(60 \text{ min/h})(8 \text{ h/day})}{115} = 1.09 \text{ in/day}$$

6. Calculate the number of operating days.

$$365 - 60 = 305 \text{ days/year}$$

7. Calculate the field area.

$$A = \frac{365Q + V_s}{DL_wF} = \frac{365(0.5)(133{,}685 \text{ ft}^3\text{/Mgal}) + 3000}{(305)(1.09)(3630)}$$

$$= 20 \text{ acres}$$

Design Considerations

Considerations for design of overland flow systems include winter operation, storage of wastewater, storage of rainfall runoff, distribution systems, runoff collection, vegetation selection and management, slope design and construction, and control systems. Operational considerations are presented in Chap. 15.

Winter operation

In general, OF systems shut down for cold winter weather when effluent quality requirements cannot be met because of cold temperatures or when ice begins to form on the slope. Sometimes the reduction of the application rate can allow the operation to continue during cold weather. If a shutdown is required, wastewater must be stored. The most conservative approach would be to assume a storage period that is equal in length to that required for SR systems (Chaps. 8 and 10). At wastewater and soil temperature above 50°F (8°C), the BOD removal efficiency is independent of temperature.[13] In low-temperature studies in New Hampshire,[15] the following relationship between effluent BOD and temperature was developed:

$$E_{\text{BOD}} = 0.226T^2 - 6.53T + 53 \qquad (11.6)$$

where E_{BOD} = effluent BOD, mg/L
T = soil temperature, °C

Equation (11.6) was developed for an application rate of 0.06 gal/(min·ft) [0.048 m^3/(h·m)]. At a soil temperature of less than 39°F (3.9°C) the effluent BOD will exceed 30 mg/L, based on Eq. (11.6).

Wastewater applications should cease when an ice cover forms on the slope. Operation of sprinkler systems can be very difficult at air temperatures below freezing. In locations where nighttime temperatures fall below 32°F (0°C) but daytime temperatures exceed 36°F (2°C), a day-only operation may be chosen in which all the field area is used within 10 to 12 h.

Storage of rainfall runoff

Research and field studies at a number of systems[13,18] have found that rainfall runoff either during or after wastewater applications did not significantly affect the concentration of the major constituents in the runoff. However, because of the increased flow, the mass of constituents discharged does increase.

Based on work at the Davis, Calif., overland flow system it has been found that stormwater discharges are the result of natural organics and litter on the slope and not wastewater constituents and in fact were less than the losses from control slopes where no wastewater had been applied. When mass discharges are the controlling parameter for permits, it is necessary to obtain higher discharge allowances during storm events or during high-flow periods in the receiving stream. The alternatives are to collect and recycle part of the stormwater runoff or to store it until it attains acceptable quality for discharge.

Distribution systems

Municipal wastewater can be surface-applied to OF slopes; however, industrial wastewater should be sprinkler-applied. Surface application using gated pipe offers lower energy demand and avoids aerosol generation. Slide gates at 2-ft (0.6-m) spacings are recommended over screw-adjusted orifices. Pipe lengths of 300 ft (100 m) or more require in-line valves to allow adequate flow control and isolation of pipe segments for separate operation.

Process Design—Overland Flow Systems 275

With the orifice-pipe or fan-spray types of low-pressure distribution, the wastewater application is concentrated along a narrow strip at the top of each slope. As a consequence, a grass-free application strip 4 to 6 ft (1.2 to 2 m) wide should be provided with these types of distribution systems to allow operators to inspect the area easily and to access the outlets without damaging wet slopes. Gravel is a suitable material for this unvegetated strip, but it tends to work into the soil and requires replacement over time. The recent redesign of the distribution system for the city of Davis, Calif., OF system is shown in Fig. 11.3.

Sprinkler distribution is recommended for wastewater with BOD or TSS levels of 300 mg/L or more. Impact sprinklers located about one-third of the way down the slope are generally used. Wind speed and direction must be considered in spacing between sprinklers.[25]

Slope design and construction

The OF site is divided into individual treatment slopes each having the selected design length. Site geometry may require

Figure 11.3 Spray heads for distribution of wastewater onto overland flow slopes at city of Davis, Calif.

that the slope lengths vary somewhat. Slopes should be grouped into a minimum of four or five hydraulically separated, approximately equal application zones to allow operating and harvesting or mowing flexibility. This arrangement allows one zone to be taken out of service for mowing or maintenance while continuing to operate the system at design application and loading rates.[23]

Smooth sheet flow down the slope is critical to consistent process performance, so emphasis must be placed on the proper construction of the slopes. Naturally occurring slopes, even if they are the required length and grade, seldom have the uniform grade and overall smoothness that is required to prevent channeling, short-circuiting, and ponding. Therefore, it is necessary to completely clear the site of all vegetation and to regrade it into a series of OF slopes and runoff collection channels. The first phase of the grading operation should be accomplished within a grade tolerance of 0.1 ft (0.03 m). If buried piping is used, this grading phase is generally followed by the installation of the distribution piping and appurtenances.

After the slopes have been formed in the first grading operation, a farm disk should be used to break up the clods, and the soil should then be smoothed with a land plane. Usually a grade tolerance of plus or minus 0.05 ft (0.015 m) can be achieved with three passes of the land plane. Surface distribution piping may be installed at this stage.

Soil samples of the regraded site should be taken and analyzed by an agricultural laboratory to determine the amount of lime (or gypsum) and fertilizer that are needed. The appropriate amounts should then be added prior to seeding. A light disk should be used to eliminate any wheel tracks on the slopes as final preparation for seeding.

Vegetation selection and establishment

The various grass mixtures used for overland flow systems are described in Chap. 5. In the northern humid zones, various combinations of orchard grass, Reed canarygrass, tall fescue, and Kentucky bluegrass have been most successful. The use of a nurse grass such as perennial ryegrass is recommended because it will grow quickly and protect the soil surface while the other grasses are becoming established.

A Brillion seeder is capable of doing an excellent job of seeding the slopes. The Brillion seeder carries a precision device to drop seeds between cultipacker-type rollers so that the seeds are firmed into shallow depressions. This allows for quick germination and protection against erosion. Hydroseeding may also be used if the range of the distributor is sufficient to provide coverage of the slopes so that the vehicle does not have to travel on the slopes. Traffic on the slopes in the direction of the water flow should be avoided whenever possible to keep channelization to a minimum. Vehicle access should be in the cross-slope direction and allowed only when the soil is dry.

A good vegetative cover is essential prior to application of wastewater. Grass planting should only be undertaken during the optimum periods for planting in particular, and the overall construction schedule must be adjusted accordingly. In arid and semiarid climates, portable sprinklers may be necessary to provide moisture for germination and growth of the grass. The wastewater distribution system should not be used until the grass is established to avoid erosion of the bare soil. The construction contract should have a contingency to cover reseeding or erosion repair in the case of intense rainfall during the period between final site grading and grass establishment.

As a general rule, wastewater should not be applied at design rates until the grass has grown enough to receive one cutting. Cut grass from the first cutting may be left on the slope to help build an organic mat as long as the clippings are relatively short (<1 ft, 0.3 m). Long clippings tend to remain on top of the cut grass, thus shading the surface and retarding regrowth.

A period of slope aging or maturing and acclimation is required following initial startup before process performance will approach satisfactory levels. During this period, the microbial population on the slopes is increasing and the slime layers are forming. The initial acclimation period may be as long as 3 to 4 months. If a variance to allow discharge during this period cannot be obtained, provisions should be made to store and /or recycle the effluent until effluent quality improves to the required level.

An acclimation period also should be provided following winter storage periods for those systems in cold climates. Acclimation following winter shutdown should require less than a month. Acclimation is not necessary following shutdown for harvest unless the harvest period is extended to more than 2 or 3 weeks due to inclement weather.

The grass should be cut two or three times a year and removed from the slopes. Removal from the slope is mainly to allow the new grass to grow and to avoid decomposition by-products from being discharged off the slope. Before harvesting, each slope must be allowed to dry out so that equipment can travel over the soil surface without leaving ruts. Ruts could develop into channeling, especially if they are oriented downslope. The drying time necessary before mowing is usually about 1 to 2 weeks; however, this can vary depending on the soil and climatic conditions. After mowing, the hay should be dried before raking and baling. This may take another week or so depending on the weather. See Chap. 15 for additional details on operation and maintenance of OF systems.

References

1. Bendixen, T. W., R. D. Hill, F. T. DuByne, and G. G. Robeck, "Cannery Waste Treatment by Spray Irrigation-Runoff," *Journal WPCF,* **41:**385 (1969).
2. Gilde, L. C., A. S. Kester, J. P. Law, C. H. Neeley, and D. M. Parmelee, "A Spray Irrigation System for Treatment of Cannery Wastes," *Journal WPCF,* **43:**2011 (1971).
3. Scott, T. M., and D. M. Fulton, "Removal of Pollutants in the Overland Flow (Grass Filtration) System," *Progress in Water Technology,* **II** (4 and 5):301–313 (1979).
4. Seabrook, B. L., "Land Application of Wastewater in Australia," U.S. Environmental Protection Agency, 430/9-75-017, EPA OWPO, Washington, D.C., 1975.
5. Thomas, R. E., et al., "Overland Flow Treatment of Raw Wastewater with Enhanced Phosphorus Removal," U.S. Environmental Protection Agency, EPA-660/2-76-131, ORD, 1976.
6. Peters, R. E., et al., "Field Investigations of Advanced Treatment of Municipal Wastewater by Overland Flow," vol. 2, *Proceedings of the International Symposium on Land Treatment of Wastewater,* U.S.A. COE, CRREL, Hanover, N.H., 1978.
7. Carlson, C. A., et al., "Overland Flow Treatment of Wastewater," U.S.A. WES Misc. Paper Y-74-3, Vicksburg, Miss., 1974.
8. Peters, R. E., C. R. Lee, and D. J. Bates, "Field Investigations of Overland Flow Treatment of Municipal Lagoon Effluent," U.S.A. WES, *Tech. Report* EL-81-9, U.S.A. WES, Vicksburg, Miss., 1981.
9. Hall, O. H., et al., "Municipal Wastewater Treatment by the Overland Flow Method of Land Application," U.S. Environmental Protection Agency, EPA 600/2-79-178, EPA RSKERL, Ada, Okla., 1979.
10. Ketchum, L. H., et al., "Overland Flow Treatment of Poultry Processing Wastewater in Cold Climates," U.S. Environmental Protection Agency, EPA 600/S1-81-234, EPA RSKERL, Ada, Okla., 1979.
11. Jenkins, T. F., et al., "Pilot Scale Study of Overland Flow Land Treatment in Cold Climates," in *Proceedings: Developments in Land Methods of Wastewater Treatment and Utilization—Melbourne, Australia,* Pergamon Press, New York, *Progress in Water Technology,* **11** (4–5):207 (1978).
12. Smith, R. G., "Development of a Rational Basis for Design and Operation of the Overland Flow Process," *Proceedings: National Seminar on Overland Flow Technology for Municipal Wastewater,* U.S. Environmental Protection Agency, EPA 600/9-81-022, Washington, D.C., 1981.

13. Smith, R. G., and E. D. Schroeder, "Demonstration of the Overland Flow Process for the Treatment of Municipal Wastewater—Phase II Field Studies," Department of Civil Engineering, University of California, Davis, Report to California State Water Resources Control Board, 1982.
14. Smith, R. G., and E. D. Schroeder, "Physical Design of Overland Flow Systems," *Journal WPCF,* **55**(3):255–260 (1983).
15. Jenkins, T. F., et al., "Performance of Overland Flow Land Treatment in Cold Climates," in *Proceedings State of Knowledge in Land Treatment of Wastewater,* vol.2, U.S.A. CRREL, Hanover, N.H., 1978.
16. Witherow, J. L., and B. E. Bledsoe, "Algae Removal by the Overland Flow Process," *Journal WPCF,* **55**(10):1256–1262 (1983).
17. Clark, P. J., *Marsh Pond/Overland Flow Pilot Plant Project Report,* P. J. Clark Engineers, Rochester, N.Y., 1983.
18. U.S. Environmental Protection Agency, *Process Design Manual for Land Treatment of Municipal Wastewater,* EPA 625/1-81-013, USEPA, CERI, Cincinnati, Ohio, 1981.
19. Palazzo, A. J., *Plant Growth and Management for Wastewater Treatment in Overland Flow Systems,* SR82-5, U.S.A. CRREL, Hanover, N.H., 1982.
20. Kruzic, A. J., and E. D. Schroeder, "Nitrogen Removal in the Overland Flow Wastewater Treatment Process—Removal Mechanisms," *Research Journal, Water Pollution Control Federation,* **62**(7):867–876 (1990).
21. Martel, C. J., "Development of a Rational Design Procedure for Overland Flow Systems," *CRREL Report 82-2,* CRREL, Hanover, N.H., 1982.
22. Zirschky, J., et al., "Meeting Ammonia Limits Using Overland Flow," *Journal WPCF,* **61:**1225–1232 (1989).
23. Water Environment Federation, "Natural Systems for Wastewater Treatment," Draft, *Manual of Practice,* Alexandria, Va., 1999.
24. Crites, R. W., and G. Tchobanoglous, *Small and Decentralized Wastewater Management Systems,* McGraw-Hill, New York, 1998.
25. Reed, S. C., R. W. Crites, and E. J. Middlebrooks, *Natural Systems for Waste Management and Treatment.* 2d ed., McGraw-Hill, New York, 1995.
26. Perry, L. E., E. J. Reap, and M. Gilliand, "Pilot Scale Overland Flow Treatment of High Strength Snack Food Processing Wastewaters," *Proceedings National Conference on Environmental Engineering,* ASCE, EED, Atlanta, Ga., 1981.

Chapter 12

Process Design—Rapid Infiltration Systems

The process design of rapid infiltration systems is generally governed by the infiltration rate and permeability of the soil. Selection of the hydraulic loading rate can also affect the removal of nitrogen and phosphorus.

The preapplication treatment for RI systems ranges from primary treatment to secondary treatment (see Chap. 8). Hydraulic loading rates range from 20 to 400 ft/year (6 to 120 m/year). As shown in Table 12.1, several RI systems have been operating for more than 40 years with application of primary effluent. The system at Whittier Narrows recharges the potable groundwater and is in an urban area; thus the preapplication treatment is tertiary (filtered secondary).

Most of the 320 RI systems in the United States discharge the treated water indirectly into nearby surface water, as shown in Fig. 2.2.

The typical procedure for design of RI basins is as follows:

1. Determine the design infiltration rate (see Chap. 7).
2. Determine the RI hydraulic pathway, based on the site hydrogeology and discharge requirements to surface or groundwater.
3. Determine the treatment needs by comparing wastewater characteristics to the water quality requirements.

TABLE 12.1 Selected Rapid Infiltration Systems[1–10]

Location	Type of wastewater	Year started	Flow, mgd	Hydraulic loading, ft/year	Effluent disposition
Calumet, Mich.	Raw	1887	1.6	116	Surface
Fontana, Calif.	Primary	1953	2.9	57	Groundwater
Ft. Devens, Mass.	Primary	1941	1.0	100	Surface
Hollister, Calif.	Primary	1946	1.0	50	Surface
Lake George, N.Y.	Secondary	1939	1.1	140	Surface
Milton, Wis.	Secondary	1937	0.3	360	Groundwater
Phoenix, Ariz.	Secondary	1974	13.0	200	Reuse
Seabrook Farms, N.J.	Screened cannery	1950	3.4	53	Groundwater
Vineland, N.J.	Primary	1927	4.1	70	Surface
Whittier Narrows, Calif.	Tertiary	1963	12.5	160	Groundwater

4. Select the preapplication treatment level appropriate for the site and the treatment needs (see Chap. 8).
5. Calculate the hydraulic loading rate based on the treatment needs, the infiltration rate, and the preliminary wet/dry ratio.
6. Calculate the land requirements.
7. Check the potential for groundwater mounding and determine the need for underdrains (see Chap. 4).
8. Select a hydraulic loading cycle and the number of basin sets.
9. Calculate the application rate and check the final wet/dry ratio.
10. Lay out the basins and design berms, structures, etc.
11. Determine monitoring requirements and locate monitoring wells (see Chap. 15).

Treatment Requirements

The treatment performance at RI systems is relatively independent of infiltration rate for most constituents (see Chap. 3). For nitrogen, and to some extent phosphorus, the infiltration rate can affect the treatment performance.

Nitrification

As indicated in Chap. 3 for RI systems, application rates of up to 12 in/day (0.3 m/day) with 20 mg/L of ammonia will result in a nitrified effluent. As wastewater temperatures drop, the rate of nitrification will also decrease. For example, at temperatures of 40 to 45°F nitrification rates will be substantially less than rates at 70°F.[11] Experience at Boulder, Colo., has shown that even though nitrification declines, at temperatures of 40°F there was still removal of ammonia to 1 mg/L or less from about 9 mg/L.[12] Reducing application rates during cold weather will allow for these reduced nitrification rates and will also allow more of the applied ammonia to be adsorbed in the soil profile. For nitrification, the loading cycle should consist of short (1 day or so) application periods and relatively long (5 to 10 days) drying periods.

Nitrogen removal

Nitrogen removal by denitrification requires both adequate organic carbon and adequate detention time. The potential carbon limitation on the amount of nitrogen removal can be approximated using the following equation:

$$N = \frac{\text{TOC-5}}{2} \tag{12.1}$$

where N = change in total nitrogen, mg/L
TOC = total organic carbon in the applied wastewater, mg/L

The 5 mg/L of residual TOC is typical for municipal wastewater after passage through about 5 ft (1.5 m) of soil. The coefficient 2 in the denominator is based on experimental data where 2 g of wastewater carbon were required to denitrify 1 g of wastewater nitrogen.[11]

Nitrogen removal is also related to infiltration rate as shown in experiments with secondary effluent at Phoenix, Ariz.[13] Lance showed that although nitrogen removal was 30 percent at an infiltration rate of 12 in/day (0.3 m/day), the removal increased to 80 percent at a 6 in/day infiltration rate. Based on this research, an application rate of 6 in/day (0.15 m/day) is recommended as a maximum where 80 percent nitrogen removal is needed with secondary effluent. When primary effluent is used, the maximum application rate is recommended to not exceed 8 in/day (200 mm/day). Because nitrogen removal has rarely been required for RI, soil column testing or pilot testing with the actual wastewater and soil is recommended if these rates are to be exceeded.

To achieve the desired nitrogen removal, the application rate, or rate at which wastewater is discharged into the RI basins, may be less than the measured infiltration rate of the site. If this is the case, uniform application with surface flooding of the basins may not be possible. In these cases, sprinkler distribution may be necessary.

Studies of nitrogen removal by RI lysimeters, applying secondary effluent, confirmed the work by Lance.[13] At an application rate of 6 in/day (150 mm), the total nitrogen removal was 80 percent. The optimum nitrogen removal was found with 1 day of flooding followed by 1 day of drying. In a full-scale RI operation at Phoenix, the optimum removal of nitrogen was found with 9 days of flooding and 12 days of drying (nearly a 1:1 ratio of flooding to drying).

In the same experiments with lysimeters, sprinkling for 15 min followed by 75 min of drying was not effective in nitrogen removal. Under these conditions only 16 to 23 percent of the nitrogen (mass basis) was removed, indicating that denitrifying conditions were not developed.[14] Results of recent soil-aquifer treatment (SAT) studies[24,25] have confirmed much of the original work by Lance and Bouwer.

If nitrogen removal is critical to the design of an RI system, special procedures should be followed to ensure that ammonium adsorption, nitrification, and denitrification are optimized for the site, the climate, the wastewater characteristics, and the required performance. The procedures in Refs. 26 and 27 can be used in conjunction with pilot tests or column studies to refine the design criteria.

Phosphorus removal

A conservative estimate of the phosphorus-removal capability of an RI system can be made using Eq. (3.3). The infiltration rate and flow distance determine the detention time. If the infiltration rate is too high to effect adequate phosphorus removal within an acceptable (site-specific) flow path, the infiltration rate can be reduced by compacting the soil and by reducing the depth of wastewater applied. If the calculated phosphorus removal is not acceptable, a phosphorus adsorption test should be conducted. The result of the test should be multiplied by a factor of 5 to account for the slow precipitation that will occur over time. Phosphorus removal can also be tested using mathematical models.[15,16]

Hydraulic Loading Rate

Selecting the appropriate design hydraulic loading rate is the most critical step in the process design procedure. As indicated in Chap. 7, an adequate number of measurements must be made of the infiltration rate and of the subsurface permeability. The hydraulic loading rate is a function of the site-specific hydraulic characteristics, including infiltration, percolation, lateral flow, and depth to groundwater, as well as quality of the applied wastewater and the treatment requirements.

Design infiltration rate

The tests for infiltration rate described in Chap. 7 should be reviewed and an appropriate test selected. Using the equations in Chap. 4 [(4.3) or (4.4)], the mean infiltration rate is then calculated from the field data. During preliminary design the infiltration rate can be estimated from the NRCS permeability data, which are based on soil texture. For final design, however, actual field data should be used.

Wet/dry ratio

Intermittent application is critical to the successful operation of all land treatment systems. The ratio of wetting to drying in successful RI systems varied but is always less than 1.0. Typical wet/dry ratios are presented in Table 12.2. For primary effluent the ratios are generally less than 0.2 to allow for adequate drying and scarification and removal of the applied solids. For secondary effluent, the ratio varies with the treatment objective, from 0.1 or less where nitrification or maximum hydraulic loading is the objective, to 0.5 to 1.0 where nitrogen removal is the treatment objective. These drying periods are necessary to restore the infiltration capacity and to renew the biological and chemical treatment capability of the soil system.

Design hydraulic loading rate

The design hydraulic loading rate for RI systems depends on the design infiltration rate and the treatment requirements. The procedure is to calculate the hydraulic loading rate based on a percentage of the test infiltration rate. This value is then compared to the loading rate based on treatment requirements, and the lower rate is selected for design.

TABLE 12.2 Typical Wet/Dry Ratios for RI Systems

Location	Preapplication treatment	Application period, days	Drying period, days	Wet/dry ratio
Barnstable, Mass.	Primary	1	7	0.14
Boulder, Colo.	Secondary	0.1	3	0.03
Calumet, Mich.	Untreated	2	14	0.14
Ft. Devens, Mass.	Primary	2	14	0.14
Hollister, Calif.	Primary	1	14	0.07
Lake George, N.Y.	Secondary	0.4	5	0.08
Phoenix, Ariz.	Secondary	9	12	0.75
Vineland, N.J.	Primary	2	10	0.20

Process Design—Rapid Infiltration Systems 287

The most commonly used measurements for infiltration rates are the basin infiltration test and the cylinder infiltrometer (see Chap. 7). The relationship between annual loading rate and operating infiltration rates and cylinder infiltrometer rates is shown in Table 12.3.

The saturated vertical hydraulic conductivity is a constant with time, whereas infiltration rates decrease as wastewater solids clog the soil surface. Thus, vertical conductivity measurements overestimate the wastewater infiltration rates that can be maintained over long periods of time. For this reason, and to allow adequate time for drying periods and for proper basin management, annual hydraulic loading rates should be limited to a fraction of the measured clear water permeability of the most restrictive soil layer.

Basin infiltration tests are the preferred method. However, their small area compared to the full-scale basin allows a larger fraction of the wastewater to flow horizontally through the soil from the test site than from the operating basin. Therefore, test infiltration rates are higher than the rates operating systems would achieve. Thus, design annual hydraulic loading rates should be no greater than 7 to 10 percent of measured basin test infiltration rates.

Cylinder infiltrometers greatly overestimate operating infiltration rates. When cylinder infiltrometer measurements are used, annual hydraulic loading rates should be no greater than 2 to 4 percent of the minimum measured infiltration rates. Annual hydraulic loading rates based on air entry permeameter test results should be in the same range.

Design guidance for hydraulic loading rates is summarized in Table 12.4. Where high wet/dry ratios and mild climates are

TABLE 12.3 Typical Hydraulic Loading Rates for RI Systems[17]

Location	*L*, ft/year	Annual loading rate: % of operating infiltration rate	Annual loading rate: % of cylinder infiltration rate
Boulder, Colo.	100–160	10–38	4–10
Brookings, S.Dak.	78–118	16–24	—
Ft. Devens, Mass.	95	13	2
Hollister, Calif.	50	24	3
Phoenix, Ariz.	200	27	—
Vineland, N.J.	70	—	1.6

expected, the upper end of the range of values in Table 12.4 can be used. Conversely, where long drying periods are needed, the lower end of the range should be used.

Example 12.1: Hydraulic Loading Rate

Conditions The RI site consists of loamy sand. Basin infiltration tests yielded an average infiltration rate of 6.2 in/h. Determine the annual hydraulic loading rate.

Solution Use an average of 8.5 percent to calculate the annual loading:

$$6.2 \text{ in/h} \times 24 \text{ h/day} \times 365 \text{ days/year} \times \frac{1 \text{ ft}}{12 \text{ in}} \times 0.085$$
$$= 385 \text{ ft/year}$$

Before selecting this rate for design, check the treatment requirements and calculate the subsurface flow rate.

Land Requirements

The application area for RI systems can be determined using Eq. (12.2).

$$A = \frac{Q\,(3.06)\,(365)}{L_w} \tag{12.2}$$

where A = application area, acres
Q = average design flow, Mgal/day
3.06 = conversion, acre · ft to Mgal/day
365 = days/year
L_w = annual hydraulic loading, ft/year

TABLE 12.4 Suggested Hydraulic Loading Rates Based on Different Field Measurements

Field measurement	Annual loading rate
Basin infiltration test	7 to 10% of minimum measured infiltration rate
Cylinder infiltrometer and air entry permeameter measurements	2 to 4% of minimum measured infiltration rate
Vertical hydraulic conductivity measurements	4 to 10% of conductivity of most restricting soil layer

Other land requirements include area for preapplication treatment, roads, berms, and storage (if necessary). Access roads, typically 10 to 12 ft (3 to 3.6 m) wide, are needed so that maintenance equipment for surface scarification can enter each basin. Storage is generally unnecessary for RI systems. The equivalent of short storage for emergencies can be attained by making the basins deep enough so that some storage can be realized. Area for future expansion should also be considered.

Hydraulic Loading Cycle

Loading cycles are selected to maximize either the infiltration rate, nitrogen removal, or nitrification. To maximize infiltration rates, the engineer should include drying periods that are long enough for soil reaeration and for drying and oxidation of filtered soils.

Loading cycles used to maximize nitrogen removal vary with the level of preapplication treatment and with the climate and season. In general, application periods must be long enough for soil bacteria to deplete soil oxygen, resulting in anaerobic conditions.

Nitrification requires short application periods followed by longer drying periods. Thus, hydraulic loading cycles used to achieve nitrification are essentially the same as the cycles used to maximize infiltration rates.

Recommended hydraulic loading cycles are summarized in Table 12.5. Generally the shorter drying periods in Table 12.5 should be used only in mild climates. In cold climates the longer drying periods should be used.

Number of basin sets

The number of basins or sets of basins depends on the topography and the hydraulic loading cycle. The decision on the number of basins and the number to be flooded at one time affects both the distribution system hydraulics and the final wet/dry ratio. As a minimum, the system should have enough basins so that at least one basin can be flooded at all times (see Chap. 9). The minimum number of basins required for continuous wastewater application is presented in Table 12.6 as a function of the loading cycle.

TABLE 12.5 Suggested RI Loading Cycles

Loading cycle objective	Applied wastewater	Season	Application period,* days	Drying period, days
Maximize infiltration rates	Primary	Summer	1–2	5–7
		Winter	1–2	7–12
	Secondary	Summer	1–3	4–5
		Winter	1–3	5–10
Maximize nitrogen removal	Primary	Summer	1–2	10–14
		Winter	1–2	12–16
	Secondary	Summer	7–9	10–15
		Winter	9–12	12–16
Maximize nitrification	Primary	Summer	1–2	5–7
		Winter	1–2	7–12
	Secondary	Summer	1–3	4–5
		Winter	1–3	5–10

*Regardless of season or cycle objective, application periods for primary effluent should be limited to 1 to 2 days to prevent excessive soil clogging.

TABLE 12.6 Minimum Number of Basins Required for Continuous Wastewater Application

Loading application period, days	Cycle drying period, days	Minimum number of infiltration basins
1	5–7	6–8
2	5–7	4–5
1	7–12	8–13
2	7–12	5–7
1	4–5	5–6
2	4–5	3–4
3	4–5	3
1	5–10	6–11
2	5–10	4–6
3	5–10	3–5
1	10–14	11–15
2	10–14	6–8
1	12–16	13–17
2	12–16	7–9
7	10–15	3–4
8	10–15	3
9	10–15	3
7	12–16	3–4
8	12–16	3
9	12–16	3

Application rate

The application rate is set by the annual loading rate and the loading cycle. The application rate is used to determine the required hydraulic capacity of the piping to the basins. The application rate is calculated as follows:

1. Add the application period to the drying period to obtain the total cycle time, days.
2. Divide the number of application days per year, usually 365 except where storage is planned, by the total cycle time to obtain the number of cycles per year.
3. Divide the annual hydraulic loading by the number of cycles per year to obtain the loading per cycle.
4. Divide the loading per cycle by the application period to obtain the application rate, feet/day.

The discharge rate to the basins can then be determined using Eq. (12.3).

$$Q = 18.9\,AR \tag{12.3}$$

where Q = discharge capacity, gal/min
18.9 = conversion constant
A = basin area, acres
R = application rate, in/day

Example 12.2: Hydraulic Flow Capacity

Conditions The annual hydraulic loading rate for a RI system is 100 ft/year. The application period is 1 day, the drying period is 13 days, and the basin area is 2 acres. Determine the application rate and hydraulic flow capacity.

Solution

1. Total cycle time = 1 + 13 = 14 days
2. Number of cycles per year = 365/14 = 26
3. Loading per cycle = 100/26 = 3.85 ft/cycle
4. Application rate = 3.85/1 = 3.85 ft/day
5. Q = 18.9 (2 acres)(3.85)(12 in/ft) = 1746 gal/min

Cold Weather Operation

In regions that experience cold weather, longer loading cycles may be necessary during winter months. Nitrification, denitrification, oxidation (of accumulated organics), and drying rates all decrease during cold weather, particularly as the temperature of the applied wastewater decreases. Longer application periods are needed for denitrification so that the application rate is reduced as the rate of nitrogen removal decreases. Similarly, longer resting periods are needed to compensate for reduced nitrification and drying rates.

Where ponds are used as preapplication treatment with cold winter weather, winter storage may be required. This is because the temperature of the wastewater becomes quite low prior to land treatment and makes the applied wastewater susceptible to long-term freezing in the basin. Alternatively, RI may be continued through cold weather if warmer wastewater from the first cell of the pond system (if possible) is applied.

Rapid infiltration systems that operate successfully during cold winter weather without any cold weather modifications can be found in Victor, Mont., Calumet, Mich., and Ft. Devens, Mass. However, some modifications have been used to improve cold weather treatment in other communities. Basin surfaces that are covered with grass or weeds should be mowed during fall. Mowing followed by disking should prevent ice from freezing to vegetation near the soil surface. Floating ice helps insulate the applied wastewater, whereas ice that freezes at the soil surface prevents infiltration. Problems with ice freezing to vegetation have been reported at Brookings, S.Dak., where basins were not mowed and lagoons are used for preapplication treatment.

Another cold weather modification involves digging a ridge and furrow system in the basin surface. Following wastewater application, ice forms on the surface of the water and forms bridges between the ridges as the water level drops. Subsequent loadings are applied beneath the surface of the ice, which insulates the wastewater and the soil surface. For bridging to occur, a thick layer of ice must form before the wastewater surface drops below the top of the ridges. This modification has been used successfully in Boulder, Colo., and Westby, Wash.

