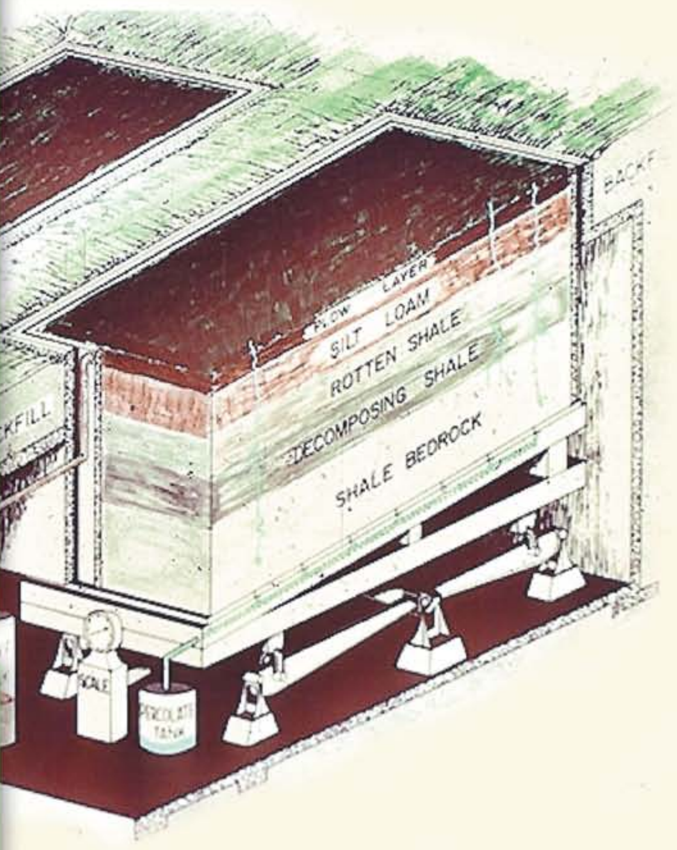
Evapotranspiration Covers for Landfills and Waste Sites



Victor L. Hauser

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Evapotranspiration Covers
for
Landfills
and
Waste Sites

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Contents

Chapter 5 Basic Technology 51

This book is dedicated to Bettye

Preface

We generate a large and ever-increasing volume of waste. The waste originates from rural and urban areas, industrial operations, mining, and other activities. In spite of efforts to reuse wastes, a large part of it is deposited in landfills, mineland dumps, etc.

Direct contact with the waste or the potential harmful effects of gasses and liquids generated within the waste may pose a threat to humans and the environment. The current method of choice for controlling harmful effects of these wastes is containment in landfills and similar structures. Containment is costly; it is relatively, but not perfectly, effective. Some waste may pose a threat to humans and the environment for millennia, thus making containment difficult.

This book does not contain arguments regarding the merits or demerits of waste containment; it does present a better way to build the part of the containment system that we call the landfill cover for municipal and industrial landfills. The principles governing the new cover are the same when used on other wastes.

The evapotranspiration (ET) cover is a better way to cover wastes at many sites. The ET cover employs two simple elements: (1) a layer of soil and (2) plants growing on the surface. The concept is ancient; however, its application to landfill covers is new. Most of us seldom think about the role of soil and plants in making life possible on our planet. The principles have worked since the beginning of time; they govern the production of the food supply for both humans and Earth's other inhabitants. This process forms the basis for the ET cover for landfills and waste.

The primary purpose of this book is to explain the innovative ET cover concept, its verification, fundamental concepts, design, construction, and maintenance. To accomplish these tasks, the book is organized into five broad categories as follows:

Part I. Chapters 1 and 2 briefly describe waste, and the role of covers in containment. Chapter 3 describes conventional and some alternative landfill covers. An important part of Chapter 3 is the analyses of performance of conventional covers as measured by several investigators. These measurements are the basis for an assessment of allowable landfill cover leakage in Chapter 8.