The third type of basin modification involves the use of snow fencing or other materials to keep a snow cover over the infiltration basins. The snow insulates both applied wastewater and soil.

Drainage

Rapid infiltration systems require adequate drainage to maintain infiltration rates and treatment efficiencies. The infiltration rate may be limited by the horizontal hydraulic conductivity of the underlying aquifer. Also, if there is insufficient drainage, the soil will remain saturated with water and reaeration will be inadequate for oxidation of ammonia nitrogen to occur.

Renovated water may be isolated to protect either or both the groundwater and the renovated water. In both cases, there must be some method of engineered drainage to keep renovated water from mixing with native groundwater.

Natural drainage often involves subsurface flow to surface waters. If water rights are important, the engineer must determine whether the renovated water will drain to the correct watershed or whether wells or underdrains will be needed to convey the renovated water to the required surface water. *In all cases, the engineer needs to determine the direction of subsurface flow due to drainage from RI basins.*

Subsurface drainage to surface waters

If natural subsurface drainage to surface water is planned, soil characteristics can be analyzed to determine if the renovated water will flow from the recharge site to the surface water. For subsurface discharge to a surface water to occur, the width of the infiltration area must be limited to values equal to or less than the width calculated in the following equation:[18]

$$W = KDH/dL \tag{12.4}$$

where W = total width of infiltration area in direction of groundwater flow, ft

K = permeability of aquifer in direction of groundwater flow, ft/day

D = average thickness of aquifer below the water table and perpendicular to the direction of flow, ft

H = elevation difference between the water level of the water course and the maximum allowable water table below the spreading area, ft

d = lateral flow distance from infiltration area to surface water, ft

L = annual hydraulic loading rate (expressed as daily rate) , ft/day

Examples of these parameters are shown in Fig. 12.1.

Example 12.3: Subsurface Drainage

Conditions An RI site is located near a river with expected subsurface flow from the RI site to the river. The aquifer below the site is 20 ft thick and has a $K = 3$ ft/day. The annual hydraulic loading is 60 ft/year. The water elevation is 30 ft below the RI basins and the lateral flow distance is 100 ft. If the groundwater mound is to be maintained at 5 ft or more from the RI basin surface, what is the maximum width of the RI basin area?

Solution The maximum elevation difference H is 30 − 5 = 25 ft. The annual loading rate expressed as a daily rate is 60/365 = 0.16 ft/day.

$$W = \frac{KDH}{dL}$$

$$= \frac{(3)(20)(25)}{(100)(0.16)}$$

$$= 94 \text{ ft}$$

Underdrains

Excessive groundwater mounding will inhibit infiltration and reduce the effectiveness of treatment. For this reason, *the capillary fringe above the groundwater mound should never be closer*

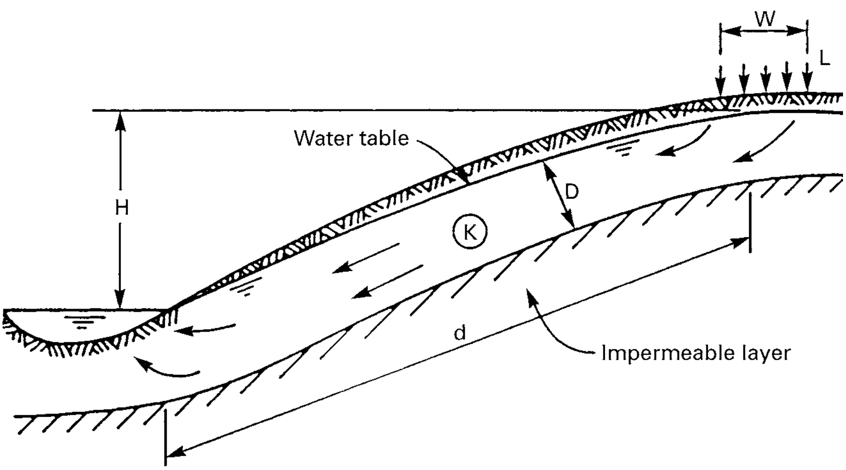


Figure 12.1 Definition sketch for lateral drainage from RI systems.

than 2 ft (0.6 m) to the bottom of the infiltration basin.[19] This distance corresponds to a water table depth of about 3 to 7 ft (0.9 to 2.1 m), depending on the soil texture. The distance to groundwater should be 5 to 10 ft (1.5 to 3 m) below the soil surface within 2 to 3 days following a wastewater application. Procedures for estimating groundwater mounding and underdrain spacings are provided in Chap. 4.

Generally, drains are spaced 50 ft (15 m) or more apart and are at depths of 8 to 16 ft (2.4 to 4.8 m). In soils with high lateral permeability, spacing may approach 500 ft (150 m). Although closer drain spacing allows more control over the depth of the groundwater table, as drain spacing decreases the cost of providing underdrains increases. When designing a drainage system, different values of d should be selected and used to calculate S, so that the optimum combination of d, H, and S can be determined. Detailed information on drainage may be found in the U.S. Bureau of Reclamation *Drainage Manual*[20] and in the American Society of Agronomy manual, *Drainage for Agriculture.*[21]

Once the drain spacing has been calculated, drain sizing should be determined. Usually, 6- or 8-in (150- or 200-mm) drainage laterals are used. The laterals connect to a collector main that must be sized to convey the expected drainage flows. Drainage laterals should be placed so that they will be free-flowing; the engineer should check drainage hydraulics to determine necessary drain slopes.

Recovery wells

Rapid infiltration systems that utilize unconfined and relatively deep aquifers should use wells if necessary to improve drainage or to remove renovated water for reuse. Wells are used to collect renovated water directly beneath the RI sites at both Phoenix, Ariz., and Fresno, Calif. Wells are also involved in the reuse of recharged waste water at Whittier Narrows, Calif., however, the wells pump groundwater that happens to contain reclaimed water, rather than pumping specifically for renovated water.

The arrangement of wells and recharge areas varies; wells may be located midway between two recharge areas, may be placed on either side of a single recharge strip, or may surround a central infiltration area. Well design is described in detail in Ref. 22.

References

1. Baillod, C. R., et al., "Preliminary Evaluation of 88 Years of Rapid Infiltration of Raw Municipal Sewage at Calumet, Michigan," in *Land as a Waste Management Alternative,* Ann Arbor Science, 1977.
2. Roy F. Weston, Inc., "Operation and Maintenance Considerations for Land Treatment Systems," EPA-600/2-82-039, Jan., 1982.
3. Satterwhite, M. B., B. J. Condike, and G. L. Stewart, *Treatment of Primary Sewage Effluent by Rapid Infiltration,* U.S. Army Corps of Engineers, Cold Regions Research and Engineering Laboratory, Dec. 1976.
4. Pound, C. E., R. W. Crites, and J. V. Olson, "Long-Term Effects of Land Application of Domestic Wastewater-Hollister, California, Rapid Infiltration Site," EPA-600/2-78-084, Apr. 1978.
5. Aulenbach, D. B., "Long-Term Recharge of Trickling Filter Effluent into Sand," EPA-600/2-79-068, Mar. 1979.
6. Benham-Blair and Affiliates, Inc., "Long-Term Effects of Land Application of Domestic Wastewater: Milton, Wisconsin, Rapid Infiltration Site," EPA-600/2-79-145, Aug. 1979.
7. Bouwer, H., et al., "Rapid Infiltration Research at Flushing Meadows Project, Arizona," *Journal WPCF,* **52**(10):2457–2470 (1980).
8. Pound, C. E., and R. W. Crites, "Wastewater Treatment and Reuse by Land Application," EPA-660/2-73-006n, Aug. 1973.
9. Koerner, E. T., and D. A. Haws, "Long-Term Effects of Land Application of Domestic Wastewater: Vineland, New Jersey, Rapid Infiltration Site," EPA-600/2-79-072, March 1979.
10. Dryden, F. D., and C. Chen, "Groundwater Recharge with Reclaimed Waters from the Pomona, San Jose Creek, and Whittier Narrows Plants," in *Proceedings of International Symposium on Land Treatment of Wastewater,* vol. 1, U.S.A. CRREL, Hanover, N.H., p. 241, Aug. 1978.
11. Leach, L. E., C. G. Enfield, and C. C. Harlin, Jr., "Summary of Long-Term Rapid Infiltration System Studies," EPA-600/2-80-165, July 1980.
12. Carlson, R. R., et al., "Rapid Infiltration Treatment of Primary and Secondary Effluents," *Journal WPCF,* **54**(3):270–280 (1982).
13. Lance, J. C., F. D. Whisler, and R. C. Rice, "Maximizing Denitrification During Soil Filtration of Sewage Water," *Journal of Environmental Quality,* **5:**102 (1976).
14. Leach, L. E., and C. G. Enfield, "Nitrogen Control in Domestic Wastewater Rapid Infiltration Systems," *Journal WPCF,* **55**(9): 1150–1157 (1983).
15. Ryden, J. C., J. K. Syers, and I. K. Iskandar, "Evaluation of a Simple Model for Predicting Phosphorus Removal by Soils During Land Treatment of Wastewater," U.S. Army Corps of Engineers, CRREL, *Special Report* 82-14, June 1982.
16. Enfield, C. G., "Evaluation of Phosphorus Models for Prediction of Percolate Water Quality in Land Treatment," *Proceedings of the International Symposium on Land Treatment of Wastewater,* vol. 1, CRREL, Hanover, N.H., p. 153, Aug. 1978.
17. U.S. Environmental Protection Agency, *Process Design Manual,* Land Treatment of Municipal Wastewater, EPA 625/1-81-013, Oct. 1981.
18. Bouwer, H., "Infiltration-Percolation Systems," in *Proceedings of the Symposium on Land Application of Wastewater,* Newark, Delaware, p. 85, Nov. 1974.
19. Bouwer, H., "Zoning Aquifers for Tertiary Treatment of Wastewater," *Ground Water,* **14**(6):386 (1976).
20. *Drainage Manual,* U.S. Department of Interior, Bureau of Reclamation, 1978.
21. van Schifgaarde, J. (ed.), *Drainage for Agriculture,* American Society of Agronomy, Series on Agronomy, no. 17, 1974.
22. Campbell, M. D., and J. H. Lehr, *Water Well Technology,* McGraw-Hill, New York, 1973.
23. Arizona State University, University of Arizona, University of Colorado, *Soil Treatability Pilot Studies to Design and Model Soil Aquifer Treatment Systems,* AWWA Research Foundation. Denver, Colo., 1998.
24. Quanrud, D., R. G. Arnold, A. Clark, M. Massaro, and L. G. Wilson, "Efficiency and Sustainability of Soil-Aquifer Treatment Leading to Wastewater Reclamation and Reuse," *Proceedings AWWA Water Reuse,* Orlando, Fla., 1998.

25. Fox, P., K. Naraswamy, and J. E. Drewes, "Water Quality Transformations During Groundwater Recharge at the Mesa Northwest Water Reclamation Plant," *Proceedings, Water Reuse Foundation Annual Water Reuse Research Conference,* Monterey, Calif., 1999.
26. Water Environment Federation, *Natural Systems for Wastewater Treatment. Draft Manual of Practice,* Water Environment Federation, Alexandria, Va., 1999.
27. U.S. Environmental Protection Agency, *Process Design Manual—Land Treatment of Municipal Wastewater: Supplement on Rapid Infiltration and Overland Flow,* EPA 625/1-81-013a, OWPO, Washington, D.C., 1984.

Chapter

13

Industrial Wastewater Land Application

Background

Land treatment, in many ways, was rediscovered for treatment of industrial wastewater. In 1934, corn and pea canning wastewater was reported to be applied successfully using the ridge and furrow method in Hampton, Iowa.[6] In addition to food-processing wastewaters, pulp and paper, chemical, fertilizer, meat processing, dairy, brewery, and winery wastewaters have been land applied successfully for many years.[12,36,49] The wide variety of industrial wastewaters that have been land applied is illustrated in Table 13.1.

Types of Industrial Wastewaters Land Applied

Food processing

Because of the rural location of many food-processing facilities, land application has been used widely. Vegetable processing in New York,[1] citrus processing in Florida,[62] and potato processing in Idaho[54] are industrial wastewaters and areas where land application is the treatment process of choice. Soup and tomato processing wastewater were two of the first food-processing wastewaters that were treated by spray runoff or overland flow,[3,21,49] Winery wastewaters were treated successfully using rapid infiltration.[10,16]

TABLE 13.1 Summary of Types of Industrial Wastewaters Land Applied[12,59]

Industry	References
Food processing:	12, 17, 27
Brewery	15, 29
Canning and frozen foods	
Vegetables	2, 9, 31, 37, 39
Soup	3, 21, 32
Fruit, except citrus	17, 37
Citrus fruit	36, 62
Pineapple	18
Coffee and tea	35, 41
Dairy products	
Milk plants	7, 33
Cheese	38, 53
Meat processing	23, 52
Winery stillage	10, 16
Winery wastewater	14
Pulp and paper:	
Sulfite	4
Kraft	5
Semichemical	58
Strawboard	40
Hardboard and insulation	47, 48
Boxboard and paperboard	30
Deinking	20
Miscellaneous:	
Tanning	46
Pharmaceuticals	11
Biological chemicals	61
Explosives	34
Wood distillation	25

Pulp and paper

As shown in Table 13.1, there have been many types of pulp and paper mill wastewater that have been land applied.[59] Much of the literature on land application of pulp and paper wastewater dates from the 1950s and 1960s. Experiments with insulation board mill wastewater resulted in the demonstration that BOD loading rates over 2000 lb/(acre·day) caused vegetation to be killed.[48]

Other industrial wastes

Other industrial wastewaters that have been land applied include chemical, fertilizer, tannery, pharmaceutical, explosives, and oily wastewaters. Chemical industrial wastewaters that have been land applied are described in Overcash and Pal.[45]

Water Quality and Pretreatment Requirements

Wastewaters to be land applied need to be characterized before the limiting design parameter (see Chap. 2) can be determined. Constituents of concern can include BOD, TSS, nitrogen, phosphorus, pH, temperature, TDS, metals, and sodium. Pretreatment to reduce the concentrations of specific constituents may be required or may reduce the size of the land area needed for land treatment.

Wastewater constituents

Industrial wastewaters may contain significant concentrations and wide variations of constituents such as BOD, TDS, nitrogen, and metals. Ranges of concentrations in land-applied wastewaters are summarized in Table 13.2. The impact and importance of these constituents are described in the following.

BOD. The degradable organic matter, as measured by the BOD test, can be present in very high concentrations in industrial wastewater. Because the soil mantle is very efficient in the removal of BOD, it is often more cost-effective to apply the wastewater to the land than to remove it by pretreatment. BOD loading rates are discussed under the design section.

TABLE 13.2 Characteristics of Various Industrial Wastewaters Applied to the Land[49]

Constituent	Food processing	Pulp and paper	Dairy
BOD, mg/L	200–10,000	60–30,000	4000
COD, mg/L	300–15,000		
TSS, mg/L	200–3000	200–100,000	
Inorganic dissolved solids (IDS), mg/L	1800	2000	1500
Total nitrogen, mg/L	10–100		90–400
pH, units	3.2–12	6–11	5–7
Temperature, °F	145	195	

Organics in the form of sugars are more readily degradable than starchy or fibrous material. Consequently, those industrial wastewaters that contain predominantly sugars, such as food-processing wastewaters, may be applied at a higher organic loading rate than wastewaters from the pulp and paper industry, which often contain starchy or fibrous organic material.

Total suspended solids. Suspended solids may include coarse solids, such as peelings and chips, or fine solids such as pulp or silt. The presence of high concentrations of suspended solids in a wastewater does not restrict its application to a land treatment system because suspended solids can normally be separated quite simply by physical pretreatment. Failure to provide adequate suspended solids removal, however, can lead to operational problems with clogging of sprinkler nozzles or nuisance problems with solids settlement in surface irrigation systems. Surface buildup as a result of uneven distribution or high concentrations of TSS can lead to reduced infiltration rates and inhibition of plant growth in ponded areas of irrigated fields.

Total inorganic dissolved solids. Salts, correctly measured only by the total inorganic (fixed, not volatile) solids test, are important to land treatment systems because there are no effective removal mechanisms for salt. The plants will take up a minor amount of TDS (usually the macronutrients and micronutrients), and some compounds will precipitate in the soil (metal complexes and phosphate compounds). As a result of the minimal removal, mineral salts either build up their concentration in the soil or are leached to the groundwater. Industrial wastewaters with very high inorganic solids concentrations are generally not suitable for land application unless special provisions are made to collect soil drainage.

It is very important to measure the inorganic dissolved solids in the industrial process water because the standard total dissolved solids (TDS) test will include the organic acids, alcohols, and other dissolved organic compounds that may be present in the wastewater. As an example, a milk-processing wastewater was tested for inorganic dissolved solids (IDS), TDS, and electrical conductivity (EC) for both the wastewater and the shallow groundwater (after slow rate land treatment). The results are summarized in Table 13.3. The ratios of IDS/TDS and IDS/EC

TABLE 13.3 Comparison of Inorganic and Total Dissolved Solids Measurements in Industrial Wastewater and Shallow Groundwater

Water source	Inorganic dissolved solids (IDS), mg/L	TDS, mg/L	EC, dS/m	IDS/TDS ratio	IDS/EC ratio
Process wastewater	1203	2250	1680	0.53	0.71
Shallow groundwater	1000	1200	1700	0.83	0.58
Upgradient groundwater	200	300	310	0.67	0.64

are presented for both waters and for upgradient shallow groundwater. A typical ratio of IDS/EC in clean water is 0.64.[60] The organic portion of the wastewater TDS is 48 percent of the total TDS and exceeds 1000 mg/L. The slow rate land treatment process reduces the organic TDS to 200 mg/L.

Nitrogen. Industrial wastewaters may be high in nitrogen, as are livestock, potato, dairy, and meatpacking wastewaters. For these wastewaters, nitrogen is often the limiting design factor. Other industrial wastewaters are nitrogen-deficient, and nitrogen may need to be added to allow complete biological treatment.[49] The C:N ratio does not have to be in as close a balance for land treatment as it does for suspended growth systems, however, C:N ratios beyond 30:1 will affect crop growth or biological nutrient removal because of the competition for available nitrogen.

pH. The pH of industrial wastewater can vary tremendously, even hourly, depending on the type of wastewater and the cleaning agents used. A range of pH between 3 and 11 has been applied successfully to the land.[12] If the low pH is from the presence of organic acids, land treatment will have a neutralizing effect as the organic acids are oxidized or degraded.

Temperature. High-temperature industrial wastewater, such as spent cooking liquors from pulping operations, can sterilize soil, thereby precluding the growth of vegetation and reducing the treatment capability of the soil mantle.[22] High-temperature wastewaters should therefore be cooled prior to land application.

Color. The color in most industrial wastewaters is associated with degradable organic material and is effectively removed as the wastewater percolates through the soil mantle. In some wastewaters, such as spent sulfite liquor, the color is due to inert compounds such as lignins. It has been observed that the color from inert compounds can move through the soil.[5] Groundwater contamination is of concern from land application of industrial wastewaters with color resulting from inert components.

Metals. Heavy metals are effectively removed by most soil systems. Metals can be the limiting design factor in slow rate and rapid infiltration systems, and the rate of retention in the soil may affect the longevity of a soil system due to buildup in the soil (see Chap. 17).

Sodium. The sodium adsorption ratio, and the problems caused by high values, are defined in Chap. 3. Some industrial wastewaters that use caustic for cleaning may have a high sodium adsorption ratio and may require pretreatment for correction.

Pretreatment options

Pretreatment for industrial wastewaters may range from fine screening to biological treatment. The more typical of the pretreatment operations and processes are described in the following.

Fine screening. Fine screening is usually a minimum level of pretreatment prior to land application of industrial-process rinse water. Fine screens can range from fixed parabolic inclined screens to rotary-drum screens.[19] Coarse solids that can clog sprinkler heads or settle out at the head end of flood irrigation checks can be removed economically using fine screens. Screens also protect downstream pumps or other pretreatment units from large objects that may get washed into the wastewater stream.

Ponds. Ponds can range from anaerobic to deep facultative to aerated. Aerated lagoons or ponds are quite common to the pulp and paper industry and to many food-processing wastewaters. Ponds can be used to equalize the flows, reduce peak organic loadings, and store the wastewater for short periods of time. If significant winter storage is required and the wastewater has a relatively high BOD, pretreatment will usually be needed to reduce the BOD to 100 mg/L or less[49] to avoid odor production.

Alternatively, the storage pond can be aerated to avoid odor production.

Adjustment of pH. If the pH of the wastewater is outside the range of 4 to 9 due to inorganic acids or bases, pH adjustment may be needed. Sometimes an equalization pond will serve to let the wastewater self-neutralize, particularly if large swings in the wastewater pH occur diurnally. Generally the pH will attenuate quickly as a result of land treatment, and adjustment is not normally needed.

Cooling. High-temperature wastewaters (above 150°F) should be cooled so that adverse effects on vegetation and soil do not occur. High-temperature wastewaters can also have detrimental effects on plastic pipelines. If the wastewater temperature needs to be reduced, either ponding or cooling towers can be used.

Dissolved air flotation. Dissolved air flotation (DAF) is a unit process in which pressurized flow containing tiny air bubbles is released into a special tank or clarifier.[19] The dissolved air will float suspended solids and the DAF unit will remove the solids through a float skimming device. Sedimentation also occurs in DAF units so that the settled solids must be removed. DAF units are most effective for treating settleable solids and fats, oil, and grease (FOG).

Constructed wetlands. An increasing use is being made of constructed wetlands for pretreatment of industrial wastewaters.[14,19,51] Treatment of livestock wastewater with constructed wetlands after treatment through ponds is becoming used widely.[26] Removals of various constituents through three different constructed wetlands are summarized in Table 13.4.

Dairy wastewater has been treated using constructed wetlands with a detention time of 7.7 days, a hydraulic loading rate of 1.55 in/day (39.4 mm/day), and a mass COD loading rate of 494 lb/(acre·day) [554 kg/(ha·day)].[43]

Anaerobic digestion. Anaerobic digestion can be used to reduce the organic content of wastewater and produce methane gas. Anaerobic digestion can be conducted in a variety of reactors and using a variety of processes.[19] Typically a BOD of about 2500 mg/L or higher is needed in an industrial wastewater to

TABLE 13.4 Dairy Wastewater Treatment Using Constructed Wetlands[26]

	Percent removal		
Constituent	Lagrange Co., Ind.	OSU*	Desoto Co., Miss.
BOD	79	61	75
COD	—	47	
TS	—	49	26
TSS	72	73	64
TDS	36	—	12
TKN	64	57	
NH_3-N	64	54	90
NO_3-N	62	75	
TP	74	66	61
SP*	63	63	63

*OSU = Oregon State University; SP = soluble phosphorus.

make anaerobic digestion attractive. Anaerobic digestion using some of the low-rate methods is generally favored in the food-processing industry.

Slow Rate Land Treatment

The procedure for design of slow rate land treatment systems is presented in Chap. 10. A few design considerations specific to industrial wastewater and two brief case studies are included here.

Design considerations

Design considerations specific to industrial wastewaters include the higher solids and organics loadings and the distribution systems. Another aspect of industrial wastewater slow rate systems is the tendency to operate through winter conditions.

Organic loading rates. Oxygen exchange into soils greatly depends on air-filled pore spaces because the diffusion coefficient of oxygen is over 10,000 times more rapid in air than in water. As a result, if organic loadings are intermittent and atmospheric oxygen is allowed to diffuse directly into the soil, high organic loading rates can be sustained without the generation of odors.[51]

Research at Cornell on acclimated soils receiving food-processing wastewater documented that organic loading rates on a COD basis can exceed 4000 and 17,000 lb/(acre·day) for soil temperatures of 16 and 28°C, respectively.[27] Field sampling of the groundwater at application rates exceeding 8000 lb/(acre·day) of COD was less than 0.8 percent of the applied COD.[28] Based on the experience in New York State, guidelines have been established that organic loading rates should not exceed 500 lb/(acre·day) based on BOD.[1]

BOD loading rates for various food-processing land application systems are summarized in Table 13.5. Earlier BOD loading rate limits of 100 lb/(acre·day) have proved to be too conservative.[45]

Distribution systems. The preferred method of wastewater distribution is sprinkler application (irrigation). Surface application (flood or furrow irrigation) allows the solids to settle out near the point of application and produces a nonuniform distribution of solids and organics. Flood or furrow irrigation also results in saturated flow through the soil and may reduce the effectiveness of treatment for some constituents and result in

TABLE 13.5 BOD Loading Rates at Existing Industrial Slow Rate Systems[19,50]

Location	Industry	BOD loading rate, lb/(acre·day)
Almaden, McFarland, Calif.	Winery stillage	420
Anheuser-Busch, Houston, Tex.	Brewery	360
Bisceglia Brothers, Madera, Calif.	Winery stillage	279
Bronco Wine, Ceres, Calif.	Winery	128
Citrus Hill, Frostproof, Fla.	Citrus	399
Contadina, Hanford, Calif.	Tomato processing	92
Frito-Lay, Bakersfield, Calif.	Potato processing	84
Harter Packing, Yuba City, Calif.	Tomato processing	351
Hilmar Cheese, Hilmar, Calif.	Cheese processing	222
Ore-Ida Foods, Plover, Wis.	Potato processing	190
Tri Valley Growers, Modesto, Calif.	Tomato processing	200

anaerobic conditions that can cause leaching of iron and manganese. Relatively low cost methods of sprinkler application, such as center pivots, are usually preferred. See Chap. 9 for details on sprinkler application.

Attenuation of low pH. Many food-processing wastewaters have a low pH that can range from 3.7 to 6, as the result of the presence of organic acids. The action of the soil microbes in oxidizing the organic acids and the soil buffering capacity usually result in a relatively rapid attenuation of the pH. A review of sites receiving winery stillage waste with a typical pH of 3.7 found that the soil pH was reduced from 6.7 to 5.8 in the topsoil (0 to 6 in), but only from 7.1 to 6.6 at the 2-ft depth, and only from 7.45 to 7.16 at the 6-ft depth.[16]

Typical examples

Slow rate land treatment is the most popular method of industrial wastewater land treatment. Two examples of food-processing wastewater land application are presented in the following illustrating a year-round application in Idaho and a seasonal application of tomato-processing wastewater in California.

Potato process water land application system—Idaho.[8] The J. R. Simplot Company Food Group has operated a potato-processing plant in Aberdeen, Idaho, since they purchased it in 1973. This facility produces a variety of fried potato products. The 330-day processing season begins on about Sept. 1 and ends on about July 31 each year. The current average daily flow from the facility is about 700,000 gallons per day (gpd), for an annual flow of about 231 million gallons annually (MGA). All water used for potato processing is recycled through sprinkler irrigation on 469 acres of agricultural land with silt loam soil, which is planted to grass. Groundwater is about 30 to 60 ft (10 to 20 m) below the ground surface at this site.

Process water is generated during the washing, cutting, blanching, and cooling of the potatoes. Water used to wash soil from the potatoes in the raw receiving area is screened to remove potato vines, rocks, and small potatoes, and then is diverted to a set of settling basins. The settled soil is land applied on a designated area of the facility's agricultural land, and the overflow from the basins is pumped to the land application site with the process water stream. Water used within the processing plant is screened and then directed to a primary clarifier. The underflow potato solids from the clarifier are mechanically separated using centrifuges and are fed to cattle. Excess oil from the fryers is removed by a separate clarifier and recycled off site.

Southern Idaho has a semiarid climate, with an annual average precipitation of about 9 in. The growing season for grass occurs during the months of April through October. Under intensely managed conditions, grass on land application sites in southern Idaho typically consumes about 42 in of water annually.

The objective of Simplot's potato process water irrigation system is to provide a cost-effective, reliable, and environmentally sound beneficial reuse of the water, nitrogen, and other crop nutrients. The challenging aspects of this system have been the management of applied salts and organics to protect groundwater quality and to minimize odors. Simplot has met these challenges through steady improvements of the land application system over the past 17 years.

The land application system in 1973 consisted of the 108 acres of fields, which were sprinkler irrigated. In 1989, Simplot added 200 acres to the original site for a total area of 308 acres, or 279 irrigated acres. In mid-1997, Simplot added another 180-acre parcel to their land application site. This new site, currently referred to as the expansion site, brings the total irrigated area to 459 acres. All acreage is irrigated by sprinkler methods. A view of the center-pivot sprinkler system is shown in Fig. 13.1.

The first expansion of the site in 1989 reduced the annual process water loadings to approximately one-third of their former levels. Since 1989, the process water flow from the Aberdeen facility has increased by about 43 percent. Along with the higher amount of process water generated each year, the annual nitrogen generation has increased from about 165,000 to about 233,000 lb/year, a 41 percent increase. Organic generation, measured as COD, has increased from about 6.2 to about 6.4 million lb/year, a 3 percent increase. Simplot has not significantly changed the nitrogen concentration of its process water but has achieved much greater COD removal efficiencies over the past 10 years.

After years of monitoring the land sites, it was determined in about 1994 that the 279-acre site area was too small to properly recycle and treat the process water that was being generated.

Figure 13.1 Side roll sprinklers apply potato-processing wastewater throughout the winter at Aberdeen, Idaho. (*Courtesy of Cascade Earth Science.*)

The original 108-acre site continued to show several symptoms of overloaded conditions, even though the additional 200 acres was being fully utilized. Owing to frozen soil conditions, especially in the months of December through February, the process water hydraulic rates were causing prolonged ponded conditions on the 108-acre site. The prolonged ponding in those areas killed the grass, which had to be replanted each spring. Grass crop annual yields were typically about half of the expected 6 to 7 tons/acre. The high organic loadings during the nongrowing season also promoted ponding by sealing the soil surface. From a nitrogen treatment perspective, the system worked well by having the ideal conditions for denitrification.[24] However, the predominantly anaerobic soil conditions had negative impacts of causing iron and manganese to solubilize from the soil and reach groundwater, and causing odors to develop in the fields. Salts leaching from the site caused increases in total dissolved solids (TDS) in groundwater.

In 1997, Simplot expanded their process water recycling site from 279 to 468.5 acres. Application of process water to the expansion site from November 1997 through October 1998 reduced applications to the original site by about 12 percent. Overall, present process water hydraulic and nitrogen application rates to the original site are about half of pre-1989 levels. The present COD application rates have decreased by about 65 percent of pre-1989 levels.

In addition to expanding the site, Simplot undertook a multiyear evaluation of loading rates on one field of the original site in 1994. A 30-acre field irrigated with a center pivot was instrumented with soil monitoring equipment and carefully managed to maximize treatment efficiency. The study results showed that the site could reliably recycle 500 lb/(acre·year) of nitrogen, with an average crop nitrogen removal rate of 70 percent. The soil and groundwater monitoring indicated that percolate losses of nitrate were virtually nondetectable.

Through careful evaluation and planning, Simplot has expanded its land application system to accommodate the growth of its potato-processing facility in Aberdeen. The design loading rates have been confirmed with monitoring data, which is specific to the conditions of Simplot's operation. Once the loadings are balanced between the original site and the new site, the past ponding, groundwater, and odor problems of the original site will be resolved.[8]

Tomato processing system in California. Tomato-processing wastewater has been land applied at a number of sites in the central valley of California for many years. Operations include direct land application to open land, furrow, flood, and sprinkler irrigation of agricultural crops, and provision of irrigation water to private farmers for pasture application. One site has 90 acres (36 ha) for the direct land application of 1.0 Mgal/day (3875 m^3/day). Wastewater is passed through a fine screen and applied to border strips for flood irrigation. BOD and TSS concentrations have averaged 1700 and 300 mg/L, respectively, resulting in a BOD loading of 170 lb/(acre·day) [190 kg/(ha·day)] and a TSS loading rate of 30 lb/(acre·day) [33 kg/(ha·day)]. The regulatory agency has placed a limit of 200 lb/(acre·day) [224 kg/(ha·day)] of BOD to avoid the generation of odors. Upgradient and downgradient groundwater monitoring wells have been sampled regularly and have demonstrated improvement of water quality after land application and no adverse impacts on water quality of the groundwater.[2]

Overland Flow Land Treatment

The procedure for design of overland flow land treatment systems is presented in Chap. 11. A few design considerations specific to industrial wastewater and two brief case studies are included here.

Design considerations

Design considerations specific to industrial wastewaters include the higher solids and organics loadings and the distribution systems. Overland flow systems receiving high-strength wastewater need to use sprinkler application to distribute the solids and organics evenly.

Organic loading rates and BOD concentrations need to be limited to avoid overloading the oxygen transfer to the attached microorganisms. The initial work by Campbell Soup Company[21] indicated that excellent BOD removals could be expected at applied BOD concentrations of about 800 mg/L.[12] When higher-strength wastewaters were applied at similar loading rates (0.6 to 1.4 in/day) (16 to 36 mm/day), however, an oxygen transfer problem began to develop. To overcome this problem, pretreatment or recycling of the treated effluent can be used.[12]

Typical examples

Overland flow has been used to treat a variety of food-processing wastewaters including apple, tomato, potato, soup, meatpacking, poultry, peanuts, and pimientos.[12] Two examples are presented briefly to illustrate a year-round system and a seasonal system. In the year-round example the treated runoff is discharged to surface water. In the more seasonal operation, the treated runoff is reused for crop irrigation.

Soup producer in Texas. One of the oldest and best-known overland flow systems is the Campbell Soup Company's Paris, Tex., operation. Developed in the 1960s, the Paris, Tex., site has had its origins documented[21] has been researched by EPA[32] on the performance, Vela[57] on the microbiology, and Tedaldi[56] on the long-term effects.

The original 300-acre (120-ha) site was expanded to 900 acres (360 ha) by 1976. The original slopes ranged from 1 to 12 percent, but those from 2 to 6 percent demonstrated the best performance, least erosion, and least ponding. The overland flow terraces are 200 to 300 ft long (60 to 90 m). The hydraulic loading rate was 0.6 in/day (15 mm/day). The slopes are seeded to a mixture of Reed canarygrass, tall fescue, red top, and perennial ryegrass. Solid set sprinklers are used. Application periods are 6 to 8 h/day for 5 days/week. The performance of the system is summarized in Table 13.6.

Tomato processor in California. A 320-acre (129-ha) overland flow was constructed near Davis, Calif., in 1969 to treat 4 Mgal/day (15,100 m^3/day) of tomato-processing wastewater. Screened wastewater is pumped to the overland flow field and sprinkled onto constructed 2.5 percent slopes. The slopes are 175 ft (53 m) long based on the experience at Paris, Tex. Reed canarygrass predominates as the vegetation. The cannery operates 3 to 4 months during the summer (July through mid-October) fresh processing season and, for the past few years, operates a remanufacturing processing from October through March. The solid set sprinklers are shown in Fig. 13.2.

Treated runoff averages 2 mgd (7550 m^3/day). The treated runoff is reused for crop irrigation on a nearby ranch. The performance of the overland flow system is summarized in Table 13.7.

Rapid Infiltration Land Treatment

The design of rapid infiltration systems is described in Chap. 12. Few RI systems exist for industrial wastewater. The reasons include the difficulty in siting RI systems and the typical high

TABLE 13.6 Performance of Paris, Tex., Overland Flow System[12,21,32]

Constituent	Influent	Effluent
BOD, mg/L	572	3.1
COD, mg/L	806	45
TSS, mg/L	245	38
Total N, mg/L	17.2	2.8
Total P, mg/L	7.4	4.3
Chloride, mg/L	44	43
pH, units	4.4–9.3	6.6

Figure 13.2 Solid set sprinklers apply tomato-processing wastewater to overland flow slopes.

TABLE 13.7 Performance of Overland Flow System at Davis, Calif.

Constituent	Influent	Effluent
BOD, mg/L	1490	17
TSS, mg/L	1180	25
pH, units	4.5	8.16

SOURCE: Brown and Caldwell files, Sacramento, Calif.

strength of industrial wastewater, which requires a high level of treatment. An RI system at Seabrook Farms, N.J., was one of the first in the country.[49]

The few RI systems that exist are at the low end of the hydraulic loading rate range for municipal wastewater. The loading rates for BOD, TSS, and nitrogen, however, are generally quite high.

Cheese processing wastewater, California. Hilmar Cheese Company has been producing cheese products and land-applying the process water at their plant near the town of Hilmar, 5 miles south of Turlock, Calif., since 1985. The land use surrounding the plant site is primarily agricultural, with a mixture of fodder, orchard, and pasture crops being grown. The soils in the area are characteristically sandy, and there is a relatively shallow groundwater table (10 ft or 3 m). The land has been leveled for surface irrigation.

The area used for rapid infiltration has been expanded with each increase in process water flow, reaching 140 acres (56 ha) by 1998. The process water flow rate is 0.75 Mgal/day (2840 m^3/day). The average loading rate is 2.6 in/week (65 mm/week) because the application area is rotated between wastewater applications for about 6 months and cropping with either corn or barley for 6 months. The BOD loading rate can range from 80 to 655 lb/(acre·day) [89 to 734 kg/(ha·day)], with 222 lb/(acre·day) [248 kg/(ha·day)] being typical.

A comparison of the process water characteristics and the monitoring well groundwater quality is presented in Table 13.8. As shown in Table 13.8, the upgradient groundwater has much higher nitrate-nitrogen values as a result of areawide fertilization practices. The downgradient wells have much lower nitrate-nitrogen as a result of denitrification.

Hilmar Cheese is reclaiming by-products from the cheese production including the whey protein and lactose. An ultrafiltration system concentrates the remaining fats and proteins into a slurry that is used for cattle feed.[55]

Winery wastewater, California. Winery wastewater is characterized by low pH, relatively high BOD, and a low nutrient content. Land application using rapid infiltration basins has been practiced successfully at a number of California wineries for many years.[10,13,17]

TABLE 13.8 Treatment Performance for Hilmar Cheese Infiltration System[44]

Constituent	Process water	Upgradient groundwater	Downgradient groundwater
BOD, mg/L	2852	2	2
TKN, mg/L	93	1.1	9.3
Nitrate-N, mg/L	18	35	0.4
EC, dS/m	1688	650	1,100
TDS, mg/L	2727	480	600
IDS, mg/L	1155	340	540

TABLE 13.9 Comparison of Water Supply and Winery Washwater Quality[13]

Constituent	Water supply	Washwater
BOD, mg/L	—	950
Total nitrogen, mg/L	7.5	33
Nitrate-N, mg/L	7.5	5.3
TDS, mg/L	742	1098
pH	8.0	4.1–7.9
TSS, mg/L	—	286

A central valley winery was constructed in 1974 with a rapid infiltration system for treatment and disposal of process water. Products include wine and wine coolers. Washwater is collected into a central sump and pumped to a series of seven individual rapid infiltration basins. Washwater flows vary by the season, being highest during the August to October crush period. Annual average washwater flows are 0.2 Mgal/day (760 m^3/day).

Operation of the infiltration system is cyclical. Washwater is loaded onto one basin at a time for a period of several days and then the washwater is moved to the next basin. The basins cover 10 acres (4 ha) and are rectangular. In the late winter, when the flows are reduced, about half the basins are taken out of service and planted to an annual cereal crop, such as oats, wheat, or barley. During July, after the crop is harvested, the basins are ripped to a depth of 6 ft (2 m). The basins are then disked and leveled for the next washwater application.[13]

The washwater quality varies with the season. BOD values are highest during the crush (up to 4700 mg/L) and lowest during the spring (about 300 mg/L). The average washwater quality is presented in Table 13.9. The total nitrogen concentration averages 33 mg/L and the BOD/nitrogen ratio averages 28:1. The pH ranges from 4.1 to 7.9. The low values of pH occur during the crush but do not have an adverse effect on either the soil or the groundwater.[13]

References

1. Adamczyk, A. F., “Land Disposal of Food Processing Wastewaters in New York State,” in R. H. Loehr (Ed.), *Land as a Waste Management Alternative,* Ann Arbor Science Publishers, Ann Arbor, Mich., 1977.

2. Beggs, R. A., and R. W. Crites, "Odor Management for Land Application of Food Processing Wastewater," *Proceedings of the 6th International Symposium on Agricultural and Food Processing Wastes,* Chicago, Ill., 1990.
3. Bendixen, T. W., et al., "Cannery Waste Treatment by Spray Irrigation-Runoff," *Journal WPCF,* **41:**385 (1969).
4. Billings, R. M., "Stream Improvement through Spray Disposal of Sulphite Liquor at the Kimberly-Clark Corporation, Niagara, Wisconsin, Mill," *Proceedings of the 13th Industrial Waste Conference,* Purdue University, **96:**71 (1958).
5. Blosser, R. O., and E. L. Owens, "Irrigation and Land Disposal of Pulp Mill Effluents," *Water and Sewage Works,* **111:**424 (1964).
6. Bolton, P., "Disposal of Canning Plant Wastes by Irrigation," *Proceedings of the Third Industrial Waste Conference,* Purdue University, Lafayette, Ind., 1947.
7. Breska, G. J., et al., "Objectives and Procedures for a Study of Spray Irrigation of Dairy Wastes," *Proceedings of the 12th Industrial Waste Conference,* Purdue University, **94:**636 (1957).
8. Bruner, D. J., S. B. Maloney, and H. Hamanishi, Expansion of a Spray Irrigated Land Application System for a Year-Round Potato Processing Facility in Idaho, *Cascade Earth Science,* Pocatello, Idaho, 1999.
9. Canham, R. A., "Comminuted Solids Inclusion with Spray Irrigated Canning Waste," *Sewage & Industrial Wastes,* **30:**1028 (1958).
10. Coast Laboratories, *Grape Stillage Disposal by Intermittent Irrigation,* prepared for Wine Institute, San Francisco, Calif., 1947.
11. Colovos, G. C., and N. Tinklenberg, "Land Disposal of Pharmaceutical Manufacturing Wastes," *Biotech. Bioengineering,* **4:**153 (1962).
12. Crites, R. W., "Land Treatment and Reuse of Food Processing Waste," presented at the 55th Annual Conference of the Water Pollution Control Federation, St. Louis, Mo., 1982.
13. Crites, R. W., "Winery Wastewater Land Application," *Proceedings of a Conference on Irrigation Systems for the 21st Century,* Irrigation and Drainage Division, American Society of Civil Engineering, Portland, Oreg., 1987.
14. Crites, R. W., "Constructed Wetlands for Wastewater Treatment and Reuse," presented at the Engineering Foundation Conference, Environmental Engineering in the Food Processing Industry, XXVI, Santa Fe, N.Mex., 1996.
15. Crites, R. W., et al., "Treatment of Brewery Spent Grain Liquor by Land Application," *Proceedings of the Third Annual Conference on Treatment and Disposal of Industrial Wastewater and Residues,* Houston, Tex., 1978.
16. Crites, R. W., and R. C. Fehrmann, "Land Application of Winery Stillage Wastes," *Industrial Wastes,* **27:**14 (1981).
17. Crites, R. W., C. E. Pound, and R. G. Smith, "Experience with Land Treatment of Food Processing Wastewater," *Proceedings of the Fifth National Symposium on Food Processing Wastes,* Monterey, Calif., 1974.
18. Crites, R. W., and R. G. Stratton, "Land Application of Pineapple Process Water for Reuse," presented at the Hawaii WPCA, Honolulu, Hawaii, 1994.
19. Crites, R. W., and G. Tchobanoglous, *Small and Decentralized Wastewater Management Systems,* McGraw-Hill, New York, 1998.
20. Flower, W. A., "Spray Irrigation for the Disposal of Effluents Containing Deinking Wastes," *TAPPI,* **52:**1267 (1969).
21. Gilde, L. C., et al., "A Spray Irrigation System for Treatment of Cannery Wastes," *Journal WPCF,* **43:**2011 (1971).
22. Guerri, E. A., "Sprayfield Application Handles Spent Pulping Liquors Efficiently," *Pulp & Paper,* **45:**93–95 (1971).
23. Henry, C. D., et al., "Sewage Effluent Disposal through Crop Irrigation," *Sewage & Industrial Wastes,* **26:**123 (1954).
24. Henry, C. L., and S. A. Wilson, *Denitrification Following Land Application of Potato Processing Wastewater,* Agronomy Abstracts, American Society of Agronomy, Madison, Wis., 1988.
25. Hickerson, R. D., and E. K. McMahon, "Spray Irrigation of Wood Distillation Wastes," *Journal WPCF,* **32:**55 (1960).

26. Hunt, P. G., et al., "State of the Art for Animal Wastewater Treatment in Constructed Wetlands," *Proceedings of the Seventh International Symposium on Agricultural and Food Processing Wastes,* ASAE, Chicago, Ill., 1995.
27. Jewell, W. J., and R. C. Loehr, "Land Treatment of Food Processing Wastes," presented at the American Society of Agricultural Engineering, Winter Meeting, Paper 75-2513, Chicago, Ill., 1975.
28. Jewell, W. J., et al., *Limitations of Land Treatment of Wastes in the Vegetable Processing Industries,*. Cornell University. Ithaca, N.Y., 1978.
29. Keith, L. W., and W. D. Lehman, *Land Treatment of Food Processing Wastewater—Case History, Utilization, Treatment, and Disposal of Waste on Land,* Soil Science Society of America, Madison, Wis., 1986.
30. Koch, H. C., and D. E. Bloodgood, "Experimental Spray Irrigation of Paperboard Mill Wastes," *Sewage & Industrial Wastes,* **31:**827 (1959).
31. Lane, L. C., "Disposal of Liquid and Solid Wastes by Means of Spray Irrigation in the Canning and Dairy Industries," *Proceedings of the 10th Industrial Waste Conference,* Purdue University, **89:**508 (1955).
32. Law, J. P., R. E. Thomas, and L. H. Myers, "Cannery Wastewater Treatment by High-Rate Spray on Grassland," *Journal Water Pollution Control Federation,* **42:**1621–1631 (1970).
33. Lawton, G. W., et al., "Spray Irrigation of Dairy Wastes," *Sewage & Industrial Wastes,* **31:**923 (1959).
34. Lever, N. A., "Disposal of Nitrogenous Liquid Effluent from Modderfontein Dynamite Factory," *Proceedings of the 21st Industrial Waste Conference,* Purdue University, **121:**902 (1966).
35. Loehr, R. C., et al., "Full-Scale Land Treatment of Coffee Processing Wastewater," *Journal Water Pollution Control Association,* **60**(11):1948–1952, 1988.
36. Ludwig, H., et al., "Disposal of Citrus Byproducts Wastes at Ontario, California," *Sewage & Industrial Wastes,* **23:**1255–1266 (1951).
37. Luley, H. G., "Spray Irrigation of Vegetable and Fruit Processing Wastes," *Journal WPCF,* **35:**1252 (1963).
38. McKee, F. J., "Spray Irrigation of Dairy Wastes," *Proceedings of the 10th Industrial Waste Conference. Purdue University,* **89:**514 (1955).
39. Madison, M., and M. Henderson, "Zero Discharge All-Weather Land Application with Soil Storage," *Proceedings of the 66th Annual Conference of the Water Environment Federation,* Anaheim, Calif., 1993.
40. Meighan, A. D., "Experimental Spray Irrigation of Strawboard Wastes," *Proceedings of the 13th Industrial Waste Conference, Purdue University,* **96:**456 (1958).
41. Molloy, D. J., "`Instant' Waste Treatment," *Water Works Wastes Engineering,* **1:**68 (1964).
42. Monson, H., "Cannery Waste Disposal by Spray Irrigation—After 10 Years," *Proceeding of the 13th Industrial Waste Conference, Purdue University,* **96:**449 (1958).
43. Moore, J. A., et al., "Treating Dairy Flush Water in a Constructed Wetlands," *Proceedings of the Seventh International Symposium on Agricultural and Food Processing Wastes,* ASAE, Chicago, Ill., 1995.
44. Nolte and Associates, *Report of Waste Discharge,* Hilmar Cheese Company, Sacramento, Calif., 1996.
45. Overcash, M. R., and D. Pal, *Design of Land Treatment for Industrial Wastes, Theory and Practice,* Ann Arbor Science Publishers, Ann Arbor, Mich., 1979.
46. Parker, R. R., "Disposal of Tannery Wastes," *Proceedings of the 22nd Industrial Waste Conference, Purdue University,* **129:**36 (1967).
47. Parsons, W. C., "Spray Irrigation of Wastes from the Manufacture of Hardboard," *Proceedings of the 22nd Industrial Waste Conference, Purdue University,* **129:**602 (1967).
48. Philipp, A. H., "Disposal of Insulation Board Mill Effluent by Land Irrigation," *Journal WPCF,* **43:**1749 (1971).
49. Pound, C. E., and R. W. Crites, *Wastewater Treatment and Reuse by Land Application,* vol. II, U.S. Environmental Protection Agency, EPA-660/2-73-006b, Washington, D.C., 1973.

50. Reed, S.C., and R.W. Crites, *Handbook on Land Treatment Systems for Industrial and Municipal Wastes,* Noyes Data, Park Ridge, N.J., 1984.
51. Reed, S. C., R. W. Crites, and E. J. Middlebrooks, *Natural Systems for Waste Management and Treatment,* 2d ed., McGraw-Hill, New York, 1995.
52. Schraufnagel, F. H., "Ridge-and-Furrow Irrigation for Industrial Waste Disposal," *Journal WPCF,* **34:**1117 (1962).
53. Scott, R. H., "Disposal of High Organic Content Wastes on Land," *Journal WPCF,* **34:**1117 (1962).
54. Smith, J. H., et al., "Treatment of Potato Processing Wastewater on Agricultural Land: Water and Organic Loading, and the Fate of Applied Plant Nutrients," in R. C. Loehr (Ed.), *Land as a Waste Management Alternative,* Ann Arbor Science Publishers, Ann Arbor, Mich., 1977.
55. Struckmeyer, T., Personal communication. Vice President Hilmar Cheese Company, Hilmar, Calif., 1999.
56. Tedaldi, D. J., and R. C. Loehr, "Performance of an Overland Flow System Treating Food-Processing Wastewater," *Research Journal Water Pollution Control Federation,* **63:**266 (1991).
57. Vela, G. R., "Effect of Temperature on Cannery Waste Oxidation," *Journal Water Pollution Control Federation,* **46**(1), 198–202 (1974).
58. Voights, D., "Lagooning and Spray-Disposal of Neutral Sulfite Semi-Chemical Pulp Mill Liquors," *Proceedings of the 10th Industrial Waste Conference, Purdue University,* **89:**497 (1955).
59. Wallace, A. T., "Land Disposal of Liquid Industrial Wastes," in R. L. Sanks and T. Asano, *Land Treatment and Disposal of Municipal and Industrial Wastewater,* Ann Arbor Science, Ann Arbor, Mich., 1976.
60. Westcot, D. W., and R. S. Ayers, "Irrigation Water Quality Criteria," in T. Asano and G. S. Pettygrove, *Irrigation with Reclaimed Municipal Wastewater—A Guidance Manual,* California State Water Resources Control Board, *Report* 84-1, 1984.
61. Woodley, R. A., "Spray Irrigation of Organic Chemical Wastes," *Proceedings of the 23rd Industrial Waste Conference, Purdue University,* **132:**251 (1968).
62. Wright, J. F., *Land Application of Citrus Wastewater,* Florida Department of Environmental Protection, State of Florida, 1993.

Chapter 14

Cost and Energy Considerations

Costs

There are eight major categories of capital costs for land treatment systems:

1. Transmission
2. Pumping
3. Preapplication treatment
4. Storage
5. Field preparation
6. Distribution
7. Recovery
8. Land

In addition, there are costs associated with monitoring, administration buildings, roads, and service and interest factors. There also may be costs for fencing, relocation of residents, and purchase of water rights. Depending on the site management, SR and OF systems may have costs associated with crop planting, cultivating, and harvesting.

Operation and maintenance (O&M) costs are associated with all of the eight categories of capital costs except for land purchase and field preparation. These O&M costs can be divided into categories of labor, power, and materials. Labor and materials for distribution and recovery are presented in this chapter. Power costs for pumping can be estimated from the energy requirements. All costs in this chapter are for July 1999 using an *Engineering News-Record* Construction Cost Index (ENRCCI) of 6076. These costs are only planning-level values and should not be used for designed system cost estimating.

Transmission

Transmission of wastewater to application sites can involve gravity pipe, open channels, or pressure forcemains. Pumping can also be involved with gravity flow transmission but is required for forcemain transmission. Costs of transmission depend on the pipe or the channel size and can be estimated using Refs. 1 and 2.

Pumping

Pumping facilities for land treatment, as described in Chap. 9, range from full pumping stations to tailwater pumping facilities (see Recovery). Capital costs for transmission pumping depend on the type of structure that is designed. For example, a fully enclosed wet well–dry well structure, pumps, piping, and valves, controls, and electrical can cost \$500,000 for a 1 Mgal/day (3785 m^3/day) peak flow and a 150-ft (45-m) total pumping head. For structures that are built into the dike of a pond, the capital cost of the pumping station for the same flow and head can be \$300,000.

Preapplication treatment

Preapplication treatment for land treatment (Chap. 8) ranges from preliminary screening to advanced secondary treatment. Where a completely new land treatment system is to be constructed, it is usually cost-effective to minimize preapplication treatment and use screening or short-detention-time ponds for overland flow (OF) and treatment ponds for slow rate (SR) and rapid infiltration (RI). Costs of preapplication can be estimated from data in Refs. 1 to 4. Many processes can be used for preapplication treatment, including wetlands or overland flow for treatment prior to RI or SR systems.

Overland flow slope construction costs include the same items as for land leveling. A cut of 500 yd^3/acre would correspond to nominal construction on preexisting slopes. A cut of 1000 yd^3/acre

Cost and Energy Considerations 323

corresponds to constructing 150-ft (45-m)-wide slopes at 2 percent slope from initially level ground. A cut of 1400 yd^3/acre corresponds to 250-ft (75-m) slope widths on 2.5 percent slopes from initially level ground.

Storage

Storage ponds vary in cost depending on initial site conditions, need for liners, and the depth and volume of wastewater to be stored. Cost data are available in Refs. 1 to 3 and 5.

Field preparation

Costs for field preparation can include site clearing and rough grading, land leveling, and overland flow slope construction. Costs of each of these types of field preparation are presented in Table 14.1 for various conditions. Site-clearing costs include bulldozing of existing vegetation, rough grading, and disposal of debris on site. Off-site disposal of debris will cost 1.8 to 2.2 times the values in Table 14.1. Land leveling costs include surveying, earthmoving, finish grading ripping in two directions, disking, equipment mobilization, and landplaning. In many cases, 200 yd^3/acre will be sufficient, while 750 yd^3/acre represents considerable earthmoving.

TABLE 14.1 Costs of Field Preparation[1]

ENR CCI = 6076

Type of cost	Capital cost, $/acre
Site clearing	
Grass only	30
Open field, some brush	220
Brush and trees	1450
Heavily wooded	2890
Land leveling	
200 yd^3/acre	360
500 yd^3/acre	720
750 yd^3/acre	1010
Overland flow slope construction	
500 yd^3/acre	1300
1000 yd^3/acre	2170
1500 yd^3/acre	2890

Distribution

Slow rate systems are capable of using a wide variety of sprinkler and surface distribution systems. In contrast, OF systems usually employ fixed sprinkler or gated pipe surface distribution and RI systems generally employ surface spreading basins.

Solid set sprinkling, described in Chap. 9, is the most expensive type of sprinkler system. As shown in Table 14.2, portable and continuous-move systems are considerably less expensive on an initial capital cost basis. Capital and O&M costs are presented in detail for solid set and center pivot sprinkling.

Solid set sprinkling. The capital and O&M costs for buried solid set systems are presented in Fig. 14.1. For the SR system in Fig. 14.1, the laterals are spaced 100 ft (30 m) apart and the sprinklers are 80 ft (24 m) apart on the lateral. Laterals are buried 18 in (0.45 m) and mainlines are buried 36 in (0.9 m). The pipe material is PVC, and the risers are galvanized steel. Flow to the laterals is controlled by hydraulically operated automatic valves. There are 5.4 sprinklers per acre at the specified spacing. If more sprinklers are included (smaller spacing), increase the capital and labor costs by using Eq. (14.1):

$$\text{Cost factor} = 0.68 + 0.06\,(S) \qquad (14.1)$$

where cost factor = multiplier times from Fig. 14.1
S = sprinklers/acre

For overland flow, the slopes are 250 ft (75 m) wide at a 2.5 percent grade. The laterals are 70 ft (21 m) from the top of the

TABLE 14.2 Comparison of Sprinkler Distribution Capital Costs[5]

Sprinkler type	Comparative cost
Portable hand move	0.13
Traveling gun	0.22
Side roll	0.22
Center pivot	0.50
Linear move	0.65
Solid set	1.00

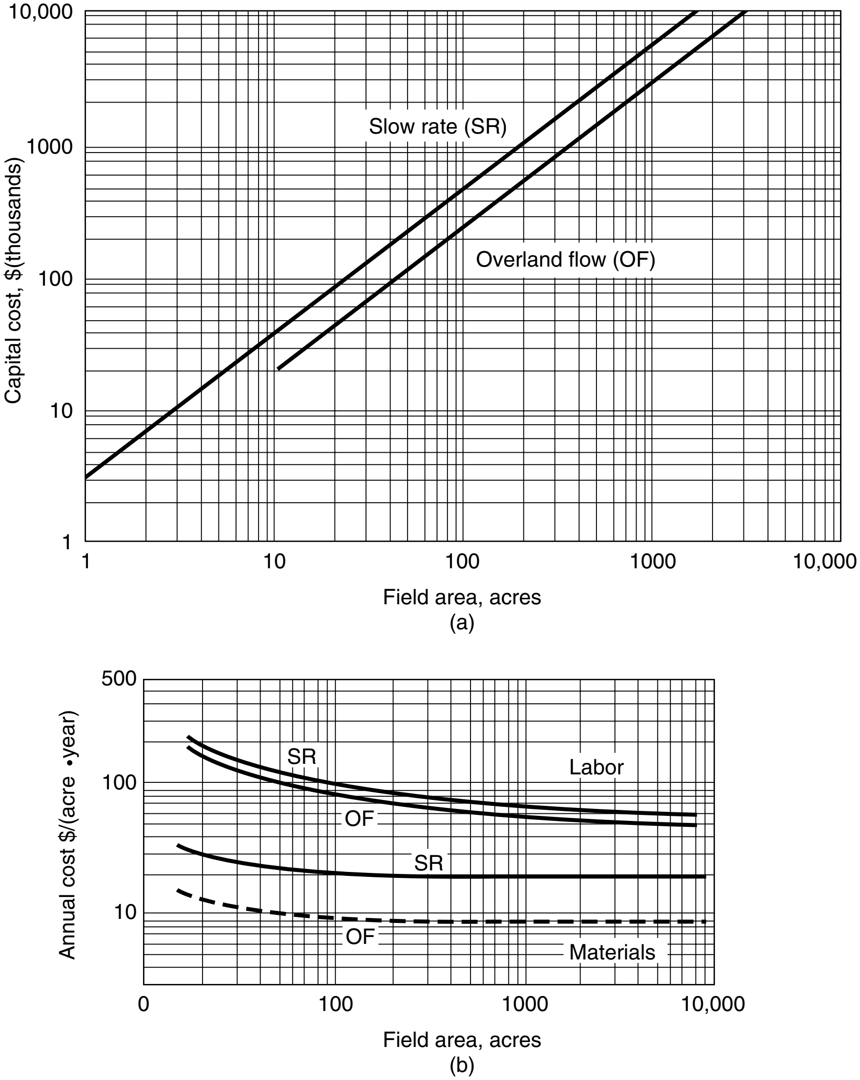


Figure 14.1 Solid set sprinkling (buried) costs, ENR CCI = 6076. (*a*) Capital cost; (*b*) operation and maintenance cost.

slope, and sprinklers are 100 ft (30 m) apart. Other factors are the same as for the SR system.

For O&M, the labor rate is $15/h including fringes. Materials cost includes replacement of sprinklers and valve controllers every 10 years.

Center pivot sprinkling. Capital and O&M costs for center pivot sprinkling are given in Fig. 14.2. The center pivot machines are electrically driven and heavy-duty units. Multiple units are included for areas over 40 acres (16 ha) with a maximum area per unit of 132 acres (53 ha). Distribution piping is buried 3 ft (0.9 m).

Labor costs are based on \$15/h and power costs are based on 3.5 days/week operation for each unit and \$0.08/kWh. Materials cost includes minor repair parts and overhaul of units every 10 years.

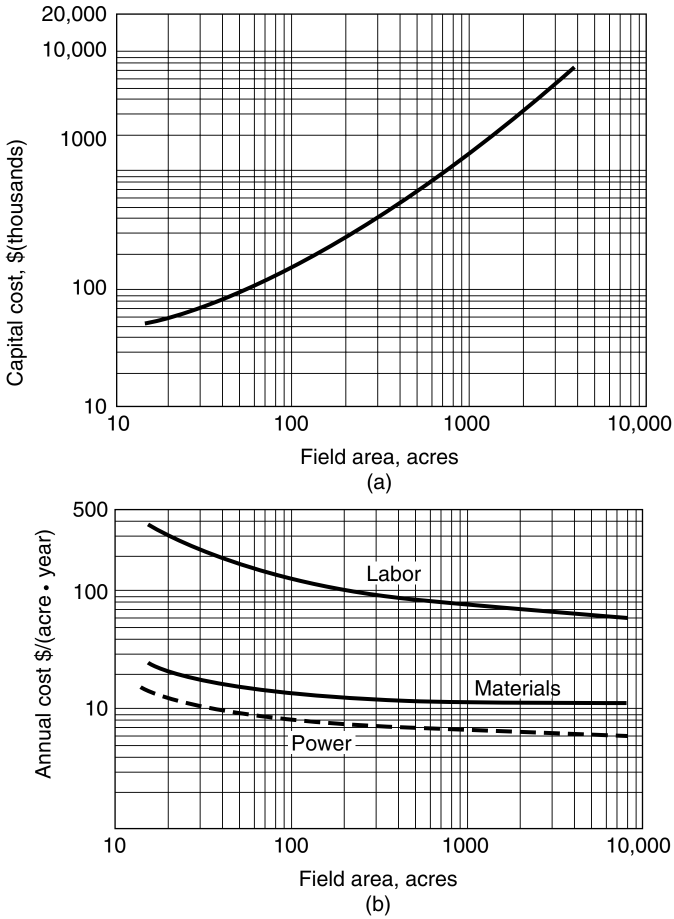


Figure 14.2 Center pivot sprinkling costs, ENR CCI = 6076. (*a*) Capital cost; (*b*) operation and maintenance cost.

Surface distribution for OF or SR. Costs for gated pipe distribution for OF and SR systems are presented in Fig. 14.3. The OF slope is 200 ft (60 m) wide with the gated aluminum pipe distribution at the top of the slope. For SR systems, the furrows or borders are 1200 ft (360 m) long on rectangular-shaped fields. Graded border systems, under similar conditions of border length, can use buried pipelines with alfalfa valves (see Fig. 9.6) at similar capital costs.