Part II. Chapter 4 describes the ET cover concept and its proof. New ideas usually require new research; the ET cover is an exception because the proof is already available. It remains for us to gather the recorded proof and apply the concept.

Part III. Chapters 5 and 6 contain fundamental technology required to apply the ET cover. Chapter 7 discusses potential application of the ET cover.

Part IV. Chapter 8 discusses design steps, and Chapter 10 contains in-depth application of fundamental technology to selected design components. Chapter 9 presents an in-depth discussion of models for cover design and their potential accuracy; it evaluates the accuracy of three different models against field measurements.

Part V. Chapter 11 presents construction requirements that are unique to ET covers. Chapter 12 discusses maintenance and monitoring issues pertinent to ET covers, and Chapter 13 contains summary information.

Several available reference books and papers are noted in the book to assist the reader in finding additional information needed for design to meet unusual conditions.

Acknowledgments

Because the technology required for ET covers includes a large number of different scientific and engineering disciplines, I am indebted to many individuals.

Two research scientist colleagues at the Agricultural Research Service of the USDA deserve special mention: they are Dr. Howard M. Taylor, soil physicist, who introduced me to the field of plant root growth and the effect of soil strength on plant production and Dr. F. W. (Wes) Chichester, who taught me about plant nutrition and soil modification.

The reviewers of this book—Dr. J. R. Williams, Texas Agricultural Experiment Station; Dr. Peter J. (Pete) Shouse, The US Salinity Laboratory, Agricultural Research Service of the USDA; and anonymous reviewers—provided useful and valuable evaluations. Their comments were very useful and improved the book.

The Author

Dr. Victor L. Hauser, P.E., is an agricultural engineer; he has B.S., M.S., and Ph.D. degrees from Oklahoma State University, the University of California at Davis, and Texas A&M University. He was a research engineer for the USDA, Agricultural Research Service, responsible for research projects in the Great Plains of the United States. His research included water management and crop production, hydrology, soil modification to improve plant production, mineland reclamation; grass establishment, soil erosion control, irrigation, hydrogeology, groundwater recharge, and water quality. He collaborated with engineers and scientists from the Great Plains states on successful water conservation research and with Dr. M. Rebhun, Israel Institute of Technology, to develop innovative and successful water clarification systems for groundwater recharge.

As research leader for the Agricultural Research Service, he participated in research planning and publication of results on hydrology, water management, rangeland management, soil modification, entomology, ecology of rangelands, flood control, and irrigation. His research covered the southern half of the Great Plains states.

As principal engineer for Mitretek Systems, Dr. Hauser provided technical review of remediation activities for groundwater, landfills, fuel spill sites, and similar site remediation activities for the U.S. Air Force, Navy, and Army. He developed technical publications on landfill covers, phytoremediation, and other topics for the U.S. Air Force.

Dr. Hauser is an active member of the American Society of Agricultural and Biological Engineers, the American Society of Civil Engineers, the American Society of Agronomy, the Soil Science Society of America, and Sigma Xi. He is a Fellow of the American Society of Agricultural and Biological Engineers and a registered professional engineer in Texas. He has authored 84 technical papers and 60 reports, technical publications, and other papers.

1 Introduction

The people of the modern world produce a large volume of waste products including municipal garbage and waste, mining, industrial, and atomic waste. Other materials including fuel, solvents, industrial chemicals, etc., become waste when discharged onto the land. These materials typically have low value, which leads to their classification as waste; however, they have the potential to contaminate the environment. The waste volume, and thus the area covered by them, is typically large.

Because of the fear of possible harmful effects that may result from these wastes, costly resources are allocated to control the contamination threat. Municipal and industrial wastes are commonly deposited in landfills. Mining waste is typically discharged onto the land surface or, in the case of strip mining, deposited in the hole left by excavation for ore. Atomic wastes, fuel, and chemicals may be present in landfills and in soils and groundwater over large areas.