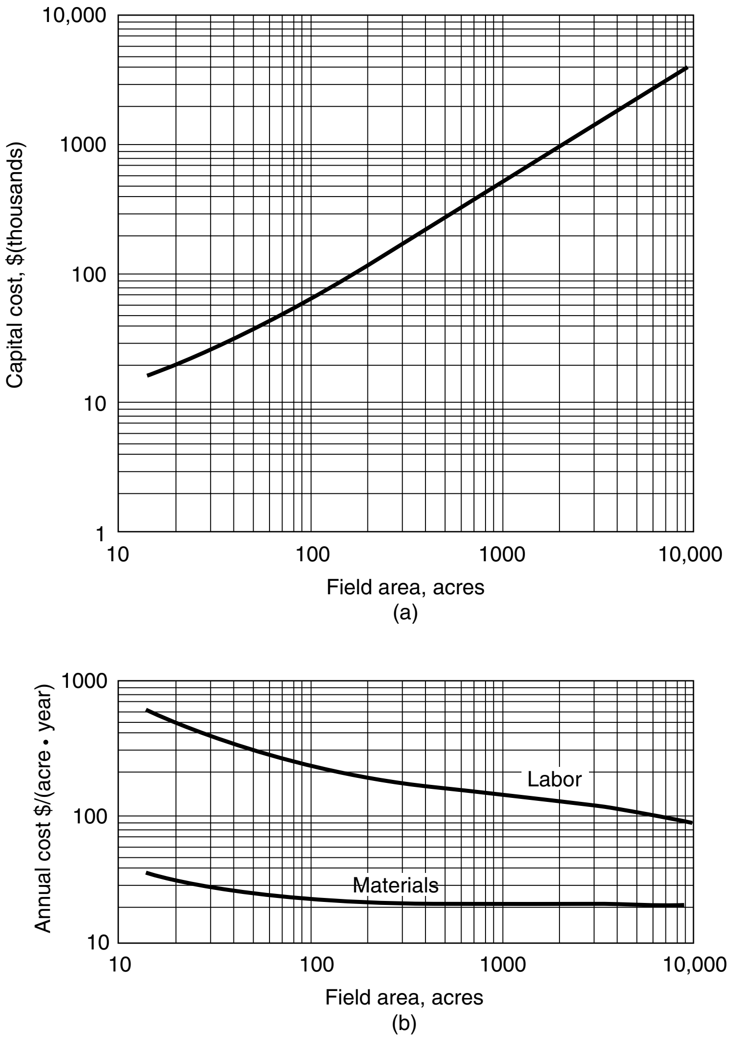


Figure 14.3 Gated pipe—overland flow or ridge-and-furrow slow rate costs, ENR CCI = 6076. (*a*) Capital cost; (*b*) operation and maintenance cost.

Labor costs are based on a \$15/h wage including fringes. Materials cost includes replacement of gated pipe after 10 years.

Rapid infiltration basins. Costs for RI basins are presented in Fig. 14.4. There are a minimum of 2 basins and a maximum basin size of 20 acres (8 ha). Costs include inlet and outlet control structures and control valves. Dikes are 4 ft (1.2 m) high with an inside slope of 3:1, an outside slope of 2:1, and a 6-ft-(1.8-m)-wide dike crest. Dikes or berms are formed from excavated native material. Labor costs are based on a \$15/h wage including fringe benefits. Materials cost includes rototilling or disking the basin surface every 6 months and major repair of the dikes every 10 years.

Recovery

Recovery systems can include underdrains (for SR or RI), tailwater return for SR surface application, runoff collection for OF, and recovery wells for RI.

Underdrains. Costs for underdrain systems are presented in Table 14.3 for spacings between drains of 100 and 400 ft (30 and 120 m). Drains are buried 6 to 8 ft (1.8 to 2.4 m) deep and discharge into an interception ditch along the length of the field.

Labor costs are based on a \$15/h wage rate including fringes, and labor involves inspection and unclogging of drains at the outlets. Materials cost includes high-pressure jet cleaning of drains every 5 years, annual cleaning of interception ditches, and major repair of the interception ditch after 10 years.

Tailwater return. Tailwater from ridge-and-furrow or graded border systems must be recycled either to the storage ponds or to the distribution system. Typically 25 to 30 percent of the applied flow should be expected as tailwater. Capital costs, presented in Table 14.4, include drainage-collection ditches, storage sump or pond, pumping facilities, and a 200-ft (60-m) return forcemain. Labor, at \$15/h including fringe benefits, includes operation of the pumping system and maintenance of the ditches, sump, pump, and return system. Materials cost includes major repair of the pumping station after 10 years. Power cost is based on \$0.08/kWh.

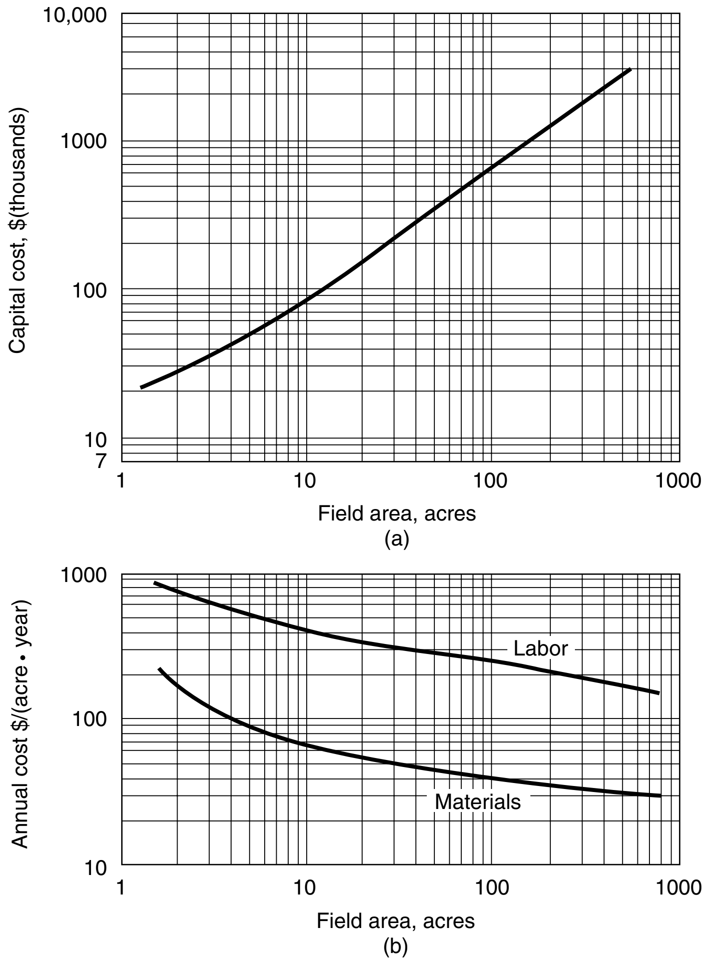


Figure 14.4 Rapid infiltration basin costs, ENR CCI = 6076. (*a*) Capital cost; (*b*) operation and maintenance cost.

Runoff collection for OF. Runoff collection can consist of an open ditch or a buried pipeline with inlets. Costs for open ditches, presented in Table 14.5, include a network of ditches sized for a 2-in/h storm, culverts under service roads, and concrete drop structures every 1000 ft (300 m) (for larger systems). For gravity pipe systems, the costs include a network of interceptor pipes with inlets every 250 ft (75 m) and accessholes every 500 ft (150 m).

Labor costs are based on $15/h including fringe benefits. Materials cost includes biannual cleaning of ditches and major repair every 10 years.

TABLE 14.3 Costs of Underdrains[1]

ENR CCI = 6076

Type of cost	$/acre
Capital costs:	
100-ft spacing	2890
400-ft spacing	1090
O&M costs:	
Labor	
100-ft spacing	52
400-ft spacing	22
Materials	
100-ft spacing	140
400-ft spacing	90

TABLE 14.4 Costs of Tailwater Return Systems[1]

ENR CCI = 6076

Type of cost	Cost
0.1 Mgal/day of recovered water:	
Capital, $	60,000
O&M:	
Power, $/year	375
Labor, $/year	375
Materials, $/year	180
1.0 Mgal/day of recovered water:	
Capital, $	145,000
O&M:	
Power, $/year	4,000
Labor, $/year	900
Materials, $/year	700

Recovery wells. Costs for recovery wells for RI systems are presented in Table 14.6 for well depths of 50 and 100 ft (15 and 30 m). Capital costs include gravel-packed wells, vertical-turbine pumps, simple shelters over each well, controls, and electrical work. Labor, at $15/h, includes operation and preventive maintenance. Materials cost includes repair work performed by contract, and replacement of parts. Power cost is based on $0.08/kWh. Monitoring wells are generally a minimum of 4 in (100 mm) in diameter and typically cost $40 to $60/ft ($130 to $200/m).[1]

TABLE 14.5 Costs of Runoff Collection for Overland Flow[1]

ENR CCI = 6076

Type of cost	$/acre
Capital costs:	
Gravity pipe system	2300
Open ditch system	360
O&M costs:	$/acre·year
Labor	
Gravity pipe	8
Open ditch	30
Materials	
Gravity pipe	7
Open ditch	40

TABLE 14.6 Costs of Recovery Wells[1]

ENR CCI = 6076

Type of cost	Cost
1.0 Mgal/day of recovered water:	
Capital, $:	
50-ft depth	29,000
100-ft depth	50,000
O&M, $/year:	
Power, 50-ft depth	9,500
Power, 100-ft depth	18,900
Labor	6,000
Materials	800

Land

Land can be controlled by direct purchase, lease, or contract. The land for preapplication treatment and storage is usually purchased; however, field area for SR systems is sometimes leased or a contract is formed with the landowner. Options used by selected communities for land acquisition and management for selected SR systems are presented in Table 14.7. As shown in Table 14.7, contracts for effluent use are utilized in several SR systems. Fee simple purchase is generally used for OF and RI sites.

TABLE 14.7 Options for Land Acquisition and Management at Selected SR Systems[6,7]

Location	Area, acres	Acquisition option	Management option
Bakersfield, Calif.	2,400	Fee simple	Leaseback to farmer
Camarillo, Calif.	475	Contract	Landowner accepts water
Dickinson, N.Dak.	250	Contract	Cash lease for water sale to farmer
Lubbock, Tex.	4,000	Fee simple and contract	Leaseback, farmer owns effluent
Mesa, Ariz.	160	Fee simple	Leaseback for cash rent
Muskegon, Mich.	10,400	Fee simple	Managed by county
Petaluma, Calif.	550	Contract	Cash rent for irrigation equipment
Roswell, N.Mex.	285	Contract	Cash lease for water sale to farmer
San Antonio, Tex.	740	Fee simple	Managed by city
Tooele, Utah	1,200	Contract	Cash lease for water sale to farmer

Land application of biosolids

The principal costs involved in land application of liquid or dewatered biosolids are for hauling and applying the biosolids. Truck hauling is the most popular method of transport, especially for small- to medium-sized facilities. Cost factors for trucking biosolids are presented in Table 14.8.[9]

Benefits

Revenue-producing benefits from land treatment systems can include sale of crops, lease of land, sale of wastewater or recycled water, and contracts that may involve all of these benefits. Examples of revenue-producing benefits are presented in Table 14.9. The examples are for SR systems, which generally have the greatest potential for revenue production. Crop sale from OF systems can offset a small portion of O&M costs but generally cannot be expected to more than offset the cost of harvesting and removal of the grass or hay. For RI systems in water-short areas, the potential for recovery and reuse of the percolate should be investigated.

TABLE 14.8 Capital and Operating Costs of Sludge Hauling[8]

ENR CCI = 6076

Sludge type	Truck type	Capacity	Capital costs, $ × 1000	Operation costs, $/mile
Liquid	Tank truck	1200 gal	65–70	0.57
		2500 gal	110–125	0.75
		5500 gal	165–190	0.87
Dewatered	Dump truck	8–10 yd^3	65–70	0.57
		10–15 yd^3	125–130	0.75
		15–25 yd^3	140–160	0.87
	Bottom dump truck	25 yd^3	180–200	1.05

TABLE 14.9 Benefits of Land Treatment Systems[5–10]

Sale of crops	$/year
Muskegon, Mich.	900,000–1,000,000
San Angelo, Tex.	58,000–71,000
Lease of land	**$/acre·year**
Bakersfield, Calif.	80
Coleman, Tex.	5
Manteca, Calif.	40
Mesa, Calif.	50
Winters, Calif.	20
Sale of effluent	**$/acre·ft**
Cerritos, Calif.	40
Irvine Ranch, Calif.	118
Las Virgines, Calif.	160
Marin MWD, Calif.	300

Sale of crops can be a significant source of revenue if the community is willing to invest in the necessary equipment for crop harvest and storage. For example, Muskegon County realized gross revenues of $1,000,000 from the sale of corn.[10]

Cash rent for SR cropland is very popular in the west, with 5-year agreements being common. Rents range from $5 to $80/acre ($2 to $32/ha). Contracts for wastewater irrigation, rental of irrigation equipment, or the use of pastureland for cattle grazing have also been utilized. Examples include El Reno, Okla.; Dickinson, N.Dak; Mitchell, S.Dak.; Tuolumne County, Calif.; Santa Rosa, Calif.; and Petaluma, Calif.[8,12]

Energy Requirements

The energy requirements for land treatment systems include power for pumping, preapplication treatment, wastewater distribution, and fuel for crop planting and harvesting and for biosolids transport and spreading. In addition, energy is needed for heating and cooling of buildings, lighting, and vehicle operation.

Pumping

Pumping for transmission, distribution, tailwater return, and recovery is a major energy use in most land treatment systems. The energy required can be calculated using Eq. (14.2):

$$\text{Energy use} = \frac{(Q)\,(TH)\,(t)}{(F)\,(E)} \tag{14.2}$$

where energy use = annual usage, kWh/year
Q = flow rate, gal/min
TH = total head, ft
t = pumping time, h/year
F = constant, $3960 \times 0.746 = 2954$
E = overall pumping efficiency, decimal

The overall efficiency depends on the type of wastewater and the specifics of pump and motor selection. In the absence of specific information on pump and motor efficiency, the following overall pumping system efficiencies can be used:

Raw wastewater	0.4
Primary effluent	0.65
Secondary effluent, tailwater, recovery of groundwater	0.75

Land treatment of wastewater

Distribution energy can be calculated using Eq. (14.2). Energy for preapplication can be estimated from Refs. 13 and 14. Energy for crop production is minor compared to energy for distribution. For example, energy requirements for corn production are 5.7 kWh/acre and for alfalfa are 2.5 kWh/acre. Fuel usage can be converted to energy using 124,000 Btu/gal for gasoline and 14,000 Btu/gal for diesel.[13,15]

Land application of biosolids

Transport and spreading of biosolids requires fuel for energy. For example, if 5 million gallons per year of liquid biosolids is hauled 20 mi (12 km) (one-way distance) in a 2500-gal (9463-L) capacity truck, a total of 80,000 mi/year would be driven. If the truck gets 4.5 mi/gal of diesel, the 17,800 gal/year of fuel would be equivalent to 2.5×10^9 Btu/year.

Energy Conservation

Sprinkler distribution systems are candidates for energy conservation. Impact sprinklers may require 150 to 200 ft (45 to 60 m) of head to operate. Recent advances have been made in sprinkler nozzle design to allow operation at lower pressures without sacrificing uniformity of application. Use of drop nozzles with pressure requirements of 50 ft (15 m) of head can result in significant energy conservation.

Energy conservation is also possible in land treatment systems through the use of surface distribution. A comparison of primary and secondary energy usage of various land and aquatic treatment systems is presented in Table 14.10.

Energy conservation through the use of land application of wastes can also be realized through savings in energy use for manufacturing of commercial fertilizer. A presentation of energy needs to produce fertilizer, and the energy value of nutrients in wastewater is given in Table 14.11.[15]

TABLE 14.10 Energy Requirements for Land and Aquatic Treatment Systems[3]

Equivalent energy, 1000 kWh/year

System	Primary energy	Secondary energy	Total energy
PT + RI	187	102	289
Ponds and wetlands	121	198	319
PT + SR(surface)	187	135	322
PT + OF	192	159	351
Ponds and hyacinths	167	195	362
PT + SR(spray)	327	173	500

PT = primary treatment; RI = rapid infiltration; SR = slow rate, and OF = overland flow.

TABLE 14.11 Energy Value of Nutrients in Wastewater[14]

Nutrient	Content of effluent, mg/L	Content of effluent, lb/(acre·ft)	Energy to produce, transport, and apply fertilizer, kWh/lb	Energy value of nutrients in wastewater, kWh/(acre·ft)
Nitrogen as N	20	54	2.79	190
Phosphorus as P	10	27	0.10	13
Potassium as K	15	38	0.10	10

References

1. Reed, S. C., R. W. Crites, R. E. Thomas, and A. B. Hais, “Cost of Land Treatment Systems,” U.S. Environmental Protection Agency, EPA 430/9-75-003, Washington, D.C., 1979.
2. U.S. Environmental Protection Agency, “Construction Costs for Municipal Wastewater Conveyance Systems: 1973–1979,” EPA 430/9-81-003, Washington, D.C., 1981.
3. Tchobanoglous, G., J. E. Colt, and R. W. Crites, “Energy and Resource Consumption in Land and Aquatic Treatment Systems,” *Proceedings Energy Optimization of Water and Wastewater Management for Municipal and Industrial Applications Conference,* U.S.DOE, vol. 2, New Orleans, 1979.
4. Richard, D., T. Asano, and G. Tchobanoglous, The Cost of Wastewater Reclamation in California, Department of Civil and Environmental Engineering, University of California, Davis, 1992.
5. Crites, R. W., “Costs of Constructed Wetlands,” *Proceedings WEFTEC ‘98,* Orlando, Fla., Water Environment Federation, Alexandria, Va., 1998.
6. Crites, R. W., “Economics of Reuse,” *Proceedings Water Reuse Symposium II,* vol. 3, AWWA, pp. 1745–1751, 1981.
7. Christensen, L. A., *Irrigating with Municipal Effluent,* U.S.D.A, ERS-672, Washington, D.C., 1982.
8. Crites, R. W., Innovative and Alternative Treatment at Petaluma, CA, presented at the Hawaii Water Pollution Control Association Annual Conference, Honolulu, Hawaii, 1982.
9. U.S. Environmental Protection Agency, *Process Design Manual—Land Application of Sewage Sludge and Domestic Septage,* EPA/625/R-95/001, Washington, D.C., 1995.
10. Walker, J. M., “Wastewater: Is Muskegon County’s Solution Your Solution?” U.S. Environmental Protection Agency, EPA-905/2-76-004, Washington, D.C., 1979.
11. Roy F. Weston, Inc., “Operation and Maintenance Considerations for Land Treatment Systems,” EPA-600/2-82-039, 1982.
12. National Association of Conservation Districts, “The Role of Conservation Districts and the Agricultural Community in Wastewater Land Treatment,” EPA-430/9-77-011, 1981.
13. Wesner, G. M., et al., “Energy Conservation in Municipal Wastewater Treatment,” EPA-430/9-77-011, 1978.
14. Middlebrooks, E. J., and C. H. Middlebrooks, “Energy Requirements for Small Flow Wastewater Treatment Systems,” U.S.A. CRREL, *Special Report* 79-7, 1979.
15. Water Pollution Control Federation, “Energy Conservation in the Design and Operation of Wastewater Treatment Facilities,” *Manual of Practice* No. FD-2, 1981.

Chapter

15

Operation, Maintenance, and Monitoring

The proper operation and maintenance (O&M) of land treatment systems is essential for the realization of performance expectations. Land treatment systems are less labor-intensive than conventional wastewater technologies. However, a broader range of skills may be required for those land treatment systems that incorporate an agricultural or silvicultural component.

The major focus of this chapter is on the unique aspects of O&M and monitoring for land treatment systems. The mechanical elements (i.e., pumps, valves, etc.) that are common to all wastewater systems are not discussed.

Slow Rate Systems

The type of SR system can range from a remote forested site with no public access to a golf course or park with frequent public use. Agricultural systems can be managed by the industry or the municipality, or the wastewater can be delivered to private farmers for their use. Each of these systems will have different requirements for O&M. Both the type of system and the management plan are determined during design, but there is the potential for subsequent change. For example, a change from forest to crop production or a decision to allow public access on the site may then require higher levels of pretreatment and disinfection.

Staffing requirements

The number of operating personnel and the skill levels required will depend on the type of system and on its size. Figure 15.1 presents an estimate of the personnel needs of typical municipal SR land treatment systems. The figure shows the approximate number of hours per day for the smaller systems and the number of full-time employees required for the larger systems. These estimates are for a "typical" system; an agricultural operation producing row crops will require more time for O&M than indicated, a forested site will require less.

General skills

The general skills required for routine operation of all types of SR systems are essentially the same as those needed for routine

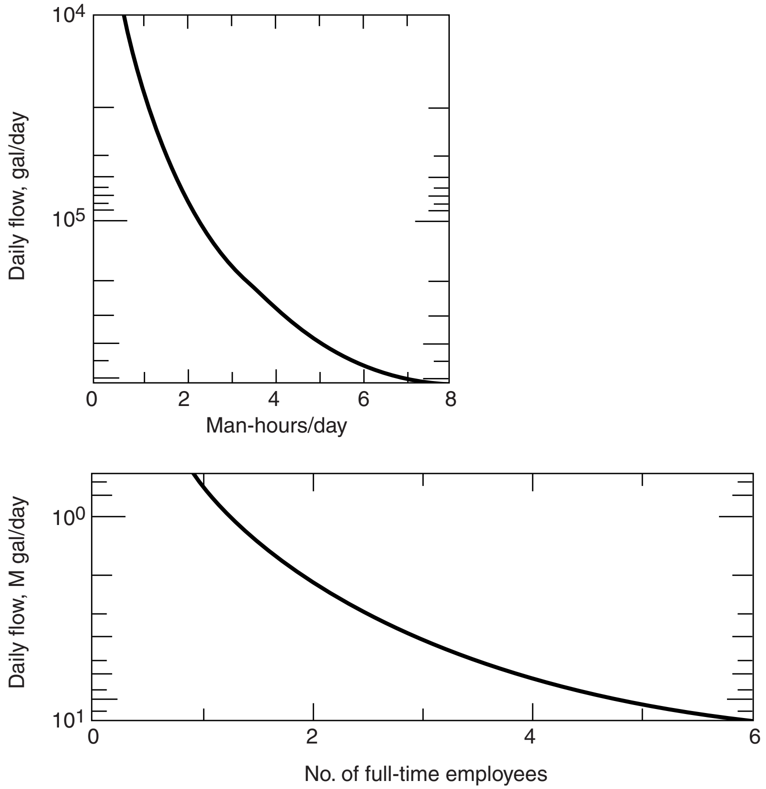


Figure 15.1 Personnel needs for land treatment portion of SR systems. (*After Ref. 5.*)

operation of any simple waste treatment system. A unique requirement for SR land treatment is deciding when to turn the water on and off or when to switch the application to a different part of the site. A basic program and schedule of operations will have been determined for each project during final design. However, this may require adjustment by the operator if flow increases, if a year is especially wet or dry, or if the vegetation used in the system is changed.

Special skills

The operator of a forested site will sometimes need expert advice to help with problems such as insect infestations or plant diseases, or to determine which trees to cull or when to clear-cut. The operator of an agricultural site will require all of the farming skills normally associated with the particular type of crop (pastures, hay crops, or row crops).

Recreational sites require particular attention to water quality to maintain adequate health protection. In addition, the wastewater application scheduling for recreational sites requires careful control so as not to interfere with recreational activities. That will usually involve nighttime or off-season application. Many recreational sites will include a carefully maintained turf-grass cover.

Process control and monitoring

The information needed for operation of the system is obtained through the monitoring program. Monitoring needs can be divided into two categories. There is compliance monitoring to certify that the system is meeting the requirements of the federal, state, and local agencies that are responsible. There is also routine process monitoring to ensure that all internal components in the system are functioning as designed. This type of monitoring is necessary if regulatory requirements do not exist. However, it is often possible to satisfy both regulatory and operating needs at the same time if the monitoring program is planned carefully.

Compliance monitoring. The federal government and all states have regulations controlling discharges to surface waters. Land treatment systems that collect the treated water with underdrains or wells and then discharge it to surface waters will need a permit, as will most overland flow systems. Although a discharge permit may not be required for the case where the treated water remains in the ground or emerges into surface water at some remote place, these systems are not ignored by the regulatory agencies. Many states now require permits to discharge to groundwater. Their criteria range from very specific regulations that have the force of law, to general guidelines that may be strongly recommended but which are more flexible in application than regulations. There are also case-by-case determinations that depend on the site conditions and operational plan of a particular system.

The U.S. Environmental Protection Agency guidelines for the level of preapplication treatment believed suitable for various types of land treatment systems are given in Table 8.1. All of the 50 states have an interest in and some level of control over the monitoring of land treatment systems, even if there is no surface discharge. The monitoring requirements for a particular system will have been determined during design and will be written into the O&M manual.

Monitoring requirements. The majority of states are concerned about the quality of the wastewater to be applied, and many have specific regulations or guidelines. Groundwater protection is a case-by-case concern, and it depends largely on the groundwater use in the vicinity of the facility and the classification of the aquifer. Monitoring of the soil is usually of the process-control type to make sure the system operates properly or to warn of long-term effects that might inhibit the future use of the site for other purposes. Crops may also be monitored for operational purposes. The potential for aerosol contamination is of little concern to most state agencies, except on a case-by-case basis for recreational operations and those that are close to the public.

A typical example of the type and frequency of monitoring required for applied wastewater is shown in Table 15.1. The BOD, pH, nitrogen, and phosphorus are familiar water-quality parameters tested in most systems. Many other parameters (metals, etc.) are not shown in Table 15.1. Either they are not generally present in sufficient concentration in the typical domestic-municipal wastewaters or their presence has no direct effect on the proper operation of the system.

TABLE 15.1 Typical Monitoring Schedule for Applied Wastewater

	Size of system, mgd	
Parameter	0–1.0	>1.0
BOD	Q	M
Suspended solids (SS)	Q	M
pH	Q	W
Kjeldahl-nitrogen	Q	W
Ammonium-nitrogen	Q	M
Nitrate-nitrogen	A	M
Phosphorus	A	Q
Potassium	A	Q
Sodium	A	Q
Calcium	A	Q
Magnesium	A	Q
Chloride	A	M
Total dissolved solids	A	M

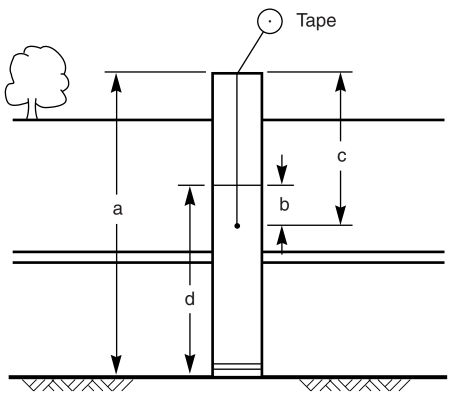
Q = quarterly, A = annually, M = monthly, and W = weekly.

Groundwater monitoring. Groundwater is usually monitored at the system boundaries when the quality of drinking water aquifers is a factor. Nitrate-nitrogen (NO_3-N) is the parameter of greatest concern, but it is advisable to measure the organic and ammonium nitrogen as well because they can be oxidized subsequently to nitrate-nitrogen. In general, SR systems that can remove enough nitrogen to meet drinking water standards at the project boundaries will also remove all of the other constituents of concern in typical municipal wastewaters. Frequent sampling is not necessary because groundwater moves relatively slowly and rapid changes in quality will not be observed. Samples taken once or twice per year should be sufficient. The design of those systems that operate only seasonally should include an estimate of the travel time for the percolate to reach the project boundary, and the sampling operation should be scheduled accordingly.

Since there may be little vertical mixing of the groundwater and the system percolate, the sampling depth of the monitoring wells must be carefully selected during design. Wells that are too deep will probably not obtain samples that have been influenced by the land treatment operation. The location and depth of monitoring wells should be determined during design. However, it may be necessary to add new wells if operational conditions change or if groundwater levels were not properly determined during design. Figure 7.4 illustrates the design features for a typical shallow monitoring well that, depending on soil conditions, could be installed to depths of 10 to 15 ft (3 to 4.5 m) by the system operator. Deeper wells will generally require mechanical drilling techniques.

Groundwater monitoring wells are sometimes installed within the application site as well as at the project boundaries. These wells monitor performance immediately beneath the application site and measure the depth to groundwater under the application site. Figure 15.2 illustrates one relatively easy technique for measuring the depth to water in monitoring wells. Since samples are taken infrequently from these monitoring wells, the water standing in the casing will not be representative of the true groundwater quality. At least three casing volumes should be pumped, or removed with a well bailer, prior to well sampling.

The location of monitoring wells is based on the determination of the groundwater flow direction made during system design. As shown in Fig. 15.3, the perimeter wells are installed on the



a = top of casing elevation above datum
b = length of wetted tape
c = tape reading — read exactly at the top of the casing
d = piezometric head, relative to a given datum
c-b = dtw (depth to water)
a-dtw = d (piezometric head at the center of the screen, relative to indicated datum plane).

Figure 15.2 Water-level determination in observation wells. (*After Ref. 2.*)

hydraulic downgradient of the site. In addition a monitoring well should be installed on the upgradient side to measure water quality before the groundwater flows beneath the site.

Measuring the groundwater elevation in these wells can confirm that the direction of flow is as predicted in design. Springs or seeps in unexpected locations after the system starts up are usually a sign of groundwater movement, and additional wells may be needed in those directions.

Storage ponds

Many of the newer SR systems combine preapplication treatment and storage in a single pond system. Monitoring needs include regular measurement of water level in the storage pond

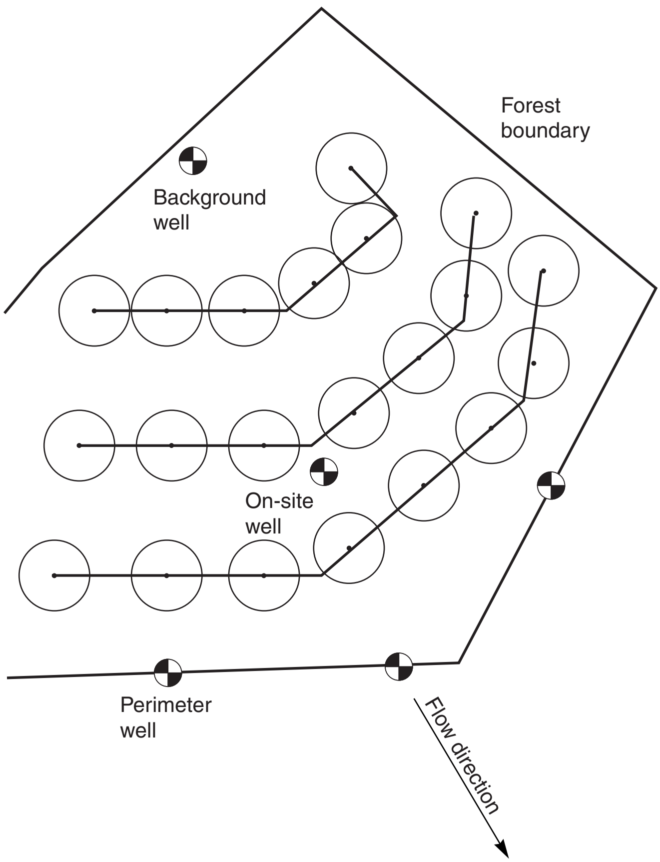


Figure 15.3 Typical monitoring well layout. (*After Ref. 5.*)

as well as water-quality tests just before and during the period of land application.

Water level in the pond should be measured at least weekly during the operating season. The method of observation can range from a simple marker board or staff gauge visually observed, to automatic, and sometimes transmitting, water-level recorders. Direct observation by operators is recommended, even if automated equipment is installed, to allow them to also observe dikes and other pond structures.

In any particular year there may be more or less water in the storage pond than was predicted during design owing either to changes in wastewater flows or to extremes in precipitation. The operator must then revise the application schedule accordingly to make certain that the vegetation on the site gets enough water and also to achieve the specified pond water level at the end of the season. Usually, the pumping system has been designed to deliver a certain flow and is not adjustable. However, the operator can vary the operating time for the pumps, start the application season earlier, extend it, or change the amount of water put on particular parts of the site. Suggestions for appropriate action on each case are listed below.

Operation procedures for more water than normal in storage

1. Forest, pasture, and hay crop sites. Start application earlier (as soon as frost is out of the ground) and extend the season into late fall. If different soils exist, apply more water to areas with coarser soils by increasing pumping time. Apply more water to the entire site by increasing pumping time, but do not allow ponding or runoff of wastewater.
2. Agricultural row crops. Continue application for longer period after crop harvest. Consult with the county agricultural extension agent and plant a more water-tolerant crop that year. Increase application to the maximum amount recommended by the extension agency for the crop grown. Plant a rye grass mixture on the coarsest soils on the site. Continue normal row cropping and application practice on the rest of the site. Apply at the highest possible rates on the grassed plot, and plow under the grass and return to normal practice the following year.

3. Recreational sites. Increase the application period to the maximum possible without interfering with public access, and/or restrict access to a portion of the site and apply at higher rates on that portion, and continue application after the recreational season has ended.

Operation procedures for less water than normal in storage

1. Forest, pasture, and hay crop sites. In arid climates, reduce the amount to be applied per week but continue applications to the whole site. In humid climates, take a portion of the site out of service; continue the application on the rest at design rates. If vegetation on the out-of-service portion shows stress, then apply some water.
2. Agricultural row crops. In both arid and humid climates, calculate how much water is available for application, and determine the water needs per acre of the crop to be grown. Plant only the number of acres that can be supported with available flow.
3. Recreational sites. Reduce the amount to be applied per week but continue applications to the whole site. In dry climates this will probably require extra water the following year to leach salts from the root zone if the application has been reduced severely.

Application site monitoring

Monitoring at the application site is necessary to ensure that the system operates properly. Monitoring tasks will include observing the sprinklers, pumps, and other mechanical equipment and determining soil fertility and crop quality at agricultural sites. These requirements usually apply to all sites and essentially consist of routine visual observations and record keeping. With seasonally operated systems it is essential to know when the soils thaw in the spring and when they freeze in the winter if these factors control the application schedules developed during design. The actual time of freezing and thawing will vary from year to year and may be different than the design assumptions. An especially heavy rainfall during the application season may require adjustment in the routine weekly schedule. If the amount of rainfall from a single storm or closely spaced storms is equal to the amount of wastewater scheduled for application, it may be necessary to delay application for a few days so that there is no runoff. The operator must also observe areas where there might be ponding in low spots. These shallow puddles can lead to odor and insect problems and must be eliminated. Watching the sprinkler patterns will reveal clogged nozzles or other mechanical problems in the system. If the site is underdrained, the drain outlets should be routinely inspected to make certain that they are flowing. If monitoring wells exist on the site, the depth of water in the well should be regularly measured. In general, if the groundwater table gets within 5 ft (1.5 m) of the surface, wastewater applications should be temporarily reduced or stopped.

Longer-term monitoring is to ensure soil fertility and good crop quality, and this requires periodic sampling and testing. Table 15.2 presents a suggested monitoring program for the soils at an agricultural site. The number of samples taken will depend on the number of different soil types at the site and the size of the site. Specific guidance can be obtained from the county agricultural extension agent, but for the general case there should be a composite soil sample representing each of the major soil types.

TABLE 15.2 Soil Monitoring on Agricultural Sites[5]

Annual sample and test	Baseline and every 5 years
pH (for lime or gypsum needs)	pH (for lime or gypsum needs)
Available phosphorus	Nitrogen
Exchangeable/extractable	Cation exchange capacity, % organic matter
Potassium	Exchangeable/extractable
Sodium	Potassium
Magnesium	Phosphorus
Calcium	Copper
	Zinc
	Nickel
	Cadmium
	Total
	Boron
	Copper
	Zinc
	Nickel
	Cadmium

Baseline samples should be taken and tested either during the final stages of design or just before the system is put into operation. A pH determination is needed to see if lime or gypsum is required to adjust soil pH for the crop to be grown (see Fig. 7.16). Phosphorus and potassium results are needed to decide if supplemental fertilization is required. These tests should be repeated annually for high-value crops; however, once every 3 years is suitable for hay and similar crops. The county agricultural extension agent can help interpret these results and tell the operator how to correct any problems.

Table 15.3 lists the suggested parameters and frequency of tests for vegetation monitoring at agricultural sites. If a system is designed for nitrogen or phosphorus removal, then the total nitrogen and phosphorus concentration in the harvested crops should be measured and crop yield should be determined. This will allow calculation of removal performance by the crop to ensure that the system is functioning as designed. If forage grasses or silage are the crop and if these are fed to livestock, then high nitrate content in grasses may cause health problems in the livestock. The analysis may be important if wastewater with a high nitrogen content ($>$30 mg/L) is used and if the application season has been unusually wet and cool. The county agricultural extension agent should be consulted for advice on the testing need in a particular year. The vegetation should be tested for the metals listed in Table 15.3 at the same frequency as the soil tests to establish long-term trends.

The number of samples required for these tests and the part of the plant to sample are critical to the reliability of results. Hay cuttings and green chop for silage from small fields can be sampled immediately after harvest, since a representative composite sample can be obtained from the mixed materials. Large or scattered fields and other crops should be sampled in the field

TABLE 15.3 Vegetation Monitoring on Agricultural Sites[5]

Component	Frequency
Total nitrogen and phosphorus	Annual sample if N or P removal is required by system
Nitrate (NO_3) for forage grasses and silage	At harvest if recommended by extension agent for livestock protection
Copper, zinc, nickel, cadmium	At first harvest and every 5 years thereafter to establish trends.

with recommended sampling patterns. It is best to sample the leaves rather than the plant fruits, since the leafy matter will usually show increase in metal content first and thereby given an earlier warning of potential problems. Table 15.4 recommends techniques for vegetation sampling.

Routine operating procedures. Factors of concern include application rates and schedules, crop management, and the unique requirements for forested and recreational sites.

Application rates and schedules. Control of the water to be applied is common to all systems and requires the following operator decisions:

- Startup and shutdown schedule
- Quantity of wastewater to be applied each shift
- Frequency of application
- Field or section to be used

The details of these decisions may change from year to year depending on the climate, rainfall, and type of crop, but the final result must be to apply the total amount of wastewater required during the application season. A specific program will have been formulated during design, and instructions will be included in the O&M manual. However, the operator must have the knowl-

TABLE 15.4 Vegetation Sampling—Field Pattern and Plant Part[5]

Crop	Pattern	Plant part
Alfalfa	× diagonals of field, 50–100 clumps	Upper stem cutting in early flower stage
Corn	× diagonals or along row at least 50 plants into field	Center one-third of leaf, just below lower center; at full tassel
Wheat and grains	× diagonals, 200 or more leaves	First four leaf blades from top of plant
Grass and sod	× diagonals	Clippings or whole tops
Soybeans	Random leaves from at least 5% of plants, 50–100 leaves	Youngest mature leaves, after pod formation
Tree fruits	× diagonals in orchard, one leaf from north, south, east, and west sides of tree	Mature leaves, shoulder height, 8–12 weeks after full bloom

edge and the capability to alter the schedule to accommodate special conditions.

Year-round operations. At sites where the wastewater is treated year-round and where there is usually little storage volume, the operator has little flexibility to make adjustments. The daily land treatment applications must match the daily wastewater flow. In most cases the operator can decide which field to use and how long to continue the application to that field. During the startup phase the operator should use the schedule provided by the design engineer. However, the design is often based on average site conditions. The operator should carefully watch each area to see if the water is rapidly infiltrating, ponding, or running off. Some parts of the site may be able to take more water than the design value and some parts less. The operator can then make adjustments to put more water on the better soils and less on the poorer locations.

Seasonal flow operations. Systems where the wastewater flow is seasonal are not uncommon. These might include camp grounds, ski resorts, and seasonal industries. Wintertime flow in cold climates will usually require wastewater storage for land application in the warm months. Operators need to know the dimensions of the pond, the length of the application season, the amount of wastewater that will flow into the pond during the season, and an estimate of rainfall or evaporation during the season. With this information they can calculate the applications and time schedules for each week.

Year-round flow, seasonal applications. The basic procedures are similar to those in the previous case except that the entire annual wastewater flow (stored flow plus daily wastewater generated) must be applied during the application season. In addition, if the site is designed for agricultural row crops, startup will usually come after planting and application will be stopped for harvest and cultivation. There must not be any erosion, but with many systems it is possible to resume application to the bare fields after harvest is complete and to continue until freezeup.

Crop management. Management of the crop is a major requirement at agricultural sites. A particular crop is usually selected during design and planted early in the first year of operation. It may be possible, thereafter, to change the crop either to improve the performance of the system or to increase the value of the harvest. See Chap. 5 for detailed discussion on crop types and responses.

Cutting management. The type of cutting management for harvesting forage grasses will depend on the desired level of nitrogen removal. If maximum yields and high nitrogen removal are desired, grasses should be cut more frequently and at the proper times; the initial cutting should be at the early heading stage of growth and subsequent cuttings should be every 4 to 5 weeks for the remainder of the season. The early heading stage will vary with climate, but it will usually be sometime during the middle to late spring.

1. If lower nitrogen removals, in the range of about 160 lb/acre of nitrogen, are needed, then fewer cuttings are needed and operations costs can be saved. Initial cuttings for this purpose should be at the late flowering stage of growth, with one extra cutting toward the end of the growing season. With this cutting method, the majority of the nitrogen will be removed at the initial harvest.
2. Grasses should be managed properly so that they can survive at the site as long as possible. Under proper management, grasses at the site can persist for 3 years or more. They are usually invaded by weedy grasses, some of which are desirable. The weed quackgrass has performed well in SR systems in terms of nitrogen removal and forage quality. When undesirable weeds predominate, fields must be renovated to maintain treatment efficiency. When reseeding, use standard methods for field renovation along with desirable types of forage grasses.
3. With corn much of the nitrogen is removed during a short 4- to 6-week period in summer. This is usually between the knee-high and the tasseling stages of growth.
4. Growing another crop with the corn can improve nitrogen removal by an additional 40 to 80 lb/acre and can lower the percolate nitrogen concentration. In intercropping (see Chap. 5), corn is grown during the summer months, while a cereal crop (e.g., rye) or forage grass (e.g., reed canarygrass) is grown during the spring and fall. The cereal or grass removes nitrogen during the slower corn uptake periods and thereby lengthens the application season. The disadvantages of this system

are that the actual corn yields will be lower owing to increased competition with the grasses and that a higher level of management is required.

5. Turfgrasses, grown for sod production or maintained in a lawn, can remove nitrogen during the entire growing season. When started from seed for sod production, nitrogen removal will be lower. The sod is usually harvested after 12 to 18 months. Weekly mowings during periods of active growth are desirable.

Operations at forested sites. Operations at forested sites will require the same decisions regarding how much water is needed, where to apply it, and how long to let it run that were discussed above. In general, the frost-free season is longer for forests than for an agricultural field, and in northern climates forest soils that have an early snow cover may not freeze at all. In these cases wastewater application can continue all winter. Winter operation requires quick drainage of exposed pipes at the end of the application period. If not planned for during design, the operator will have to install drains at all low spots in the piping system before attempting winter operation. Other operational requirements for forested sites relate to tree management and will require expert advice. Every 3 to 4 years, an experienced forester should tour the site and make recommendations on culling or harvest and other management practices that will ensure a healthy stand of trees.

Recreational sites. Recreational systems have the same basic requirements as the cases previously discussed. They are more difficult to operate, since the recreational function and schedule usually take precedence over the wastewater renovation. The operator has to plan operational schedules for wastewater applications so as not to interfere with the recreational activities.

Emergency procedures. A major concern is disruption of the operating schedule for wastewater applications because there is usually a limited storage capacity available. Since emergencies cannot be predicted, it is prudent for the operator to keep some part of the available storage free. This may require pumping slightly more water than the average schedule would require during the early part of the season.

Extended power failures also disrupt operations. The design should have provided the capability for standby power at the pumping stations. Systems that use center pivot distribution rigs with electrical drive motors should also have a portable standby generator for direct field connection when required.

If treatment and storage ponds are part of the system and there is public access to the site or if the site is close to a community, odors may be a concern from time to time. Odors should not be a problem from properly designed and operated land treatment systems, but they may be possible if wastewater characteristics or pond conditions change suddenly. The operator must be prepared to cope immediately with such a situation.

Application to the pond of a chemical such as potassium nitrate should suppress the odors and allow time for the cause of the problem to be identified and corrected. A recommended procedure is to apply 100 lb/acre of potassium nitrate on the first day and then 50 lb/acre pond surface on each day thereafter if odors persist. The chemical should be applied in the wake of a motor boat.

Odors will generally not occur on the actual land application site unless septic wastes are used or if stagnant puddles and ponds of wastewater are allowed to stand. The latter will also be the cause of insect problems. The operator must routinelyinspect the application site and eliminate these low spots by filling with new soil.

Maintenance procedures

The dikes and berms for ponds will require regular maintenance. Earthen dikes must be checked regularly for muskrats and other burrowing animals. Soil-cement, plastic membrane, or asphalt liners must be regularly inspected and repaired. Damage from waves or ice in the winter is the most common problem.

Systems that use sprinklers must have a regular schedule for inspection and cleaning. All lines and pipes in seasonal operations should be regularly drained, even if freezing is not expected, to avoid corrosion. In addition to sprinkler maintenance, the larger center pivot rigs require attention to their tires and gear boxes for proper lubrication at the start of the operation season.

Overland Flow

The grass in overland flow systems should be cut two or three times a year and removed from the slopes. Removal from the slope is mainly to allow the new grass to grow and to prevent decomposition by-products from being discharged off the slope. Before harvesting, each slope must be allowed to dry out so that equipment can travel over the soil surface without leaving ruts. Ruts can develop into channeling, especially if they are oriented downslope. The drying time necessary before mowing is usually about 1 to 2 weeks; however, this can vary depending on the soil and climatic conditions. After mowing, the hay should be dried before raking and baling. This may take another week or so depending on the weather.

Suggested monitoring programs for soils and vegetation are the same for OF as for SR systems. If the grass is used as fodder, samples may be required during each harvest and may be analyzed for various nutritive parameters such as protein, fiber, total digestible nutrients, phosphorus, and dry matter. These analyses can be conducted by the agricultural department of most state universities.

Rapid Infiltration

The general O&M requirements for RI systems are similar to those used at any earthen basin. The special requirement for RI is maintenance of the design infiltration capacity.

In order to minimize any problems with the basins, the operator should inspect them daily and record in the daily log sheets the depth of standing water in the various basins and the amount of time it takes them to drain. This will allow calculation of the wastewater infiltration rate and identification of those basins where the infiltration rate has decreased to a level where restoration of the basin surface is needed. The operator should inspect the berms of the infiltration basins frequently. Vegetation such as tree seedlings and brush should be removed. The operator should also note any signs of erosion on the berms, and inspect the hydraulic system used to apply the wastewater to the basins to determine if it is functioning properly. Low spots where wastewater can remain ponded should be filled in. During winter operations the entire system must be inspected, paying particular attention to problems of freezing and ice formation.

Restoring the basins to an acceptable infiltration capacity is normally accomplished by disking or scarifying the dry soil surface to break up the organic mat that develops. Another method is to completely remove the top layer of soil and replace it with a suitable soil. This method uses more labor and equipment than disking, and it will also require large earthmoving equipment. Care must be taken to limit the amount of vehicular traffic on the beds to reduce the amount of compaction of the soil layers.

In colder climates the operator should disk the dry surface of the basins about once each year during the late summer and fall. This should keep the basins from clogging during the winter season. Chapter 12 contains additional guidance on winter operations.

Biosolids Systems

The land application of municipal and industrial biosolids has many O&M requirements that are similar to those of SR systems. Chapter 17 discusses in detail the design of the major biosolids application concepts. The biosolids systems differ from SR in application methods and scheduling, more frequent soils monitoring for the LDP, and a greater concern for nuisance issues such as odors and spillage.

Monitoring Requirements

Table 15.5 lists typical monitoring requirements for agricultural utilization of biosolids at "agronomic" rates (see Chap. 17). The major parameters of concern are (1) pH maintenance at 6.5 to reduce potential metal migration, and (2) soil P and K if optimum crop yields are a project goal. Nitrate in groundwater is generally a problem only when the biosolids application(s) exceed the N needs of the crop.

Application scheduling on agricultural sites

The timing of biosolids applications must correspond to farming operations and is influenced by crop, climate, and soil

TABLE 15.5 Typical Site Monitoring Requirements for Biosolids Applications at or Below Agronomic Rates*[6]

Soil pH	Soil test for P and K†	NO_3 in groundwater	Cd in crop
Yes (2)‡	Yes (2)	No	No

*Numbers in parenthesis refer to frequency of analysis; 2 = every 2 years.
†Soil test for available N can be used, if appropriate.
‡Frequency depends on amount of N applied, depth to groundwater, and amount of leachate. Regulatory agencies will dictate frequency.

properties. Biosolids cannot be applied during periods of inclement weather. In some states, biosolids cannot be applied to soils that are frozen or covered with snow. Soil moisture is a major consideration which impacts the timing of biosolids application. Traffic on wet soils during or immediately following heavy rainfalls may result in compaction and reduced crop yields; muddy soils also make vehicle operation difficult. Application to frozen or snow-covered ground with greater than 3 percent slope may result in excessive runoff into adjacent streams. In addition, biosolids applications must be scheduled around the tillage, planting, and harvesting operations for the crops grown.[6]

Biosolids use on disturbed land

As described in Chap. 17, this concept involves the use of biosolids as an organic soil amendment to restore disturbed land such as strip-mined areas. The typical approach is to apply a single large biosolids application, with the amount determined by the LDP which is often total allowable cadmium. The operations during the brief application period generally involve large trucks and earthmoving equipment for spreading and incorporating the biosolids.

Prior to biosolids application, the surface should be roughened or loosened to offset the compaction caused during the site leveling or grading operation. This will help to improve the surface water infiltration and permeability, and slow the movement of any surface runoff and erosion. A heavy mining disk or chisel plow is typically necessary to roughen the surface. It is advisable that this be done along the contour.

The timing of biosolids application depends on the climate, soil conditions, and growing season. It is generally not advisable to apply biosolids to frozen or snow-covered ground, since it cannot be immediately incorporated and seeded. The biosolids should not be applied during periods of heavy rainfall, since this greatly increases the chances of surface runoff. Biosolids can be applied in periods of prolonged extreme heat or dry conditions, if it is incorporated quickly so that considerable amounts of nitrogen are not lost before the vegetation has a chance to establish itself.

Biosolids applications should be scheduled to accommodate the growing season of the selected plant species. If the soil conditions are too wet when biosolids is applied, the soil structure may be damaged, bulk density increased, and infiltration decreased due to heavy vehicle traffic on the wet soil. This may increase the possibility of soil erosion and surface runoff.

If the area to receive biosolids is covered under federal or state mining regulations, the biosolids application must be scheduled to comply with the revegetation regulations. For example, in Pennsylvania mined land can be seeded in the spring as soon as the ground is workable, usually early in March, but seeding must terminate by May 15. Late summer seeding season is from Aug. 1 until Sept. 15, and biosolids application and seeding of mined land covered by these regulations must comply with these requirements.

Application methods

The best-suited technique depends on the type of biosolids (liquid or semisolid) and on whether it is a surface or subsurface application. Table 15.6 provides guidance for surface-applied liquid biosolids, Table 15.7 for subsurface-applied liquid biosolids, and Table 15.8 for dewatered biosolids.

TABLE 15.6 Surface Application Method and Equipment for Liquid Biosolids[6]

Method	Characteristics	Topographical and seasonal limitations
Tank truck	Capacity 500 to more 2000 gal; it is desirable to have flotation tires; can be used with temporary irrigation setup; with pump discharge can achieve a uniform application rate	Tillable land; not usable at all times with row crops or on very wet ground
Farm tank wagon	Capacity 500–3000 gal; it is desirable for wagons to have flotation tires; can be used with temporary irrigation setup; with pump discharge can achieve a uniform application rate	Tillable land; not usable at all times with row crops or on very wet ground

TABLE 15.7 Subsurface Application Methods, Characteristics, and Limitations for Liquid Biosolids[6]

Method	Characteristics	Topographic and seasonal limitations
Flexible irrigation hose with plow or disk cover	Use with pipeline or tank truck with pressure discharge; hose connected to manifold discharge on plow or disk	Tillable land; not usable on very wet or frozen ground
Tank truck with plow or disk cover	500 gal commercial equipment available; biosolids discharge in furrow ahead of plow or disk mounted on rear on 4-wheel-drive truck	Tillable land; not usable on very wet or frozen ground
Farm tank wagon with plow or disk cover	Biosolids discharged into furrow ahead of plow mounted on tank trailer; application of 170–225 wet tons/acre; or biosolids spread in narrow band on ground surface and immediately plowed under; application of 50–120 wet tons/acre	Tillable land; not usable on very wet or frozen ground
Subsurface injection	Biosolids discharge into channel opened by a chisel tool mounted on tank truck or tool bar; application rate 25–50 wet tons/acre; vehicles should not traverse injected area for several days	Tillable land; not usable on very wet or frozen ground

TABLE 15.8 Methods and Equipment for Application of Dewatered Biosolids

Method	Characteristics
Spreading	Truck-mounted or tractor-powered box spreader (commercially available); biosolids spread evenly on ground; application rate controlled by over-the-ground speed; can be incorporated by disking or plowing
Piles	Normally hauled by dump truck; spreading and leveling by bulldozer or grader needed to give uniform application

References

1. Weston, Roy F., Inc., "Evaluation of Operation and Maintenance Practices and Design Considerations of Land Application Systems," EPA 600/2-82-039, U.S. Environmental Protection Agency, MERL, Cincinnati, Ohio, 1982.
2. U.S. Environmental Protection Agency, *Process Design Manual for Land Application of Wastewater,* EPA 625/1-81-013, U.S. EPA CERI, Cincinnati, Ohio, 1981.
3. U.S. Environmental Protection Agency, *Operations Manual—Stabilization Ponds,* EPA 430/9-77-012, U.S. Environmental Protection Agency, OWPO, Washington, D.C., 1977.
4. U.S. Environmental Protection Agency, *Field Manual—Performance, Evaluating and Troubleshooting of Municipal Wastewater Treatment Facilities,* EPA 430/9-78-001, U.S. Environmental Protection Agency, OWPO, Washington, D.C., 1978.
5. U.S. Army Corps of Engineers, *Engineer Manual—Land Treatment Systems Operation and Maintenance,* EM1110-2-504, U.S. Army Corps of Engineers, Washington, D.C., 1983.
6. U.S. Environmental Protection Agency, *Process Design Manual—Land Application of Sewage Sludge and Domestic Septage,* EPA 625/R-95-001, U.S. Environmental Protection Agency CERI, Cincinnati, Ohio, 1995.

Chapter 16

Small-Scale Systems and Innovative Concepts

The procedures in this chapter are intended for communities of 2500 population or less. The basic objectives for any land treatment system are the same regardless of size, however, the design of small systems should include special emphasis on the ease of operation and on minimizing construction and operating costs. Most communities in this size range cannot hire full-time treatment plant operators, and the treatment system must be capable of providing consistent reliable treatment in the absence of frequent attention. In general, most treatment systems that meet these objectives are nonmechanical and have no discharge to surface waters.

The concepts discussed in this chapter include:

- Large-scale septic tank and in-ground disposal systems
- Small-scale applications of the basic land treatment systems (SR, OF, RI)
- Constructed wetlands and other innovative use of the soil ecosystem for wastewater treatment

The procedures for planning and design of small systems are similar to but less detailed than the requirements for large facilities as described in Chaps. 6 through 12. Maximum use is made of local expertise and existing published information. The local Natural Resources Conservation Service (NRCS) staff, the county agent, and local farmers can provide assistance and advice. In effect, the procedures described in this chapter for SR, OF, and RI systems reduce the cost and complexity of site investigation, planning, and system design by increasing the magnitude of the safety factors involved. This approach is typically acceptable for most small systems. However, if land costs are high or the LDP for design is not a routine parameter, then the detailed approaches described in the earlier chapters should be followed.

On-Site Septic Tank Systems

This is the most common form of on-site wastewater disposal in the United States, and design procedures are well established for the typical single-family unit. However, the concept is finding increasing use in commercial applications, public buildings, and cluster-type residential developments. In these cases the flow can easily exceed 1000 gal/day and often approaches 10,000 to 20,000 gal/day for a single system.

The land component in these systems is typically considered a disposal operation, so the LDP for design is the hydraulic capacity of the natural soils. Treatment does occur, but since the wastewater application point is typically below the ground surface, the responses involve the soil and not the surface treatment responses for the parameters of concern.

A few shallow auger borings and some variation of the familiar percolation test are usually the source of design information for a single-family system. The severe limitations of the U.S.PHS percolation test are widely recognized, but it is still the most commonly used test for on-site systems, regardless of size. It is not an appropriate basis for the design of systems when the daily flow approaches or exceeds 1000 gal/day.

Hydraulic failure will occur when the system cannot accept and then transmit, via subsurface flow, the design wastewater volume. This can be caused by biological clogging at the application point interface, by high groundwater conditions, or by soils with unsuitable permeability in the horizontal direction. The latter two can be evaluated by a proper site investigation. The larger the system the more extensive should be the field investigation. Test pits are a key element in identifying soil conditions and groundwater locations, and the methods described in Chap. 7 should be followed.

Measurement or accurate estimates of the vertical and horizontal permeability of the various soil layers are necessary for design. Again, the procedures described in Chap. 7 can be applied. Healy and Laak[1] have developed a variation of the pump-out auger hole test, using a test pit. Figure 16-1 illustrates the geometry of their test. The water table must be within 8 to 10 ft (2.4 to 3 m) of the surface so it can be reached with a backhoe excavation. The test can either observe the rate of water-level rise in the pit and a final determination of the equilibrium level or wait until the level stabilizes and then pump out at least 1 ft (0.3 m) of water and then observe the rate of rise. Because flow into the pit has both vertical and horizontal components, the permeability value determined is an overall "average" for the affected soil. This permeability can be determined with the following equations:

$$Q = \frac{\pi K (H^2 - h_0^{\,2})}{2.3 \log (R/r_0)} \tag{16.1}$$

where Q = volumetric rate of flow, ft³/h [$= (\Delta h/\Delta t)(A)$]
$\Delta h/\Delta t$ = rate of water level rise, ft/h
A = area of water surface, ft² (may be different for each observation, since hole is irregular)

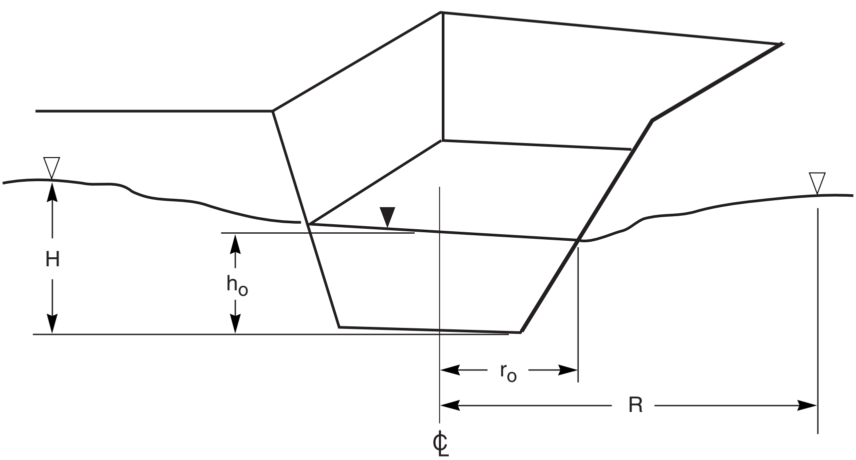


Figure 16.1 Definition sketch—pit permeability test.

K = "average" permeability of soil, ft/h
H = height to stable groundwater, ft
h_0 = height to water level in pit at time t, ft
R = distance from pit centerline to stable water level, ft
r_0 = distance from pit centerline to edge of water level in pit, ft

For the typical case R/r_0 can be assumed to be equal to 4. Substitution in Eq. (16.1), and rearranging terms produces

$$K = \frac{(\Delta h)(A)}{(\Delta t)[2.27(H^2 - h_0^2)]} \tag{16.2}$$

Design loading

Healy and Laak[1] suggest a design approach based on the long-term acceptance rate. They suggest that at a particular optimum hydraulic loading rate the accumulation of clogging biological materials will be in equilibrium with the decomposition rate, so that flow could continue indefinitely under these conditions. Table 16.1 contains selected values from their work relating the soil permeability to the "long-term acceptance rate" in terms of feet of wastewater per year for domestic septic tank effluents, assuming a 1-ft head of water in the disposal trenches or bed. Most on-site designs are based on a hydraulic loading expressed in terms of gallons per square foot per day. The relationship is given by

$$L_{wg} = L_{wf}(0.0205) \tag{16.3}$$

where L_{wg} = long-term acceptance rate, gal/ (ft^2 · day)
L_{wf} = long-term acceptance rate, ft/year

A comparison of the values in Table 16.1, with Fig. 4.6 in Chap. 4 indicates that the tabulated values are within the range shown on Fig. 4.6. However, coarse-textured soils (K>2 in/h) have much more conservative values in Table 16.1. This means that the biological clogging layer controls flow in the coarse soils with a subsurface point of wastewater application. The higher values permitted in Fig. 4.6 are based on a surface application which allows for aerobic decomposition of the accumulated organics.

Designs for finer-textured soil (K<2 in/h) can use either Table 16.1 or Fig. 4.6 to determine hydraulic loading; designs for coarser

TABLE 16.1 Soil Permeability—Disposal Field Wastewater Loading

Soil permeability K, in/h	Acceptance rate L_{wf}, ft/year
0.14	13
0.30	15
0.70	18
1.4	19
2.9	21
7.0	27
14.0	38
30.0	63
70.0	120

soil (K>2 in/h) should be the values in Table 16.1. An alternative is to design for a higher value and then plan for periodic chemical restoration with hydrogen peroxide as described in a later section of this chapter. This approach may be necessary if the available area will not be sufficient for a large disposal field.

Example 16.1: Determine Application Bed Area for a 1000 gal/day Flow

Conditions Test pit permeability results: A = 10 ft^2, H = 3.0 ft, h_0 = 2.5 ft, $\Delta h/\Delta t$ = 0.2 in/h.

Solution

1. Use Eq. (16.2).

$$K = \frac{(\Delta h)\,(A)}{(\Delta t)\,[2.27(H^2 - h_0^2)]}$$

$$= (0.2)\,\frac{10}{2.27\,(9 - 6.25)}$$

$$= 0.32 \text{ in/h}$$

2. From Table 16.1. Use K = 0.32; L_{wf} = 15.5 ft/year.
3. Use Eq. (16.3).

$$L_{wg} = (15.5)(0.0205) = 0.32 \text{ gal/(ft}^2\cdot\text{day)}$$

$$\text{Bed area for 1000 gal/day} = \frac{1000}{0.32} = 3147 \text{ ft}^2$$

Groundwater mounding

An estimate of the groundwater mounding that will occur beneath a large-scale disposal bed or trench is necessary to ensure successful performance. The detailed procedures in Chap. 4 for calculating mound characteristics can be used for on-site disposal systems as well as RI basins. A number of simplified calculation techniques have been developed for application to the smaller-scale on-site disposal systems.[2–5] Only one of these methods is presented here as a demonstration. It is recommended that more than one procedure be used for very-large-scale systems to develop a range of possible conditions for final evaluation by the designer. Reference 5 is particularly valuable in that respect, since it presents several different models.

Figure 16.2 defines the mound geometry for the simplified calculation procedure developed by Finnemore and Hantzsche[2] based on theoretical considerations presented by Hantush.[6] The related equations are

$$h = H + \frac{Z_m}{2} \tag{16.4}$$

where h = distance from boundary to midpoint of the long-term mound

H = height of stable groundwater table above impermeable boundary, ft

Z_m = long-term maximum rise of the mound, ft

$$Z_m = \frac{QC}{A}\left(\frac{L}{4}\right)^n \left(\frac{1}{Kh}\right)^{0.5n} \left(\frac{t}{S_y}\right)^{1-0.5n} \tag{16.5}$$

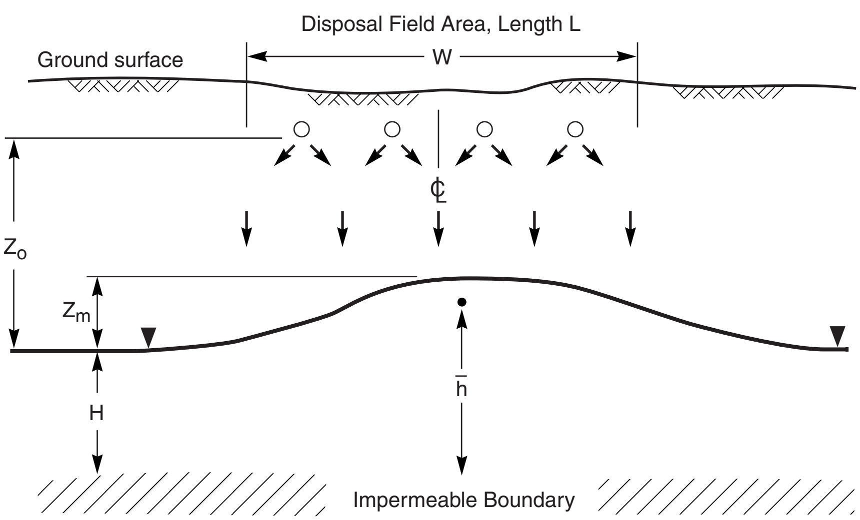


Figure 16.2 Definition sketch—mound geometry for simplified calculation procedure.

Small-Scale Systems and Innovative Concepts 365

where Q = average flow, ft^3/day
A = area of disposal field, ft^2
C = constant, see Table 16.2
L = length of disposal field, ft
K = horizontal permeability of soil, ft/day
h = see Eq. (16.4)
n = exponent, see Table 16.2
S_y = specific yield of aquifer, see Chap. 4
t = time since beginning of wastewater application, days

The K value can be determined in the field with slug tests or bailing tests as described in Chap. 7. In the general case the horizontal conductivity of most soils is significantly higher than the vertical conductivity. Therefore, a conservative estimate of mound rise will be produced if the vertical conductivity is used in Eq. (16.5). At very short time periods Eq. (16.5) will predict high, but conservative, predictions of mound rise. A period of 10 years is recommended by the authors[2] for calculation purposes.

An iterative approach may be needed for the solution since it is necessary to assume a Z_m for Eq. (16.4) to determine h, so that Eq. (16.5) can be solved for Z_m.

Example 16.2: Determine Mound Height After 10 Years

Conditions Wastewater discharge = 2500 gal/day, disposal bed: $L = W = 100$ ft, $H = 50$ ft, $S_y = 0.2$, soil permeability = 1 in/h, $Z_0 = 6$ ft.

Solution

$$\frac{L}{W} = \frac{100}{100} = 1$$

From Table 16.2:

$$C = 3.4179$$

$$n = 1.7193$$

$$K = (1 \text{ in/h})(24 \text{ h/day})(1 \text{ ft/12 in}) = 2 \text{ ft/day}$$

$$Q = (2500)(1/7.48) = 334 \text{ ft}^3\text{/day}$$

$$t = (10 \text{ years})(365 \text{ days/year}) = 3650 \text{ days}$$

1. First estimate: Assume $Z_m = 5.0$ ft. So $h = 50 + 5/2 = 52.5$ ft. Then, using Eq. (16.5):

$$Z_m = \frac{(334)(3.4179)}{10{,}000} \left(\frac{100}{4}\right)^{1.7193} \left(\frac{1}{(2)(52.5}\right)^{0.8597} \left(\frac{3650}{0.2}\right)]^{0.1404}$$

2. Second iteration: $h = 50 + 2.14/2 = 51.07$

$$Z_m = (0.114)(253.2)(0.01874)(3.965)$$

$$= 2.14 \text{ ft}$$

It is clear that the calculation for this example is not sensitive to the initial estimate of Z_m since H is very large compared to Z_m. In these cases it is acceptable to assume

$$h = H \tag{16.6}$$

The calculation is very sensitive when the groundwater depth H is relatively small. In the example, had H been only 12 ft, then the mound would rise 6 ft in the 10 years for the conditions specified and the system would be in a failure mode since the original depth to groundwater Z_0 was only 6 ft. The H value selected for use in Eq. (16.5) should be the mean normal saturated depth of the aquifer. The mound height that is then determined should be added to the highest seasonal water-table elevation for the site to obtain the worst-case condition.

Changing the configuration of the disposal field may reduce the groundwater mounding. For example, in the previous case a square area 100 ft × 100 ft (30 × 30 m) was assumed. Adopting a rectangular area of 50 ft × 200 ft (15 × 60 m) would change the constants derived from Table 16.2, and for the initial conditions specified in Example 16.1, the mound would rise 1.9 ft as compared to 2.1 ft for the square configuration.

TABLE 16.2 Constants for Eq. (16.5)

Length to width ratio L/W of disposal field	C	n
1	3.4179	1.7193
2	2.0748	1.7552
4	1.1348	1.7716
8	0.5922	1.7793

Soil mound systems

Mound systems were developed to overcome site constraints imposed by high water tables, slowly permeable soils, and shallow in situ soils.[7] Figure 16.3 illustrates the basic design features. In effect the constructed mound raises the application bed above the natural soil surface so that the larger base area of the mound serves as the design infiltration surface for the natural soils. Most regulatory agencies have specific design requirements regarding size, slopes, and construction materials. The standard percolation test is usually accepted for design of the soil mound since infiltrations into and out of the mound are controlling parameters. Evaluation of subsequent percolate and groundwater flow in the natural soils will require the procedures discussed in previous sections of this chapter.

The basic design approach for a soil mound is a two-step operation. Percolation tests are run in the natural soils on the site at the depth of concern. Table 16.3 can then be used to calculate the base area of the mound. Then, based on the type of soil used to construct the mound, the area of the application bed in the mound is determined. Table 16.4 relates the most commonly used fill materials for mound construction to the design rates used for determining the bed area. These values should be confirmed with additional percolation tests after construction is completed and consolidation of the fill has occurred.

The results of the conventional percolation test are expressed as the number of minutes required for the water level to drop in

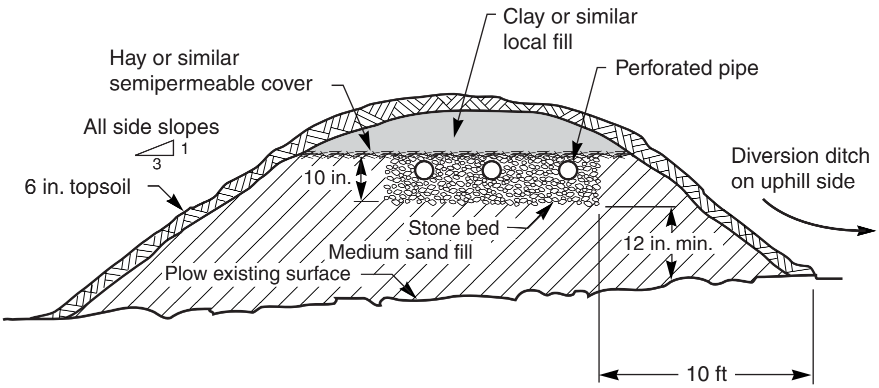


Figure 16.3 Basic design features for soil mound systems.

TABLE 16.3 Infiltration Rates for Determining Base Area of Mound[8]

Natural on-site soil	Percolation rate, min/in	Infiltration rate Q_g, gal/(day·ft^2)
Sand, sandy loam	0–30	1.2
Loam, silt loams	31–45	0.75
Silt loams, silty clay loams	46–60	0.5
Clay loams, clay	61–120	0.25

TABLE 16.4 Mound Fill Materials and Infiltration Rates[8]

Material	Characteristics, % by weight	Infiltration rate Q_g, gal/(day·ft^2)
Medium sand	>25%, 0.25–0.2 mm <30–35%, 0.05–0.25 mm <5–10%, 0.002–0.05 mm	1.2
Sandy loam	5–15% clay	0.6
Sand/sandy loam	88–93% sand	1.2

TABLE 16.5 Percolation Rate Related to Other Soil Characteristics

Percolation rate, min/in	NRCS descriptor	Permeability range, in/h
<1	Very rapid	>20
1–10	Rapid	2–20
11–60	Slow-moderate	0.2–2.0
>60	Slow	0.06–0.2

the test hole by 1 in after equilibrium has been reached. Table 16.5 can be used to relate these values to the soil permeability descriptors used elsewhere in this text.

Pressure distribution is essential for all mound systems and is recommended for all other large-scale on-site disposal systems. This will ensure uniform application over the entire design area and avoid the sequential failures that have occurred with gravity pipe networks. References 7 and 8 contain complete details for the design of the pipe networks. These usually consist of a solid pipe manifold connected to a number of evenly spaced perforated laterals. Recently, California has adopted new guidelines based on the extensive experience of Sonoma County and other counties.[20]

Rehabilitation of on-site systems

Failure is defined as the inability of these systems to move the design quantity of water at the design rate. If failure occurs soon after system startup, it may be due to poor design, poor construction, or unanticipated groundwater conditions, or some combination of the three. In many cases, groundwater problems may be resolved by surface regrading to eliminate excess surface water infiltration in the area and/or a relief drain upgradient of the system.

Failures occurring after several years of successful operation may be due to a gradual and unanticipated increase in flow or to biological clogging at the infiltration surfaces. A procedure developed at the University of Wisconsin[9] uses hydrogen peroxide, a very strong oxidizing agent, to destroy the organic deposits and restore infiltration capacity.

Lysimeter work at the University of New Hampshire[10] successfully rejuvenated sandy and loamy sand soils which had failed due to the buildup of an organic mat. A 30 percent solution of hydrogen peroxide and water was successful in all cases. A weaker solution at 7.5% H_2O_2 was also successful for sandy soils. Loading rates used were 0.25 lb H_2O_2/ft^2 of surface for sands and at least 0.50 lb H_2O_2/ft^2 for silty soils. In subsequent research it was found that one or two applications of hydrogen peroxide may be required to renovate clean sands.[21]

Small-Scale Land Treatment

Any of the three basic land treatment processes (SR, RI, or OF) is suitable for industries and small communities. Table 16.6 lists the type and sources of data required for these small land treatment systems.

Small municipal systems may offer greater flexibility with respect to system ownership and management. For example, contractual agreements (see Chap. 14) with local farmers can be developed to take and use partially treated wastewater. The staffing requirements for the system will depend on the type of system and on the operational arrangements. Figure 15.1 in Chap. 15 illustrates staff requirements for typical municipally owned and operated systems. Table 16.7 presents municipal staff requirements at several small land treatment systems.[11]

TABLE 16.6 Types and Sources of Data Needed for Design of Small Land Treatment Systems

Data	Principal source
Wastewater characteristics	Local authorities
Soil type and permeability	SCS soil survey
Temperature (mean monthly and growing season)	SCS, NOAA, local airports
Precipitation (mean and maximum monthly)	SCS, NOAA, local airports
Evaporation and ET (mean monthly)	SCS, NOAA, Agricultural extension
Land use	SCS, aerial photography from various sources
Zoning	Local agencies
Agricultural practices	County agent, SCS, Agricultural extension
Groundwater (depth and quality)	USGS, state agency, local driller's logs
Discharge requirements	State or EPA

Site identification

A simplified screening procedure can be used to determine if there are parcels of suitable land for the three concepts within a reasonable distance. This procedure can be a desktop analysis using available soils and topographic maps. At the same time, a survey should be started to identify local farmers or landowners who may be willing to participate in the land treatment project. Criteria for this initial screening are presented below. These preliminary land area requirements are very conservative and include allowances for preapplication treatment, storage, and unused land. *These equations should be used only for initial site screening, not for actual system design.*

Slow rate systems. The total area required will depend on the number of operating months per year. Most systems will operate between 6 and 12 months per year. The two equations below can be used for those conditions or interpolated for intermediate values.[12] Figure 6.2 can be used to determine the operating period.

6 months/year:

$$A = (2.73\times10^{-4})\,Q \qquad (16.7)$$

TABLE 16.7 Staff Requirements at Small Systems[12]

			Town/staff, labor days/year	
Location and daily flow, gal/day	Site type	Site control	Land component	Total system
Ravenna, Mich. 73,000	Open fields	City	7	75
Santa Anna, Tex. 75,000	Pasture	Farmer owns, city operates equipment	46	100
Wayland, Mich. 251,000	Hay, corn	City owns, farmer harvests	68	172
Winters, Tex. 300,000	Hay	Farmer owned	0	52

12 months/year

$$A = (1.94 \times 10^{-4})\, Q \tag{16.8}$$

where A = total land area required, acres
Q = average daily wastewater flow, gal/day

Desirable site characteristics for SR are:

Grade: <20% for cultivated land
<40% for forest or pastureland

Permeability: 0.2 to 0.6 in/h

Soils: Clay loam to sandy loam (GM, SM-d, Mh, Oh, MH)

Depth to groundwater: 2 to 3 ft

Parcels of land with these characteristics should be identified and marked on the map. For the typical small community it will not be economical to consider land beyond 2 to 3 mi in distance from the town or sites where the pumping head will exceed about 100 ft to reach the site.[13] Special circumstances such as no cost for the land or AWT water quality for a surface discharging alternative can justify a greater range for the screening procedure. It is not absolutely necessary that all of the land be in one contiguous parcel, especially if a number of land owners have agreed to participate in the project.

Overland flow systems. The equations for estimating total land requirements are[12].

6 months/year:

$$A = (1.68 \times 10^{-4})\, Q \tag{16.9}$$

12 months/year:

$$A = (9.07 \times 10^{-5})\, Q \tag{16.10}$$

See Eq. (16.8) for definition of terms. Figure 6.2 can be used to estimate the annual operating period. Interpolate for intermediate operating time.

Desirable OF site characteristics are:

Grade: Finished slopes 2 to 8 percent (can be constructed on flat terrain)

Permeability: 0.2 in/h or less

Soils: Clay and clay loams (SM-o, Sc, C1, O1, CN, OH)

Depth to groundwater—not critical

The “rule of thumb” on cost-effective screening distance and elevation for OF are[12] 2 to 3 mi, 150 ft pumping head.

As in the previous case, special site conditions may justify an extension of these values. All parcels of land having these characteristics should be marked on the map. It is not absolutely necessary but is desirable for the OF system to be on one contiguous parcel, since ownership and management is likely to be by the town, and system control and security will be easier with a single site.

Rapid infiltration systems. RI systems can typically operate on a year-round basis, so that only one equation is given for estimating total land area required:

$$A = (5.92 \times 10^{-5})\, Q \tag{16.11}$$

See Eq. (16.8) for definition of terms. As in the other cases, this is the total area for the system including an allowance for preapplication treatment, etc.

Desirable site characteristics:

Grade <10%

Permeability >0.6 in/h

Soils: sand and sandy loams (Gw, GP, SW, SP)

Depth to groundwater 15 ft

(Non-drinking-water aquifer)

The suggested limits for distance and elevation difference are 4 to 7 miles, 200 ft pumping head.

All parcels of land having these characteristics should be located on the map. It is recommended that the RI system be located on one contiguous parcel of land to reduce costs and allow more efficient operation by the town or industry.

Final site selection and investigation

It is unlikely that the area surrounding a small town or industry will contain a sufficient amount of suitable land for all three of the treatment concepts. One or more is likely to be eliminated in the very early stages of the screening process. A field reconnaissance is suggested in the final stages of the screening process to visually observe and verify the site characteristics identified during the map survey. A simplified ranking procedure can be used in the final selection process. Sites with the lowest land cost, lowest elevation difference, and closest proximity to the town will generally rank the highest. A field investigation should then be conducted for each of the potential sites identified in the map surveys.

The first step in the site investigation procedure should be to visit the potential site with a local NRCS representative. A few shallow hand-auger borings to identify the soil profile should be conducted to confirm the NRCS data and check for impermeable layers or shallow groundwater. Infiltration tests are usually needed only for RI sites. A few backhoe pits to 10 ft (3 m) or more are also recommended for RI sites, but drill holes are usually deferred until preliminary design.

If crops will be grown, a site visit with the county agent or local agricultural or forestry adviser is recommended. The purpose of this site visit is to obtain advice on the type of crops to use and on crop management practices.

Facility design

Because limited field investigations are conducted, very conservative design criteria are adopted. If the system design requires new facilities for preapplication treatment and storage, then a combined pond system is recommended, and Chap. 8 should be used for its design.

Hydraulic loading rates. It is assumed for this procedure that the LDP for designs are:

- SR systems—hydraulic capacity of the soil or groundwater nitrogen
- RI systems—hydraulic capacity of the soil, since site selection has eliminated sensitive aquifers from consideration
- OF systems—hydraulic loadings that will consistently produce secondary, or better, effluent quality

If some other factor is the LDP, then the detailed procedures described in earlier chapters should be used.

SR systems. The design hydraulic capacity is based on the most limiting NRCS permeability classification of the soils at the selected site. Figure 16.4 can be used to determine the weekly hydraulic loading for small SR systems. The annual loading is obtained by multiplying this value by the number of operating weeks per year.

The annual hydraulic loading based on nitrogen limits is given by

$$L_{wn} = 5.2 \left[\frac{2.3\,(P_r - \mathrm{ET}) + U}{C_n - 10} \right] \qquad (16.12)$$

where L_{wn} = annual hydraulic loading, limited by nitrogen, in/year
P_r = annual precipitation, in/year
ET = annual evapotranspiration, in/year

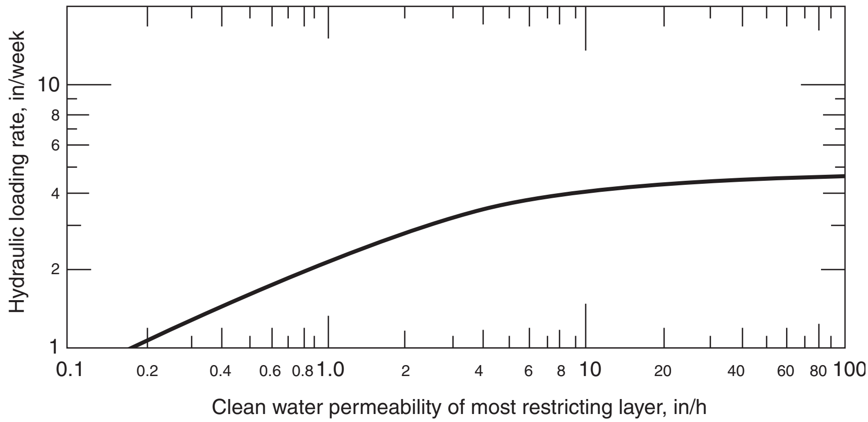


Figure 16.4 Hydraulic loading rate (in/week) during application season for small-scale SR systems. (*After Ref. 12.*)

U = annual crop uptake, lb/ (acre · year)
C_n = nitrogen concentration in wastewater, mg/L

Table 16.8 can be used to estimate crop uptake U for use in Eq. (16.12), or a more precise value selected from Chap. 5. Both the crop uptake values in Table 16.8 and the allowance for nitrogen losses in Eq. (16.12) are more conservative than the criteria presented for large-scale systems in earlier chapters.

The hydraulic loading calculated with Eq. (16.12) should be compared to the graphical determination from Fig. 16.4 and the most conservative of the two used to calculate the actual treatment area required:

$$A = \frac{Q}{(L_w)\,(3650)} \tag{16.13}$$

where A = SR treatment area, acres
Q = annual wastewater flow, ft³/year
L_w = limiting hydraulic loading, in/year

Additional land is required for preapplication treatment, storage, access roads, and sometimes buffer zones. Allowances for these factors were included in the preliminary screening calculations, but specific values must be determined during final design and system layout.

TABLE 16.8 Nitrogen Uptake Rates for Small Land Treatment Systems Design[12]

Crop	Uptake, lb/(acre·year)
Forage crops:	
Alfalfa	300
Bromegrass	130
Coastal Bermudagrass	400
Kentucky bluegrass	200
Quackgrass	240
Reed canarygrass	340
Ryegrass	200
Sweet clover	180
Tall fescue	160
Field crops:	
Barley	70
Corn	180
Cotton	80
Sorghum	90
Potatoes	230
Soybeans	110
Wheat	60

Chapter 9 contains details on wastewater distribution methods. In small communities, it is prudent to choose a distribution method that is used locally or that will result in a system that requires only part-time operational attention. If a locally used distribution method is selected, any specialized equipment and necessary expertise will be more readily available.

Traveling guns require relatively high amounts of labor and are more adaptable to systems where several odd-shaped fields are irrigated each season, so they are usually owned and operated by a local farmer. Both solid set and center pivot irrigation systems can be adapted to either municipally owned or farmer owned small irrigation systems. Center pivots will generally not be applicable for very small SR systems (below 40 acres). Typical small SR systems operate for 8 h/day for 1 day/week on a particular plot on a 7-day rotation.

Overland flow. The hydraulic loading rates for small OF systems are essentially the same as defined in Chap. 11. To simplify calculations and area determinations, the following criteria are suggested in Table 16.9.

TABLE 16.9 Design Criteria for Small-Scale Overland Flow

Type of wastewater	Hydraulic loading, in/week	Slope length, ft	Operating hours, h/day	Operating days, days/week
Screened wastewater	4	120–150	8–12	5–7
Primary effluent	5–6	100–120	8–12	5–7
Pond effluent (when algae is not a concern)	5–7	150	8–18	5–7
Secondary effluent	12–16	100–120	8–12	5–7

Storage and operating periods for OF systems can be determined with the procedures in Chaps. 11 and 8. Crop selection, distribution methods, runoff collection, etc., are also described in earlier chapters.

Rapid infiltration. A small RI system need not be designed for intensive wastewater applications at maximum RI rates, which could involve the need for recovery of renovated water and relatively high levels of operation and management. Instead, the design can be simplified to meet the objectives of wastewater treatment and still maintain ease of operation. Figure 16.5 can be used to determine the appropriate hydraulic loading rate depending on the limiting soil permeability and level of preapplication treatment intended. Other design details for RI basin systems can be found in Chaps. 9 and 12. A typical operational schedule allows 2 days of flooding followed by 10 to 18 days of drying, with the longer times needed in the winter months. A convenient program uses 2 days of flooding followed by 12 days of drying to complete a 14-day cycle. This would require a minimum of seven cells or basins in the system for continuous operation. Small basins 0.5 to 2 acres in area are easier to construct and manage for small systems, and this will influence the number of cells in the system.

Seepage ponds have been used successfully in many small communities and are similar to RI in that relatively high hydraulic loading rates are used and treatment occurs as wastewater percolates through the soil. The primary difference is that

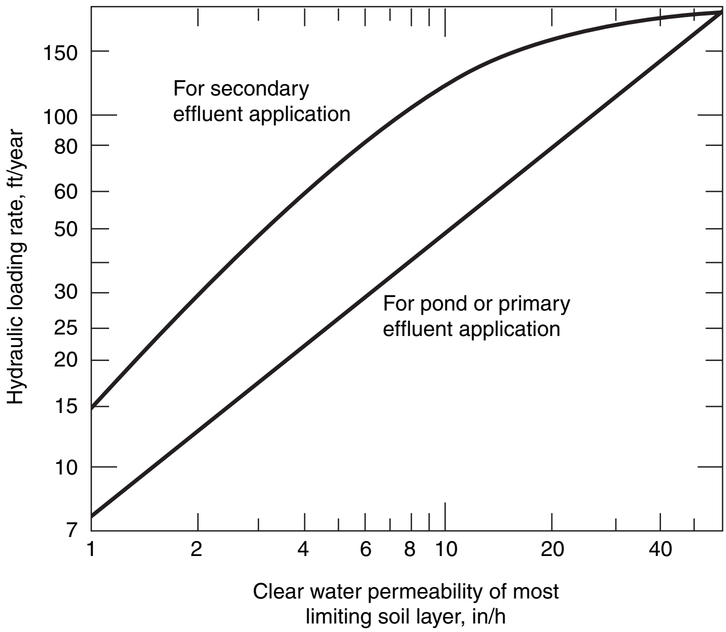


Figure 16.5 Typical annual hydraulic loading rates for small RI systems. (*After Ref. 12.*)

seepage ponds are loaded continuously, whereas RI systems use a loading cycle that includes both application and drying periods, resulting in improved treatment and maximum long-term infiltration rates. Since the infiltration surface in seepage ponds seldom has an opportunity to dry out, the infiltration rate will be retarded. The long-term acceptance rates listed in Table 16.1 should be used for seepage pond design, not the values from Fig. 16.5. The values in Table 16.1 should be conservative for most cases, since they are developed for a 1-ft head in the pond, and greater depths of water should result in higher infiltration rates. Table 16.1 is valid only if biological clogging is the cause of infiltration retardation. Infiltration tests should be run following construction of both RI and seepage basins to verify design assumptions. Inadvertent compaction of the bottom soils during construction can easily cause system failure.

Innovative Concepts

Innovative technology as discussed in this chapter refers to new concepts or variations as well as proven concepts that have not seen widespread use. This section is concerned only with those innovative concepts that depend on the land and the soil-plant ecosystem as a major component in the system.

Combinations of land treatment systems

A combination of the basic land treatment process (SR, OF, RI) to achieve a particular water-quality standard would be considered an innovative approach. There are a number of possibilities related to the overland flow concept depending on the rate of flow, depth of water, and detention time in the system. Grass filtration has been used in England and Australia since the late 19th century to polish effluent prior to final disposal. A typical operation would apply secondary effluents at relatively high rates to a grass-covered, gently sloping field to obtain further removal of BOD and SS prior to final discharge. As a first approximation, the area required might be less than half that required for overland flow designed in accordance with Chap. 11. A further increase in the depth of water and the detention time in a continuous flow system will convert the vegetation to aquatic species and result in a wetland. However, many of the treatment responses will be the same, so the range of possibilities from overland flow to a wetland can be considered as the same group rather than separate and distinct concepts. Examples of overland flow combined with constructed wetlands are the systems at Orange County, Fla.,[22] and at Sacramento Regional County Sanitation District.[23]

Constructed wetlands

The construction of a wetland where one did not previously exist can eliminate the requirement that discharge standards must be achieved prior to the wetland. A constructed wetland is part of the treatment process, so discharge standards should apply to the final system effluent. Construction of the unit is similar to OF procedures described in Chap. 11. The bottom can be natural clay or rendered relatively impermeable by compaction or with liners. Soil or other media is then needed to support the aquatic vegetation. Appropriate inlet and outlet structures complete the system.

There are three different types of constructed wetlands:

1. Vertical flow
2. Free water surface (FWS)
3. Subsurface flow (SF)

Vertical flow wetlands require a sprinkler or spray application for wastewater or a surface flow distribution for liquid sludge (see reed beds[16,17]). Vertical flow wetlands have a larger capacity for BOD and ammonia removal because of the ability (like rapid infiltration) of the system to draw air into the root zone to supply the treatment bacteria with oxygen.

Free water surface wetlands are horizontal flow units with emergent vegetation and about 1 to 2 ft (0.3 to 0.6 m) of wastewater flowing slowly through the plants. FWS wetlands are the most common treatment wetlands. A list of 20 free water surface constructed wetlands is presented in Table 16.10. Many of these listed systems have been monitored in some detail, and the results have influenced the technology assessment.[19]

Subsurface flow (SF) wetlands have been used to treat septic tank effluent and to treat small community pond effluent. An example of an on-site constructed wetland near Burlington, Vt., is shown in Fig. 16.6.

The vegetation in constructed wetlands serves several purposes:

- Roots and stems act as support medium for biological growths.
- Leaf canopy shades the liquid surface in summer, preventing algae growth.
- Plants take up nutrients.
- Plants slow the water flow, contributing to sedimentation.

Cattails, reeds, and rushes transmit oxygen from the leaves to the roots, resulting in aerobic microsites in an otherwise anaerobic environment.[16,17,19]

Removal of nitrogen and phosphorus and other elements by the plants is relatively minor, so harvest and removal of the plants is not necessary except for special situations. An example might be stringent phosphorus controls. If the plants are cut or allowed to die back in place, there could be relatively high P concentration in the spring discharges. Cattails (*Typha*) or bulrush

TABLE 16.10 Free Water Surface Constructed Wetlands

Location	Pretreatment	Area, acres	Flow, Mgal/day
Arcata, Calif.	Pond	34	2.3
Beaumont, Tex.	Pond	550	21
Benton, Ky.	Pond	7.4	0.2
Cheney, Wash.	Tertiary	100	1.5
Cle Elum, Wash.	Pond	5	1.45
Columbia, Mo.	Advanced primary	95	14.3
Eastern MWD, Calif.	Secondary	50	1.0
Ft. Deposit, Ala.	Pond	15	0.15
Gustine, Calif.	Pond	24	1.0
Kingman, Ariz.	Pond	50	1.1
Manila, Calif.	Pond	1.4	0.06
Minot, N.Dak.	Advanced secondary	124	4.5
Mt. Angel, Oreg.	Pond	9	0.9
Orange County, Fla.	Tertiary	220	1.76
Ouray, Colo.	Aerated pond	2.2	0.2
Pembroke, Ky.	Secondary	2.3	0.07
Riverside, Calif.	Secondary	47	10
Sacramento County, Calif.	Secondary	15	1.0
W. Jackson County, Miss.	Pond	56	1.6

Figure 16.6 On-site subsurface flow constructed wetlands recently planted at Ten Stones near Burlington, Vt.

(*Scirpus*) have rapidly dominated on most systems regardless of the initial species present. Work in Ontario[15] indicated that a full canopy will develop within a few months if cattail roots are initially planted on about 3-ft (0.9-m) centers. A fully vegetated constructed wetland may take one to two growing seasons, depending on the initial density.[18]

A significant developmental effort has been directed at the use of constructed wetlands for wastewater treatment in a variety of locations, with different types of wastewater and hydraulic loadings. Equations for the design or either free water surface or subsurface flow constructed wetlands are presented in Refs. 16, 17, and 24 for removal of BOD, TSS, ammonium-nitrogen, nitrate-nitrogen, total nitrogen, phosphorus, and pathogens. Removal of metals is described in Refs. 17 and 18.

References

1. Healy, K. A., and R. Laak, "Site Evaluation and Design of Seepage Fields," *Journal ASCE EED,* **100** (EE5); 1133 (Oct. 1974).
2. Finnemore, E. J., and N. N. Hantzsche, "Groundwater Mounding Due to Onsite Sewage Disposal," *ASCE Journal IDE,* **109,** (2): 199 (June 1983).
3. Fielding, M. B., "Groundwater Mounding under Leaching Beds," *Proceedings, Third National Symposium on Industrial and Small Community Sewage Treatment, ASAE,* Pub. 1-82, p. 215, 1982.
4. Mott, T. O., et al., "Flow Calculation for Household Effluent Disposal in Elevated Sand Mounds," *Journal of Environmental Quality,* **10,** (3):311 (1981).
5. Allen, D. H., "Hydraulic Mounding of Groundwater under Axisymmetric Recharge," *Research Report 24,* University of New Hampshire, Water Resources Research Center, Durham, N.H., Jan., 1980.
6. Hantush, M. S., "Growth and Decay of Groundwater Mounds in Response to Uniform Percolation," *Water Resources Research,* **3** (1): 227 (1967).
7. U.S. Environmental Protection Agency, *Design Manual—Onsite Wastewater Treatment and Disposal Systems,* EPA 625/1-80-012, U.S. EPA CERI, Cincinnati, Ohio, Oct. 1980.
8. Otis, R. J., "Pressure Distribution Design for Septic Tank Systems," *Journal ASCE EED,* **108** (EE1): 123 (1982).
9. Harkin, J. N., and M. D. Jawson, "Clogging and Unclogging of Septic System Seepage Beds," *Proceedings Second Illinois Symposium on Private Sewage Disposal Systems,* Illinois Department of Public Health, Springfield, Ill., 1977.
10. Bishop, P. L., and H. S. Logsdon, "Rejuvenation of Failed Soil Absorption Systems," *Journal ASCE EED,* **107** (EE1): 47 (1981).
11. U.S. EPA, *Process Design Manual—Land Treatment of Municipal Wastewater,* EPA 625/1-81-013, U.S. EPA CERI, Cincinnati, Ohio, Oct. 1981.
12. Reed, S. C., et al., "Wastewater Irrigation for Small Communities," in *Proceeding ASCE I&DD,* Orlando, Fla., July 2–23, p 501, 1983.
13. U.S. Environmental Protection Agency, "Generic Facilities Plan for a Small Community: Stabilization Pond, Land Treatment on Trickling Filter," *Draft Report* FRD 26, U.S. EPA FRD, Washington, D.C., June 1982.
14. Reed, S. C., et al., "Aquaculture Systems for Wastewater Treatment—An Engineering Assessment," U.S. Environmental Protection Agency, EPA 430/9-80-007, OWPO, Washington, D.C., MCD-68, June 1980.

15. Black, S. A., et al., "Sewage Effluent Treatment in an Artificial Wetland," presented at WPCF Conference, Detroit, Mich., Oct. 4–9, 1981.
16. Reed, S. C., R. W. Crites, and E. J. Middlebrooks, *Natural Systems for Waste Management and Treatment,* 2d ed., McGraw-Hill, New York, 1995.
17. Crites, R. W., and G. Tchobanoglous, *Small and Decentralized Wastewater Management Systems,* McGraw-Hill, New York, 1998.
18. Crites, R. W., G. D. Dombeck, R. W. Watson, and C. R. Williams, "Removal of Metals and Ammonia in Constructed Wetlands," *Water Environment Research,* **69**(2) (1997).
19. U.S. Environmental Protection Agency, Free Water Surface Wetlands for Wastewater Treatment: A Technology Assessment, U.S. Environmental Protection Agency, Washington, D.C., 2000.
20. California State Water Resources Control Board, *Guidelines for the Design, Installation and Operation of Mound Sewage Disposal Systems,* Sacramento, Calif., 1998.
21. Michelson, M., J. C. Converse, and E. J. Tyler, "Hydrogen Peroxide Renovation of Clogged Wastewater Soils Absorption Systems in Sands," *Transactions of American Society of Agricultural Engineers,* **32**(5): 1662–1668 (1989).
22. Schwartz, L. N., et al., "Orange County Florida Eastern Service Area Reclaimed Water Wetlands Reuse System," *Proceedings, International Specialist Conference, Wetland Systems in Water Pollution Control,* University of New South Wales, Sydney, Australia, 1992.
23. Nolte and Associates, "Sacramento Regional Wastewater Treatment Plant Demonstration Wetlands Project," *1996 Annual Report,* prepared for the Sacramento Regional County Sanitation District, Elk Grove, Calif., 1997.
24. WEF, *Natural Systems for Wastewater Treatment, Draft Manual of Practice,* Alexandria, Va., 1999.

Chapter 17

Land Application of Biosolids

Land application of biosolids (the term developed by the Water Environment Federation for processed wastewater sludge that can be beneficially recycled) and other organic residuals produced by wastewater treatment systems can often benefit both the soil and society. Biosolids and other organic residuals can supply most of the macro- and micronutrients necessary for crop growth and organic matter that can improve soil structure and moisture-holding capacity. Society benefits from the recycling of the biosolids nutrients and organic matter in a safe and effective manner, which avoids the potential impacts associated with sludge disposal practices that can lead to emissions that impact air, surface, and groundwater quality while destroying or burying the otherwise useful nutrients and organic matter. Of course, all biosolids utilization and disposal projects should be conducted in a manner that protects public health and environmental quality.

Overview of Land Application Practices in the United States

A wide range of land application practices are utilized in the United States. These include uses in agriculture, forestry, and reclamation activities, as well as uses in urban areas for maintaining parklands, golf courses, landscapes, gardens, and lawns. Some of the most common application practices across the country involve the use of liquid and cake materials in a manner very similar to the use of manures on agriculture fields producing various small grain crops (e.g., corn, wheat, and soybeans), forage and hay crops (e.g., mixed grasses, alfalfa, and Sudan grass), sod, and pastures. In some parts of the country these materials are also often applied to managed forests, rangeland, or reclamation sites (such as construction sites, mine spoils, and tailings piles). There is growing activity in the use of biosolids on areas that are marginally productive or have been drastically disturbed or contaminated in an effort to improve soil conditions and productivity (e.g., use on abandoned strip-mined areas, overgrazed rangeland, landfill closure sites, Superfund and Brownfields sites, and areas ravaged by forest fires). Highly treated biosolids products (e.g., compost and heat-dried pellets) are frequently used in urban areas by homeowners and in areas of high public contact (e.g., golf courses, parks, ball fields).

Land application has been implemented by many rural communities with adequate land available and agreeable landowners and neighbors. In some cases, dedicated or publicly owned and controlled sites are used, but more commonly, biosolids are applied to privately owned and managed farmland, reclamation sites, and forests. Such practices commonly involve digested, standard lime-stabilized or lagoon-treated biosolids materials. A growing number of communities now heat-dry, compost, or high-level lime-stabilize their biosolids, generating products that are actively marketed to fertilizer and soil blenders, farmers, landscapers, garden stores, and turf maintenance companies as a slow-release organic fertilizer or soil amendment. Overall, it is currently estimated that over half of the approximately 7 million dry metric tons per year biosolids produced by the 16,000 publicly owned treatment works (POTWs) in the United States are land applied by one means or another.[1,2]

Key Issues and Concerns

The areas of most concern that are raised when projects involving land application of biosolids and other organic residuals are proposed generally focus on the risks associated with potential impacts to human health and the environment. Possible contamination of an unsuspecting public by chemicals and/or pathogens that may be present in the biosolids is generally high on the list, followed closely by the potential to cause odors and nuisance conditions in the local area, and the potential of contaminating the soil, crops, surface and groundwater, wildlife, etc. Extensive studies have been undertaken over the past three decades in many areas associated with land application of biosolids in an effort to quantify the risks and develop management practices to limit the potential impacts of the various land application practices.

At a July 1973 research needs workshop ("Recycling Municipal Sludges and Effluents on Land")[3] held in Champaign, Ill., and again a decade later in 1983 at a similar workshop ("Utilization of Municipal Wastewater and Sludge on Land")[4] in Denver, Colo., researchers and practitioners of land treatment from all areas of the United States and abroad gathered to discuss the state of knowledge and define future research needs concerning land application practices. The data presented and discussions held during these workshops and numerous other technical gatherings since[5–11] emphasize that most studies show that with proper management and safety allowances based upon available research data, land application is a safe, beneficial, and acceptable alternative for treating and recycling municipal wastewater and biosolids. This finding was reinforced by the cross-media risk assessment conducted by EPA in conjunction with the development of the current federal regulations (40 CFR Part 503) that impose specific limitations on biosolids land application practices.

Regulatory Requirements Applicable to Land Application Practices

Since the early 1970s, federal regulations and technical guidelines served as the basis of state requirements, although some state requirements have been more restrictive than others. Nearly all states have a program for regulating biosolids use and disposal practices, including land application practices. Clean Water Act Amendments passed in 1977 and 1986 mandated comprehensive federal involvement in the control of biosolids management practices.

EPA issued its current land application requirements as a part of the risk-based Part 503 technical standards issued in February 1993 (40 CFR Part 503), which are self-implementing—the requirements apply whether or not a federal permit is issued for the project. This means that citizen suits under the Clean Water Act or EPA can enforce the regulation even before permits are issued. As a result, treatment works must monitor and keep records of biosolids quality (and in many cases land appliers must keep records of loading rates and locations receiving biosolids) and must comply with pollutant limits and other technical standards, even in the absence of a federal permit. For the most part these are also requirements under existing state programs and in some cases local programs as well. However, unlike the EPA requirements which are minimum requirements that apply across the country, most state programs are designed to also address local conditions and often include additional requirements (e.g., slope restrictions, setback distances); states also often impose similar requirements to the land application of organic residuals other than biosolids. In addition, an array of other local, state, and regional agencies may impose additional constraints and requirements on land use, agricultural practices, transportation alternatives, etc., that can greatly influence the location, design, and operation of proposed land application projects.

The Part 503 regulation addresses the use and disposal of only biosolids, including domestic septage, derived from the treatment of domestic wastewater. It does not apply to materials such as grease trap residues or other nondomestic wastewater residues pumped from commercial facilities, sludges produced by industrial wastewater treatment facilities, or grit and screenings. The EPA rule addresses beneficial use practices involving land application as well as surface disposal and incineration of biosolids. They affect generators, processors, users, and disposers of biosolids—both public and privately owned treatment works treating domestic sewage (including domestic septage haulers and nondischargers), facilities processing or disposing of biosolids, and the users of biosolids and products derived from biosolids.

Part 503 is organized into the following subparts (see Fig. 17.1): general provisions, land application, surface disposal, pathogens and vector attraction reduction, and incineration. Subparts under each of these use and disposal practices generally address applicability, general requirements, pollutant limits, management practices, operational standards, frequency of monitoring, record keeping, and reporting requirements.

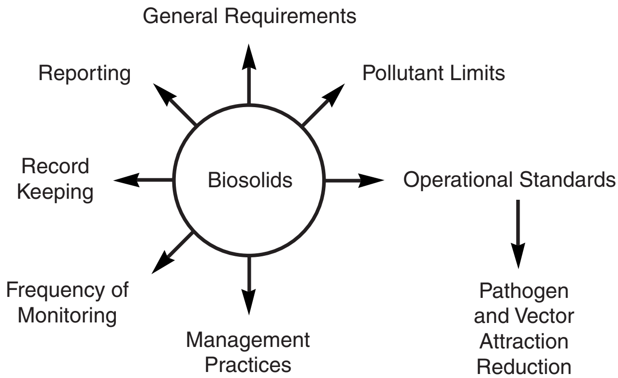


Figure 17.1 Overview of the EPA Part 503 rule's land application requirements for biosolids.

Under Part 503, land application includes all forms of applying biosolids to the land for beneficial uses at agronomic rates (rates designed to provide the amount of nitrogen needed by the crop or vegetation grown on the land while minimizing the amount that passes below the root zone). These include application to agricultural land, such as fields used for the production of food, feed and fiber crops, pasture and rangeland; nonagricultural land, such as forests; disturbed lands, such as mine spoils, constructions sites, and gravel pits; public contact sites, such as parks and golf courses; and home lawns and gardens. The distribution and marketing of biosolids-derived materials, such as composted, chemically stabilized or heat-dried products, is also addressed under land application, as is land application of domestic septage.

The rule applies to the person who prepares biosolids for land application or applies biosolids to the land. These parties must obtain and provide the necessary information needed to comply with the rule. For example, the person who prepares bulk biosolids that is land applied must provide the person who applies it to land all information necessary to comply with the rule, including the total nitrogen concentration of the biosolids.

The regulation establishes two levels of biosolids quality (see Table 17.1) with respect to nine heavy metal concentrations—pollutant ceiling concentrations and pollutant concentrations ("high-quality" biosolids); two levels of quality with respect to pathogen densities—class A and class B (see Table 17.2); and

TABLE 17.1 Part 503 Pollutant Limits and Loading Rates; Composition of Biosolids in NSSS

	Part 503 numeric criteria, Table in Part 503 Rule				NSSS results,[a] median values statistical basis	
	Table 1	Table 2	Table 3	Table 4[d]		
Pollutant	Ceiling concentration limits,[b] mg/kg	Cumulative pollutant loading rates, kg/ha	"High-quality" pollutant concentration limits,[c] mg/kg	Annual pollutant loading rates, kg/(ha·year)	Normal, mg/kg	Maximum,[e] mg/kg
Arsenic	75	41	41	2.0	5	5
Cadmium	85	39	39	1.9	7	4
Chromium[f]	3000[f]	3000[f]	1200[f]	150[f]	40	39
Copper	4300	1500	1500	75	463	456
Lead	840	300	300	15	106	76
Mercury	57	17	17	0.85	4	2
Molybdenum	75	18[f]	18[f]	0.90[f]	11	5
Nickel	420	420	420	21	29	18
Selenium	100	100	36(100)[f]	5.0	5	3
Zinc	7500	2800	2800	140	725	755

[a]From Refs. 1, 12 and 21. NSSS = National Sewage Sludge Survey.

[b]Absolute values.

[c]Monthly averages.

[d]It is anticipated that in July 2000, EPA will propose to delete Table 4 from the rule as part of a settlement with NRDC over a lawsuit concerning the original Part 503 rulemaking.

[e]Pollutant concentrations for samples below the detection limit were incorporated into estimates through the maximum likelihood procedure for multiple censor points to produce a better estimate than procedures that substitute either zero or the detection limit for nondetect samples.

[f]A Feb.25, 1994, *Federal Register* Notice deleted the values for molybdenum in Tables 2, 3, and 4; new values (expected to be higher, less stringent) are anticipated to be proposed for public comment during July 2000; Cr dropped from coverage and Se value for Table 3 raised as part of final revisions published in the *Federal Register* on Oct. 25, 1995.

TABLE 17.2 Part 503 Pathogen (Indicator Organism) Density Limits for Class A and Class B Biosolids

Classification	Fecal coliforms	Salmonella spp.
Class A*	<1000 MPN/g TS	3 MPN/4g TS
Class B	<2,000,000 MPN/g TS <2,000,000 CFU/g TS	

*In addition, density limits of >1 PFU/4g TS for enteric virus and >1/4g TS for viable helminth ova are included for evaluating sludge treatment processes that cannot meet specific operational requirements (i.e., time/temperature/pH relationships) specified in the rule.

Abbreviations: MPN = most probable number

TS = total solids

CFU = colony-forming units

PFU = plaque-forming units

Class A Processes:

- Alternative 1: Thermally treated biosolids meeting specific time and temperature regimes.
- Alternative 2: Biosolids treated by specified high pH–high temperature process.
- Alternative 3: Biosolids treated by other processes that do not meet alternative 1 or 2; relies on comprehensive monitoring of fecal coliforms or *Salmonella* spp. bacteria, enteric viruses, and viable helminth ova to demonstrate reduction of pathogens as specified in the Part 503 rule.
- Alternative 4: Biosolids treated by unknown processes; relies on comprehensive monitoring of fecal coliforms or *Salmonella* spp. bacteria, enteric viruses, and viable helminth ova to demonstrate reduction of pathogens as specified in the Part 503 rule.
- Alternative 5: Use of one of the "Processes to Further Reduce Pathogens" (PFRP) from 40 CFR Part 257 (i.e., including composting, heat drying, heat treatment, thermophilic aerobic digestion, beta ray and gamma ray irradiation, and pasteurization following specified process requirements).
- Alternative 6: Use of a process equivalent to a PFRP.

Class B Processes:

- Alternative 1: Monitoring of fecal coliforms.
- Alternative 2: Use of one of the "Processes to Significantly Reduce Pathogens" (PSRP) from 40 CFR Part 257 (i.e., including aerobic digestion, air drying, anaerobic digestion, composting, lime stabilization following specified process requirements).
- Alternative 3: Use of a process equivalent to a PSRP.

two types of approaches for meeting vector attraction reduction, biosolids processing or the use of physical barriers (see Table 17.3). Under the Part 503 regulation, fewer restrictions are imposed on the use of higher-quality biosolids. Biosolids products that meet the "high-quality" pollutant concentrations, class A pathogen reduction requirements, and use of the eight processes for meeting vector attraction reduction requirements can pass out of the regulation and be managed like any other commercial organic fertilizer and soil amendment product.

Based upon the National Sewage Sludge Survey (NSSS) published in November 1990 (see summary in Table 17.1), a large percentage of the biosolids currently produced should be capable of meeting the "high-quality" pollutant concentrations. While a majority of the POTWs currently produce biosolids treated by class B pathogen reduction processes, the number of facilities producing biosolids meeting the class A pathogen reduction requirements is increasing.

To qualify for land application, biosolids or material derived from biosolids must meet at least the pollutant ceiling concentration limits (Table 1, in Table 17.1), class B requirements for pathogens, and the vector attraction reduction requirements. Cumulative pollutant loading rates are imposed on biosolids that meet the pollutant ceiling concentrations but not the "high-quality" pollutant concentrations (Table 3 in Table 17.1). A number of general requirements and management practices apply to biosolids that are land applied (see Table 17.4) other than "exceptional-quality" biosolids or derived material that meets three quality requirements—the "high-quality" pollutant concentration, class A pathogen requirements, and vector attraction reduction biosolids processing. However, in all cases, the minimum frequency of monitoring, record keeping, and reporting requirements (see Table 17.5) must be met. More detailed guidance on the Part 503 requirements is available elsewhere.[13]

Key Design Considerations

Most biosolids, as well as other nonhazardous organic residuals from many industries, can be effectively managed by land application. This chapter considers four basic methods that are designed for treatment and reuse; landfilling, incineration, and other disposal categories are covered elsewhere.[14,15] In addition,

TABLE 17.3 Vector Attraction Reduction Alternatives

Processing Alternatives
1. *Aerobic or anaerobic digestion* which achieve a ≥38% reduction in volatile solids (VS) measures as the difference in the raw sewage sludge prior to stabilization and the treated sewage sludge ready for use or disposal.
2. *Anaerobic digestion* (if 38% VS reduction cannot be met)—demonstrated by further digesting a portion of the digested sewage sludge in a bench-scale unit for an additional 40 days at 30 to 37°C or higher and achieving a further VS reduction of <17%.
3. *Aerobic digestion* (if 38% VS reduction cannot be met)—demonstrated by further digesting a portion of the digested sewage sludge with a solids content of ≤2% in a bench-scale unit for an additional 30 days at 20°C and achieving a further VS reduction of <15%.
4. *Aerobic digestion*—specific oxygen uptake rate (SOUR) is ≤1.5 mg O_2/h/g of TS at 20°C.
5. *Aerobic processes*—(e.g., composting) temperature is kept at >40°C for at least 14 days, and the average temperature during this period is greater than 45°C.
6. *Alkaline stabilization*—pH is raised to at least 12 by alkali addition and, without the addition of more alkali, remains at 12 or higher for 2 h and then at 11.5 or higher for an additional 22 h.
7 and 8. *Drying*—TS is ≥75% when the sewage sludge does not contain unstabilized primary solids and ≥90% when unstabilized primary solids are included. Blending with other materials is not allowed to achieve the total solids percent.
Physical Barrier Alternatives
9. *Injection*—Liquid sewage sludge (or domestic septage) is injected beneath the surface with no significant amount of sewage sludge present on the surface after 1 h; sewage sludges that are Class A for pathogen reduction shall be injected within 8 h of discharge from the pathogen reduction process.
10. *Incorporation*—Sewage sludge (or domestic septage) that is land applied or placed in a surface disposal site shall be incorporated into the soil within 6 h of application; sewage sludge that is class A for pathogen reduction shall be incorporated within 8 h of discharge from the pathogen reduction process.

TABLE 17.3 Vector Attraction Reduction Alternatives *(Continued)*

Alternative for Surface Disposal of Sewage Sludge or Septage
11. *Surface disposal daily cover*—Sewage sludge or domestic septage placed in a surface disposal site shall be covered with soil or other material at the end of each operating day.
Alternative for Septage Only
12. *Domestic septage treatment*—The pH of domestic septage is raised to 12 or higher by alkali addition and, without the addition of more alkali, remains at 12 or higher for 30 min. This alternative is applicable to domestic septage applied to agricultural land, forest or reclamation sites, or placed in a surface disposal site.

TABLE 17.4 General Requirements and Management Practices for Land Application*

General Requirements
■ Bulk sewage sludge subject to cumulative pollutant loading rates shall not be applied to agricultural land, a forest, public contact, or reclamation site if any of the cumulative pollutant loading rates have been reached.
■ Preparers of bulk sewage sludge to be applied to agricultural land, a forest, public contact, or reclamation site shall provide appliers written notification of the total nitrogen concentration (dry weight) in the bulk sewage sludge and other information necessary to comply with the 503 requirements.
■ Appliers shall obtain information to comply with requirements, contact the permitting authority to determine if (and how much) material subject to cumulative loadings has been applied before.
■ Appliers of bulk sewage sludge shall provide land application site owners or lease holders with notice and information necessary to comply with the 503 requirements.
■ Preparers of bulk sewage sludge to be applied in a state other than the state in which the material is prepared shall provide written notice, prior to the initial application of the bulk material to a land application site by the applier, to the permitting authority for the state in which the bulk material is proposed to be applied.
■ Appliers of bulk sewage sludge subject to cumulative loading rates shall provide written notice, prior to the initial application of bulk sewage sludge to a land application site by the applier, to the permitting authority for the state in which the bulk sewage sludge will be applied, and the permitting authority shall retain and provide access to the notice.
Management Practices
■ Bulk sewage sludge shall not be applied to the land if it is likely to adversely affect a threatened or endangered species listed under the Endangered Species Act or its designated critical habitat.

TABLE 17.4 General Requirements and Management Practices for Land Application* *(Continued)*

Management Practices
■ Bulk sewage sludge shall not be applied to agricultural land, a forest, public contact, or reclamation site that is flooded, frozen, or snow-covered ground so that the sewage sludge enters a wetland or other waters of the United States except as provided in a permit issued under section 402 or 404 of the CWA.
■ Bulk sewage sludge shall not be applied to agricultural land, a forest, public contact, or reclamation site at above agronomic rates, with the exception of reclamation projects when authorized by the permitting authority.
■ Bulk sewage sludge shall not be applied to agricultural land, a forest, or reclamation site that is <10 m from waters of the United States unless authorized by the permitting authority.
■ For sewage sludge sold or given away, either an appropriate label shall be affixed to the material's bag or container, or an information sheet containing specific information shall be provided to the receiver of the material for land application.
Additional Specific Management Practices for Class B Biosolids
1. Food crops with harvested parts that touch the biosolids and soil mixture (such as melons, cucumbers, squash, etc.) shall not be harvested for *14 months* after application.
2. Food crops with harvested parts below the soil surface (root crops such as potatoes, carrots, radishes) shall not be harvested for *20 months* after application if the biosolids are not incorporated for at least 4 months.
3. Food crops with harvested parts below the soil surface (root crops such as potatoes, carrots, radishes) shall not be harvested for *38 months* after application if the biosolids are incorporated in less than 4 months.
4. Food crops, feed crops, and fiber crops shall not be harvested for *30 days* after biosolids application.
5. Domestic animals shall not be grazed on a site for *30 days* after biosolids application.

6. Turf shall not be harvested for *1 year* after biosolids application if the turf is placed on land with a high potential for public exposure or a law, unless otherwise specified by the permitting authority.
7. Public access to land with high potential for public exposure shall be restricted for *1 year* after biosolids application.
8. Public access to land with a low potential for public exposure shall be restricted for 30 days after biosolids application.

---

*The permitting authority may apply any or all of the general requirements or management practices to land application of bulk exceptional quality (EQ) sewage sludge or a product derived from an EQ sewage sludge on a case-by-case basis if determined needed to protect public health and the environment.

TABLE 17.5 Minimum Frequency of Monitoring, Record Keeping, and Reporting Requirements

Monitoring Frequency*

Biosolids amounts, dry metric tons per year	Monitoring frequency
>0 to<290	Once per year
290 to <1500	Once per quarter
1500 to <15,000	Once per 60 days
≥15,000	Once per month

Record Keeping†

Generators / preparers…shall develop information and retain records:

- On the concentration of each chemical pollutant regulated under Part 503
- Certification (based on results of required periodic sampling and analysis) that the material meets the applicable pollutant concentration criteria
- Certify that applicable pathogen and vector attraction reduction requirements have been met

Appliers…shall develop information and retain records:

- Description of how the applicable management practices and site restrictions have been met for each application site
- For sewage sludges limited by cumulative loading limits, keep records indefinitely of the cumulative amount of each pollutant applied to each site, information of the location and size of each site, date and time of applications, etc.
- Certification that vector attraction reduction requirements have been performed in accordance with 503 if using injection or soil incorporation

Reporting Frequency

Annual reporting is required of all class I sewage sludge management facilities (i.e., the ~1600 pretreatment POTWs and ~400 other "designated" TWTDs such as sludge only facilities) and other "major" POTWs—those with a design flow ≥1 Mgal/day or serving a population of ≥10,000 people. In addition, for sites where record keeping is required the same group of facilities shall report annually when any cumulative metal loading reaches 90% of the allowed cumulative pollutant loading rates (Part 503 Table 2 values).

*The permitting authority may impose more frequent monitoring requirements on permittees; in addition, after 2 years of monitoring at these frequencies, the permitting authority may allow the monitoring frequencies to be reduced to no less than once per year.

†Record-keeping requirements vary with the end use of the sewage sludge or derived material. Except as noted records must be kept for 5 years.

the marketing and management of high-grade biosolids-based products that are widely marketed for various commercial uses (e.g., use in fertilizer blends, topsoil, and potting soil production; use in landscaping and the establishment and maintenance of turf and plantings at golf courses, parks, and recreation areas, highway medians, home lawns, etc.) is not addressed here. The four basic categories of biosolids land application systems addressed include:

- Agricultural utilization: biosolids are used as a source of fertilizer nutrients and/or as a soil amendment.
- Forest utilization: biosolids are used to enhance forest productivity.
- Site reclamation: biosolids are used to reclaim disturbed land, such as strip-mined areas.
- Soil treatment: biosolids are incorporated in the upper soil layer for treatment by soil organisms. Most common for industrial wastes such as petroleum sludges and toxic and hazardous materials.

The LDP for design of all these systems are the sludge constituents and characteristics. For example, the annual application of an agricultural operation may be determined by nitrogen or phosphorus considerations, while the useful life of a site may be limited by one or more heavy metals. However, when liquid biosolids are used, the hydraulic capacity of the site soils may limit individual application events, while nutrients or metals may still limit annual and cumulative loadings. Other factors that play an important role in the design of any land application alternative include the availability of land, constraints created by the available application sites, capability of the equipment to be used, and climatic conditions, as well as constraints imposed by applicable local, state, and federal requirements. Nutrient management plans that account for all sources of nutrient inputs to land application sites have become an important component of project planning efforts and facilitating the use of biosolids at agronomic rates.

Biosolids Sources and Characteristics

Data will usually be available on the quantity, type of preapplication treatment provided, and characteristics of biosolids to be expected, although in some cases these may need to be estimated from similar systems elsewhere. Estimates of projected biosolids quantities and quality are needed to determine land area requirements, site life, application rates, storage requirements, etc. Information about the physical characteristics of the biosolids is needed to select appropriate transportation and application methods. Chemical characterization and type of preapplication treatment is required to determine the suitability of the biosolids for land application, which land application options may be appropriate, appropriate application rates, and monitoring parameters. Data from routine biosolids analyses required for designing and operating land application projects typically will include at least percent solids, total N, ammonia N, total P, K, As, Cd, Cu, Pb, Hg, Mo, Ni, Se, and Zn, as well as the applicable pathogen indicators and any other parameters required by local and state authorities.

Site and Process Evaluation

A preliminary estimate of the land area required for screening purposes can be determined for municipal biosolids with Table 17.6. Estimates of soil treatment area for industrial sludges should be based on the critical LDP with the criteria in Chap. 3.

Site selection follows the same general approach described in Chap. 6. Slope limitations and recommended setback distances are summarized in Tables 17.7 and 17.8 for class B biosolids. Detailed guidance for site selection and evaluation is given in Ref. 16.

Agricultural Utilization

The design approach is based on the utilization of biosolids as a supplement or replacement for commercial fertilizers. As a result, the annual application is based on either the N or P needs of the crop in a particular soil. In addition, the cumulative metal loadings from biosolids additions to individual fields must be consistent with regulatory limits (Table 2 of Part 503) unless the biosolids meet the “high-quality” pollutant concentration limits (Table 3 of Part 503). A design approach based upon the nitrogen needs of the crop should then impose no greater impact on the groundwater than conventional farming operations in the area with application of commercial fertilizers. As a result, groundwater monitoring is not typically required for agricultural systems.

TABLE 17.6 Estimated Land Area for Municipal Biosolids Applications

Option	Application period	Reported range, dry tons/acre	Typical rate, dry tons/acre
Agricultural	Annual	1–30	5
Forest	One application or at 3- to 5-year intervals	4–100	8
Reclamation	One application	3–200	35–50

TABLE 17.7 Recommended Slopes for Class B Biosolids Sites[16]

Slope, %	Comment
0–3	Ideal; no concern for runoff or erosion of liquid or dewatered cake
3–6	Acceptable for surface application or injection of liquid or dewatered cake; slight risk of erosion
6–12	Injection of liquid biosolids required in most cases, except closed drainage areas with extensive runoff control. Surface application of dewatered cake is usually acceptable
12–15	No liquid biosolids application without effective runoff control; surface application of dewatered cake is acceptable, but immediate incorporation is recommended, plus effective runoff controls
>15	Requires special measures (e.g., biosolids + fly ash mixtures) to control runoff from application site

TABLE 17.8 Recommended Setback Distances for Class B Biosolids Sites

Distance, ft.	Criteria
50–300	Injection and incorporation only near single dwellings, ponds, and lakes, 10-year high-water mark for streams, roads. No surface applications
300–1500	Injection or surface application near all the above, plus springs and water supply wells; injection only near high-density residential developments
>1500	Injection or surface application at all the above

Most states require that soils at biosolids application sites be maintained at a soil pH of 6.5 or above. Some states' cumulative limits for metals differ from the EPA Part 503 Table 2 values, so specific values must be obtained in the planning stage for each project. Information on fertilizer recommendations for a particular crop in a specific location can be obtained from the Agricultural Experiment Station in each state or from local extension personnel. A preliminary estimate of crop nutrient needs can be determined with procedures in Chap. 5. The design is then based on meeting either N or P needs. Optimum yields and crop production may then require supplemental fertilization for the other nutrients (N, P, K).

Nitrogen limits

To minimize the amount of N that will pass below the plant root zone to potentially contaminate groundwater with nitrate N, the Part 503 rule requires bulk biosolids to be applied at a rate that is equal to or less than the agronomic rate for plant-available N at the site. Since much of the biosolids nitrogen is in the organic form, it is not all immediately available to the plants. A portion will "mineralize" each year and become available, as described in Chap. 3. These contributions must be included in the mass balance for determining the annual application rate. Table 3.12 contains suggested mineralization rates for different municipal biosolids when specific rates cannot be determined. Example 3.5 demonstrates the procedures for animal manures, and it would be similar for surface applied biosolids.

Metal limitations

Biosolids with metal concentrations that exceed the Part 503 Table 3 pollutant concentration limits but still meet the Table 1 ceiling concentration limits will be required to track cumulative loading rates of metals. They might also have an annual application limit imposed by the state in addition to the Part 503 cumulative pollutant loading rates. The cumulative biosolids application rate based on metal limits is given by

$$S_m = \frac{M_L}{(C_M)\,(2000)} \tag{17.1}$$

where S_m = biosolids application rate, for the time interval selected, dry tons/acre

M_L = metal limitation of concern, lb/acre

C_M = percent metal content in the biosolids, as a decimal (e.g., 0.005% = 0.00005) with 50 ppm Cd = 0.005% Cd

Phosphorus loading determination

The design calculation when crop uptake of P is specified as the limiting parameter takes a similar form:

$$S_P = \frac{U_p}{C_P\,(2000)} \qquad (17.2)$$

where S_P = annual biosolids application rate based on crop uptake of P, dry tons/acre

U_p = annual crop uptake of P, lb/acre (see Table 5.7 for typical values)

C_P = percent available phosphorus in biosolids, as a decimal. Assume only 50 percent in the biosolids is available.

The C_P for a biosolid with 20 ppm P would be

$$C_P = (0.50)\,(0.00002) = 0.00001$$

Biosolids loading determination

The calculation procedure for biosolids loading on a nitrogen basis is a three-step procedure:

1. Determine the plant-available nitrogen N_P in the biosolids during the application year.

$$N_P = (2000)\,[NO_3 + K_v\,(NH_4) + f_1\,(ON)\,] \qquad (17.3)$$

where N_P = plant-available nitrogen in biosolids during application year, lb/dry ton of biosolids

NO_3 = percent nitrate nitrogen in the biosolids, as a decimal

K_v = volatile factor (fraction of NH_4-N not lost as NH_3 gas to the atmosphere) : 0.5 for surface applied liquid biosolids, 1.0 for incorporated liquid biosolids and dewatered digested biosolids applied in any manner

NH_4 = percent ammonia nitrogen in the biosolids, as a decimal

f_1 = mineralization factor (fraction of ON converted to N_P) for the first year as a decimal. See Table 3.12. Example: f_1 for digested biosolids = 0.3

ON = percent organic nitrogen in the biosolids, as a decimal. Can be estimated as total N − (NO_3-N + NH_4-N)

2. Determine the plant-available nitrogen N_{PR} from mineralization of the residual biosolids in subsequent years.

$$N_{PRI} = 2000\Sigma f_2\,(ON)_2 + f_3\,(ON)_3 + \cdots + f_n(ON)_n \quad (17.4)$$

where N_{PRI} = percent plant-available nitrogen from mineralization of the first year's biosolids in subsequent years, as a decimal

f = mineralization rate (Table 3.12) as a decimal; subscripts refer to the year of concern

ON = percent organic nitrogen remaining in the biosolids in a particular year. Subscripts refer to the year of concern, as a decimal

A system with continuous annual application will have to solve Eq. (17.4) for each of the subsequent years, i.e., N_{PR2}, N_{PR3}, etc. A tabular form is recommended for summation of the plant-available nitrogen from all sources for each year. The calculation will converge on a relatively constant value after 5 to 6 years if the biosolids composition remains the same.

3. The annual biosolids loading S_{NY} based on nitrogen is determined with

$$S_{NY} = \frac{U_N}{\Sigma N_P + N_{PRI} + \cdots + f_n(ON)_n} \quad (17.5)$$

where S_{NY} = annual biosolids loading in year y of concern, dry tons/acre

U_N = crop uptake of N (see Table 5.7) lb/ (acre · year)

$N_P + N_{PRI}$ = from Eqs. (17.3) and (17.4)

Land area determination

The land area calculation is a five-step process:

1. Determine S_N or S_P loading rates depending on state requirements.
2. Determine S_M based on cumulative metal limits.

3. The LDP for design is then the more stringent of steps 1 or 2 above.
4. Determine the land area required with

$$A = \frac{Q_S}{S_{LDP}} \tag{17.6}$$

where A = land area required, acres
Q_S = total annual biosolids production, dry tons/year
S_{LDP} = limiting biosolids loading from step 3 above, dry tons/ (acre · year)

5. Use Eq. (17.1) and the values in Part 503 Table 2 to determine the useful life of the site.

Example 17.1: Determine Land Area for Application of Anaerobically Digested Municipal Biosolids

Conditions

a. Biosolids production: 22 dry tons/day

b. Biosolids characteristics: As = 35 ppm; Cd = 40 ppm; Cu = 500 ppm; Pb = 500 ppm; Hg = 8 ppm; Mo = 15 ppm; Ni = 100 ppm; Se = 30 ppm; Zn = 2000 ppm; total N = 2.5%; NH_4 = 1.0%; NO_3 = 0. Note that all metals meet the Part 503 Table 1 ceiling concentration limits, while both Cd and Pb levels exceed the "high-quality" Part 503 Table 3 pollutant concentration limits requiring tracking of cumulative loading rates on a field-by-field basis.

c. Biosolids will be incorporated, so $K_v = 1$; corn is the intended crop with U_N = 160 lb/(acre·year) (Table 5.7).

d. State allows design based on N fertilization rates.

Mineralization rates (Table 3.12) for anaerobically digested biosolids:

Year	f
1	0.30
2	0.10
3	0.05

Solution

1. Organic nitrogen:

$$\begin{aligned} ON &= \text{total N} - NH_4 \\ &= 2.5 - 1 = 1.5\% = 0.015 \end{aligned}$$

a. Available nitrogen first year:

$$N_P = (2000)[0 + 1(0.01) + 0.30(0.015)]$$
$$= 29 \text{ lb/ton of biosolids}$$

b. First year's biosolids, organic N remaining in second year:

$$ON_2 = (0.015) - (0.30)(0.015)$$
$$= 0.0105$$

Amount of first year's biosolids mineralized in second year:

$$N_{PR2} = (f_2)(ON_2) = (2000)(0.10)(0.0105)$$
$$= 2.1 \text{ lb/ton of biosolids}$$

c. First year's biosolids, organic N remaining in third year:

$$ON_3 = (0.0105) - (0.10)(0.0105) = 0.00945$$

Mineralization of first year's biosolids in third year:

$$N_{PR3} = (2000)(f_3)(ON_3) = (2000)(0.05)(0.00945)$$
$$= 0.945 \text{ lb/ton of biosolids}$$

2. Repeat the calculations for biosolids applied in years 2 through 3 and tabulate results:
   a. For all applications:

Year after application	N_{PR}, lb/ton
2	2.1
3	0.9

b.

Year	Total available N, lb/dry ton	Annual biosolids loading S_N [Eq. (17.5)], dry tons/(acre·year)
1	29	6.15
2	29 + 2.1 = 31.1	5.14
3	29 + 2.1 + 0.9 = 32.0	5.0

3. Calculate the annual biosolids loading based on Cd, assuming a state limit of 0.5 lb/(acre·year)

$$S_M = \frac{0.5}{(0.00004)(2000)} = 6.25 \text{ tons/acre}$$

4. For this example, nitrogen controls the design.
5. Use the "steady-state" S_N to determine the land area:

$$A = \frac{(22 \text{ tons/day})(365 \text{ days/year})}{5.0 \text{ tons/(acre·year)}} = 1606 \text{ acres}$$

6. Determine design life of site:
   a. From Ref. 16:

Allowable cumulative loading		
Metal	lb/acre	kg/ha
Arsenic	37	41
Cadmium	35	39
Copper	1300	1500
Lead	270	300
Mercury	15	17
Nickel	380	420
Selenium	90	100
Zinc	2500	2800
Design loading = 5.0 tons/(acre·year)		

   b. Typical computation:

$$\text{Annual Pb} = (0.0005)(2000)(5.0) = 5.0 \text{ lb/(acre·year)}$$

$$\text{Useful life} = \frac{270}{5.0} = 54 \text{ years}$$

   c. Summary:

Metal	Useful life, years
Arsenic	105.7
Cadmium	87.5
Copper	260
Lead	54
Mercury	187.5
Nickel	380
Selenium	300
Zinc	500

7. Therefore, the cumulative lead loading would limit use of the site to 54 years to avoid any potential future restrictions on use of the site. The cumulative biosolids applied to this forested site would be 270 tons/acre.

Monitoring and application scheduling

The design example above is based on criteria and regulatory guidance available in late 1999. Reference 16 should be used for design of transportation and application procedures. Since the design is typically based on the most limiting parameter, monitoring for these parameters should not be necessary beyond routine agricultural soil testing for plant-available N, P, and K and to determine lime requirements for pH maintenance as appropriate for crop-production purposes.

The schedule for biosolids applications will depend on the type of crop and on the climate for the area. Biosolids are not usually applied when the ground is frozen to reduce risk of runoff losses. Biosolids can be applied to the fields for row crops prior to planting and after harvest. Biosolids application to forage grasses is usually possible in all months of the year when the ground is not frozen.

Forest Utilization

Many aspects of system design for forest sites are similar to the previous case, so criteria in Tables 17.2 and 17.3 and the related discussion are applicable. Site options include applications in existing forests or developing a new plantation. In the former case, the biosolids will be typically sprayed as a liquid, flung as a dewatered cake, or blown as dry pellets, often from specially equipped trucks designed to deal with access difficulties.

Seedlings of some tree species show poor survival when planted directly in freshly applied biosolids. It may be necessary to let the biosolids age for 6 months or more to allow for salt leaching and ammonia volatilization.

Seedlings have low nitrogen uptake rates. An intensive program of weed control is necessary, since the weeds grow faster than the seedlings and compete for nutrients, space, light, etc. Use of herbicides and cultivation between tree rows is usually required for the first 3 to 4 years. Intensive browsing by deer and damage to young trees by voles and other pest species may require special control measures, since these animals may selectively feed upon trees grown on biosolids-amended sites due to their higher food value. Young forest plantations (trees over 2 years old) are more tolerant to biosolids applications and weed control is less of a problem. However, individual liquid and cake biosolids applications may be limited to avoid heavy biosolids deposits on the foliage.

The plant nitrogen uptake will be highest in an established forest (over 10 years old) as compared to the previous cases. However, the N uptake will diminish for "mature" trees (30 to 60 years old). Application is possible under the leaf canopy so foliage problems will not occur. The major difficulty with established forests is access. The maximum range of truck-mounted spray systems is about 120 ft, while spreaders may be able to effectively apply dewatered cake or dried pellets 200 ft or more. Therefore to ensure uniform coverage a road grid system needs to be established based upon realistic spreading distances for the equipment and biosolids involved.

Forest application scheduling

In many cases it is typical to apply a large single quantity of biosolids every 3 to 5 years rather than smaller annual applications, owing to the costs and complexity of transport and access for distribution. As described in the agricultural case, a small annual application will have no greater effect on the groundwater than conventional agricultural operations. A large application every 3 to 5 years may result in some of the nitrogen being available for movement to groundwater via percolation. The nitrogen of concern would be the portion of mineralized organic N (ON) that is not taken up by the plants in the first year. This residual could be nitrified in the soil and move down to the groundwater with the net precipitation falling on the site. An estimate of this quantity can be obtained with the calculations demonstrated in Example 17.1 combined with the procedures in Chap. 10.

The basic design procedure for forested sites is the same as described in the previous case. The plant-available nitrogen is determined with Eq. (17.3). In this case when the application involves surface applied liquid biosolids, the K_v is equal to 0.5. The plant uptake values for Eq. (17.5) can be found in Table 5.10.

Biosolids loading for forest sites

There is some variation in the design approach for forested sites. In the typical forested project the annual loading will usually be based on nitrogen. There are insufficient data on cumulative metal loadings with respect to toxicity to forest plants. However, the Part 503 metal limits for land applied biosolids do apply to forested sites.

Example 17.2: Determine Land Area for Application of Anaerobically Digested Biosolids in an Established Forest

Conditions Same as Example 17.1, except $K_v = 0.5$, $U_N = 300$ lb/(acre · year) (Table 5.10). Use annual applications.

Solution

1. Nitrogen available in application year:

$$N_P = (2000)[0 + 1(0.5)(0.01) + 0.30(0.015)]$$
$$= 19 \text{ lb/ton dry biosolids}$$

2. Summary of total available N including mineralized fractions:

Year	Total available N	S_N
1	19	15.8
2	19 + 2.1 = 21.1	14.2
3	19 + 21.1 + 0.9 = 22.0	13.6

3. $$\text{Land area} = \frac{(22 \text{ tons/day})(365 \text{ days/year})}{(13.6 \text{ tons/(acre·year)}} = 590 \text{ acres}$$

4. Design life at 13.6 tons/year

   a. Typical calculation:

$$\text{Annual Pb} = (0.0005)(2000)(13.6) = 13.6 \text{ lb/(acre·year)}$$

$$\text{Useful life} = \frac{270}{13.6} = 19.8 \text{ years}$$

   b. Similarly,

Metal	Useful life, years
Arsenic	32.5
Cadmium	32.1
Copper	95.5
Lead	19.8
Mercury	68.9
Nickel	139.7
Selenium	110.2
Zinc	45.9

In this case the useful life is limited to 19.8 years because of the cumulative limit for lead to avoid any potential future restrictions on use of the site. The cumulative biosolids applied to this forested site would be 270 tons/acre. If application is limited to the 120-ft strip on either side of existing roads and accessible fire breaks, then about 20.6 mi of such roads would be required.

Application scheduling in forests will depend on the growth stage of the trees and climate for the area. Frozen ground conditions should be avoided. Applications should not be made to young plantations during the growing season to avoid foliage damage. Reference 16 provides detail on transport and application equipment.

Site Reclamation

Extensive areas of disturbed land exist throughout the United States as a result of mining operations. Also fairly widespread are areas where dredge spoils, coal wastes, or fly ash have been deposited, and construction areas (e.g., roadway cuts, borrow pits).

Most disturbed lands are difficult to revegetate. These sites generally provide a harsh environment for seed germination and subsequent plant growth. Major soil problems may include a lack of nutrients and organic matter, low pH, low water-holding capacity, low rates of water infiltration and permeability, poor physical properties, and the presence of toxic levels of trace metals. To correct these conditions, large applications of lime and fertilizer may be required, and organic soil amendments and/or mulches also may be necessary. Biosolids provide a low-cost beneficial substitute for some of these commercial products.

A major distinction between this case and the previous two is that biosolids are typically required in large amounts the first year to reestablish fertility and vegetation. As a result the design is based on a one-time application to a particular area. It is therefore necessary that there be a sufficient area of disturbed land available each year of the design life of the project. When mining operations are involved, the state and federal regulations on mine land restoration apply in addition to applicable biosolids management rules.

The general site considerations discussed previously apply to this case also. Crop selection is more unique, since revegetation is often the major goal. Before and after photographs are presented in Figs. 17.2 and 17.3 for sites that were reclaimed using biosolids.

If the aim of the reclamation effort is to establish a vegetative cover sufficient to prevent erosion, a perennial grass and legume mixture is a good crop selection. It is important to select species that are not only compatible but also grow well when biosolids are used as the fertilizer and soil conditioner. The rationale for the selection of grass and legume seeding mixtures is that the grass species will germinate quickly and provide a complete protective cover during the first year or two, allowing time for the legume species to become established and help support a sustainable vegetative cover. The grasses will also take up a large amount of the nitrogen, preventing it from leaching into the groundwater. Since legume species can fix nitrogen from the atmosphere, additional nitrogen applications are often unnecessary. In some cases trees have been successfully established on reclamation sites after a grass and legume cover has been established; in other cases trees have been directly planted into biosolids-amended mine spoils and successfully established as a vegetative cover.

Plant species to be used should be selected because of their ability to grow under droughty conditions, and their tolerance for either acid or alkaline soil material—depending upon the local climate and site conditions. Salt tolerance is also desirable.

If a site is to be reforested, it is still generally desirable to initially seed it with a mixture of grasses and legumes. The initial grass and legume cover helps to protect the site from erosion and surface runoff and to take up the nutrients supplied by the biosolids. Planting slow-growing tree species is generally not recommended because they generally do not compete well with the initial herbaceous cover. Fast-growing hardwoods such as hybrid poplars are often recommended.

Biosolids application rates

The basic design approach is to determine the maximum cumulative loading based on metals (Part 503 Table 2 cumulative loading limits) if applicable to the biosolids to be used and then apply that or an appropriate volume of biosolids needed for reclamation in a single application period. In some cases the appropriate volume may require multiple applications due to

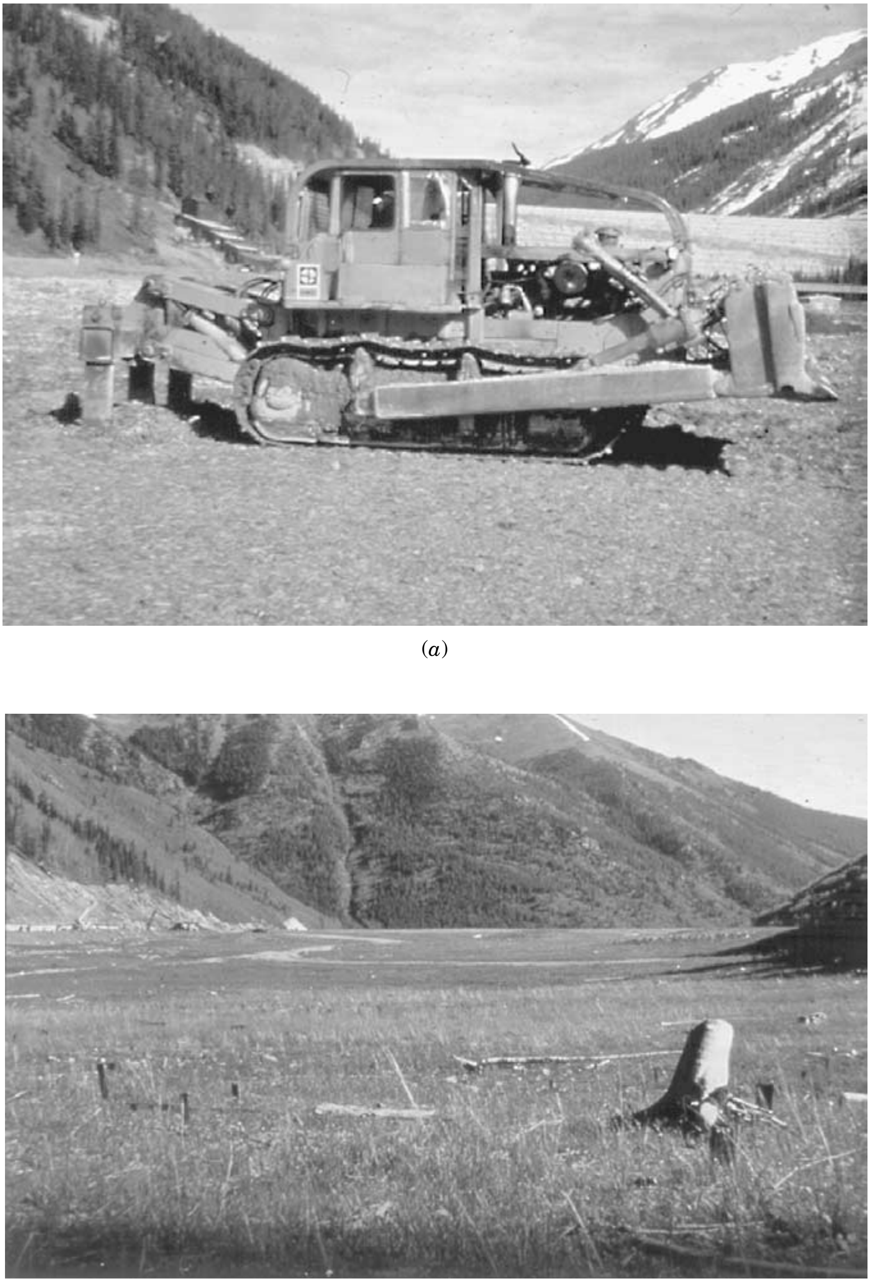


Figure 17.2 Urad, Colorado mine reclamation site. (*a*) Prior to land application of biosolids; (*b*) 1 year after land application of biosolids and revegetation.

(*a*)

(*b*)

Figure 17.3 Sproul State Forest, in Pennsylvania. (*a*) After a forest fire; (*b*) four years after land application of biosolids and revegetation.

the physical characteristics of the biosolids or site limitations. This approach is conservative in that it protects against possible future conversion of the reclaimed site to other land uses. A large initial application is necessary to ensure a sufficient pool of nutrients and organic matter for establishment of the vegetation. This high initial loading may result in some nitrate percolation beneath the site in the first year. In many situations the aquifers are not potential drinking water sources. If the state agency is concerned with groundwater quality at the project boundaries, then the procedures in Chap. 10 should be used. The input parameters for this calculation would be the unused mineralized nitrogen available in the first year and the net precipitation on the site as the percolate volume.

Example 17.3: Determine Land Area for Application of Anaerobically Digested Biosolids for Land Reclamation

Conditions Same as Example 17.1, except U_N = 250 lb/acre for grass (Table 5.7).

Solution Cumulative metal loading from Part 503 Table 2 and Example 17.1 applies.

1. From Part 503 Table 2.
   a. Typical calculation:

Biosolids contains 500 ppm Pb = (0.0005)(2000) = 1 lb/ton of biosolids

$$S_{\text{Pb}} = \frac{270 \text{ lb/acre}}{1 \text{ lb/ton}} = 270 \text{ tons/acre}$$

   b. Similarly:

Metal	Biosolids loading, dry tons/acre
As	528.5
Cd	89
Cu	1300
Pb	270
Hg	937.5
Ni	1900
Se	1500
Zn	625

2. The limiting biosolids loading would be 89 tons based on the

Cd requirements. At a biosolids production rate of 22 tons/day (Example 17.1), the required area would be

$$A = \frac{(22)\,(365)}{89} = 90 \text{ acres}$$

This much disturbed land would be required for each year of operation. Assuming a 12-year operation, which was the time determined in Example 17.1, that total land required is the same for both cases because the same limitations control.

3. For this case the plant-available nitrogen in the first year (assuming incorporation of the biosolids) would be equal to 29 lb N/ton dry biosolids (same as Example 17.1).

$$\text{Total N available} = (29 \text{ lb/ton})(89 \text{ tons/acre}) = 2581 \text{ lb/acre}$$

$$\text{Crop uptake} = 250 \text{ lb/acre}$$

$$\text{Temporary N excess} = 2581 - 250 = 2331 \text{ lb/acre}$$

In theory all of this is mineralized in the first year and some is potentially available for migration with the percolate. Any impact should occur in the first year since the biosolids is applied only once and the mineralization rates are lower in subsequent years. In the typical case this temporary 1-year impact should be acceptable and preferable to the continued environmental degradation if the site remained unrestored. However, prior approval to use such high nitrogen application rates should be obtained from the appropriate regulatory officials. An alternative approach would be to design the forest application project based upon the plant-available nitrogen content of the biosolids to meet the forest crop uptake rate, which would result in an annual biosolids loading rate of 8.6 tons/acre.

Restoration site monitoring

Monitoring, for a short period, may be more detailed for this use than for the previous two because of the larger biosolids application rates involved.

Background sampling. Composite soil samples should be collected from the site for the determination of pH, liming requirements, available nutrients, and trace metals prior to biosolids addition. Water samples from surface streams, lakes, etc., and private household wells in the area should be analyzed for nutrients and trace metals prior to biosolids application. Composite biosolids samples should be collected and analyzed to provide data for use in designing loading rates.

Application sampling. As the biosolids are delivered, grab samples should be taken and analyzed for moisture content to adjust the delivered amount of biosolids to the design rate if there is variation in the biosolids moisture content. Composite biosolids samples should be collected as the biosolids are applied, to document the actual nutrient and trace metal application rate.

Post application monitoring. Monitoring of the biosolids application site after biosolids have been applied can vary from none to extensive, depending on state and local regulations and site-specific conditions. Generally, it is desirable to analyze the soil after 1 year for soil pH changes and heavy metals (if required). In addition, surface and groundwater analysis for nitrogen forms and trace metals may be needed.

Soil Treatment Systems

This concept is possible for that group of waste constituents that are amenable to degradation by the biological organisms in the soil (see Chap. 3 for a detailed discussion). Since many of these sites are permanently dedicated for this purpose and will never be used for food crop production, the cumulative limitation may not apply. The controlling factor on design loading and scheduling is the rate at which the soil system can degrade the material of concern. The concept can be used for high rate applications of municipal biosolids but is most commonly used for industrial sludges and slurries. Historically it was also used for toxic and hazardous materials as well.

Use of the concept for hazardous wastes requires consideration of the cumulative lifetime limits for waste constituents in addition to the soil system interactions that control the short-term loading rate.[17] Restrictions now imposed on land farming of hazardous waste under 40 CFR Part 264 Subpart M have greatly limited the use of this practice for treating hazardous waste. Site closure is necessary when the lifetime limits are reached. Planning for ultimate closure is a necessary part of the activities to obtain a permit to open and operate the site. The final surface in most cases must be covered with a permanent vegetative cover to prevent erosion. If metals or other substances have reached phytotoxic levels for this final vegetation, mixing by deep plowing or other neutralization will be needed.

Dedicated soil treatment systems have been frequently used to treat and dispose of nonhazardous wastes under 40 CFR Part 257 from a wide range of industrial and other sources—food processing wastes, textile wastes, pulp and papermill sludges, oil refinery wastes, soil contaminated by oil or fuel spills, etc. In some cases, such systems have been designed around the requirements imposed on biosolids under the Part 503 rule for dedicated land application as a surface disposal practice, which include management practices, pathogen and vector attraction reduction requirements, as well as cumulative metal loading limits for arsenic, chromium, and nickel in unlined systems without leachate collection and treatment systems.[14]

The LDP for design of these soil systems can be determined with the procedures and criteria in Chap. 3. References 14, 17, 18, 19, and 20 can also contain similar information on a variety of waste materials. Site preparation in most cases includes:

- Removal of surface vegetation
- Subdivision of the area into operational plots
- Construction of runoff control dikes around the entire site
- Grading to promote surface drainage and collection of runoff for treatment and disposal

Sludges are usually surface applied at the design loading rate, allowed to dry if necessary, and then incorporated in the top 6 to 12 in of the soil. The treatment zone may extend to a depth of 5 ft depending on the type of soil, type of treatment expected, and amount of percolation allowed.

Land treatment of oil refinery wastes has been routinely practiced in the United States for over 25 years. About one-third of the refineries in the United States have had either full-scale or pilot-scale land treatment systems.[20] Oil reduction at these full-scale facilities ranges from 70 to 90 percent. Annual loadings range from 70 to almost 2000 bbl of oil/acre but are typically about 400 bbl/(acre·year). A rate of 400 bbl/(acre·year) is approximately 5.8 lb of oil per cubic foot of soil or 7.2 percent oil in the soil within a 6-in incorporation depth. This annual loading might be applied in monthly increments or two to three times per year depending on site climate and related operational factors. See Chap. 3 for further discussion on oil as the LDP and for a design example.

References

1. Bastian, R. K., "The Biosolids (Sludge) Treatment, Beneficial Use, and Disposal Situation in the USA," *EWPC* **7**(2):62–79 (1997).
2. Bastian, R. K., "Biosolids Management in the United States," *WE&T* **9**(5):45–50 (1997).
3. *Proceedings of the Joint Conference on Recycling Municipal Sludges and Effluents on Land Held in Champaign/Urbana, Ill.,* National Association of State Universities and Land-Grant Colleges, Washington, D.C., 243 pp., 1973.
4. Page, A. L., T. L. Gleason III, J. E. Smith, Jr., I. K. Iskandar, and L. E. Sommers (Eds.), *Proceedings of the 1983 Workshop on Utilization of Municipal Wastewater and Sludge on Land Held in Denver, CO., University of California, Riverside Press, Riverside, Calif., 480 pp., 1983.*
5. Page, A. L., T. J. Logan, and J. R. Ryan, "Land Application of Sludge," *Proceedings of a Workshop Effects of Sewage Sludge Quality and Soil Properties on Plant Uptake of Sludge-Applied Trace Constituents,* Las Vegas, Nev., Lewis Publishers, Inc. Chelsea, Mich., 168 pp., 1987.
6. Cole, D. W., C. L. Henry, and W. L. Nutter (Eds.), *The Forest Alternative for Treatment and Utilization of Municipal and Industrial Wastes,* University of Washington Press, Seattle, Wash., 582 pp., 1986.
7. Sopper, W. E., E. M. Seaker, and R. K. Bastian (Eds.), "Land Reclamation and Biomass Production with Municipal Wastewater and Sludge," *Proceedings of a Symposium held Sept. 16–18, 1980 in Pittsburgh Pa.,* The Pennsylvania State University Press. University Park, Pa., 524 pp., 1982.
8. Sopper, W. E., and S. N. Kerr (Eds.), "Utilization of Municipal Sewage Effluent and Sludge on Forest and Disturbed Land," *Proceedings of a Symposium March 21–23, 1977, in Philadelphia, Pa.,* The Pennsylvania State University Press, University Park, Pa., 537 pp., 1979.
9. SSSA (Soil Science Society of America), "Utilization, Treatment and Disposal of Waste on Land," *Proceedings of a Workshop Held in Chicago, Ill., Dec. 6–7, 1985, Soil Science Society of America, Madison, Wis., 318 pp., 1986.*
10. "Effects of Land Application of Biosolids in Arid/Semi-Arid Environments," *Proceedings of a Workshop Held at Colorado State University in May, 1995,* Rocky Mt. Water Environment Association, 1995.
11. NAS (National Research Council/National Academy of Sciences), *Use of Reclaimed Water and Sludge in Food Crop Production,* Water Science and Technology Board, National Research Council, National Academy Press, Washington, D.C., 178 pp., 1996.
12. U.S. Environmental Protection Agency, Standards for the Use or Disposal of Sewage Sludge; Final Rules, *Federal Register,* **58**(32):9248–9415 (Feb. 19, 1993).
13. U.S. Environmental Protection Agency, "A Plain English Guide to the EPA Part 503 Biosolids Rule," EPA/832/R-93/003, Office of Wastewater Management, Washington, D.C., 176 pp., Sept. 1994.
14. U.S. Environmental Protection Agency, *Process Design Manual: Surface Disposal of Sewage Sludge and Domestic Septage,* EPA625/R-95/002, U.S. EPA/NRMRL/CERI. Cincinnati, Ohio, 1995.
15. U.S. Environmental Protection Agency, *Process Design Manual: Sludge Treatment and Disposal,* EPA625/1-79-011, U.S. EPA/MERL, Cincinnati, Ohio, 1979.
16. U.S. Environmental Protection Agency, *Process Design Manual: Land Application of Sewage Sludge and Domestic Septage,* EPA625/R-95/001, U.S. EPA/NRMRL/CERI, Cincinnati, Ohio, 1995.

17. U.S. Environmental Protection Agency, *Hazardous Waste Land Treatment,* SW-874, U.S. EPA, OSW, Washington, D.C., 1983.
18. Parr, J. F., et al., *Land Treatment of Hazardous Wastes,* Noyes Data Corporation, Park Ridge, N.J., 1983.
19. Overcash, M. R., and D. Pal, *Design of Land Treatment Systems for Industrial Wastes,* Ann Arbor Science, Ann Arbor, Mich., 1979.
20. Ryan, J. R., et al., *Land Treatment Practices in the Petroleum Industry,* American Petroleum Institute, Washington, D.C., 1983.
21. U.S. Environmental Protection Agency, "National Sewage Sludge Survey: Availability of Information and Data, and Anticipated Impacts on Proposed Regulations," *Federal Register,* **55**(218):47210–47283 (Nov. 9, 1990).