1.1 WASTE DISPOSAL

Some municipal and industrial waste is burned, recycled, or composted. The high cost and the low value of the product limit the volume of waste that is recycled or composted. Waste burning significantly reduces its volume and consumes many waste products. However, public fear of air pollution limits the opportunity to burn waste. The volume of waste produced is large, and movement and treatment are expensive; as a result, most of it is disposed in a nearby landfill for long-term storage.

The goal for currently used remediation technology is waste containment to protect the environment and public health. This philosophy produced a system that, in effect, preserves low-value waste for an indefinite time.

Innovative methods are under development to remediate large volumes of waste. For example, the bioreactor landfill controls contaminants and at the same time rapidly degrades waste into harmless products. The bioreactor landfill quickly reduces both the threat from the waste and the waste volume. A bioreactor landfill is reusable for waste disposal; it is under development and coming into use at this time (Reinhart and Townsend 1998; US EPA 2002; ITRC 2006).

1.2 WASTE CONTAINMENT

Currently, the accepted treatment for the large volumes of low-value waste deposited in either conventional or innovative landfills is “containment” rather than

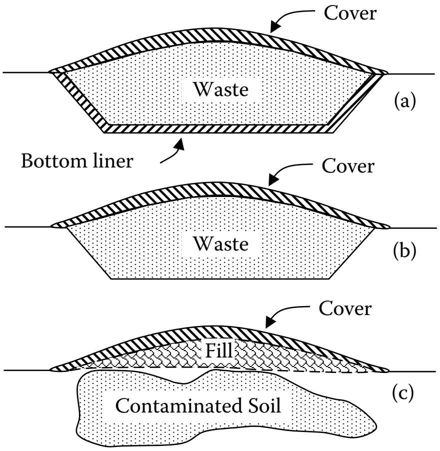

FIGURE 1.1 Three types of waste containment by covers.

remediation. Government rules and regulations rely on the containment philosophy. The purpose of containment is to prevent movement of the waste and control groundwater contamination by leachate from the waste. Containment may include a bottom liner under the waste, gas control, and other features. Almost all containment systems employ a cover to (a) minimize movement of precipitation through the waste, (b) isolate the waste, and (c) control gases if produced by the waste.

A consequence of the containment philosophy is preservation of low-value waste and its decay products for decades or centuries. The concept of waste preservation by containment imposes significant requirements on components of the containment system. In order to provide containment at reasonable cost, and for long time periods—possibly centuries—the parts of the system should be self-renewing and durable.

Figure 1.1 illustrates three types of waste containment and the use of covers for each: (a) a modern landfill with a bottom liner; (b) older landfills, mineland, and other waste with no bottom liner; and (c) a cover for soil contaminated by a chemical spill, leak, or other discharge. Landfills with bottom liners typically include leachate collection and gas control structures; any of them may need gas control. The cover may be the most costly feature of containment for the waste sites illustrated, and is usually the only containment structure for those such as (b) and (c).

This book focuses on waste containment by landfills and, in particular, on their cover requirements. The principles of cover design are similar for other waste sites as well.

1.3 COVERS FOR LANDFILL CONTAINMENT

The application of the containment remedy usually requires the design and installation of a landfill surface cover. Other components, such as gas collection and disposal, groundwater treatment and containment, and the collection and disposal of leachate, may also be required. The cover, whether conventional or innovative, should work in harmony with other parts of the containment system.

Because the intention is to contain the waste for decades or centuries, the cover should be self-renewing and durable. Reconstruction of a cover in the future will be expensive and creates the risk that contaminants may escape the containment system during construction activities. All components of a containment system in the United States are subject to rules and regulations by the U.S. government and the states.

1.4 LAWS AND REGULATIONS

The federal regulations governing hazardous and municipal landfills in the United States are found in the Code of Federal Regulations (CFR)—for example, 40 CFR 264 for hazardous waste and 40 CFR 258 for municipal solid waste. State statutes usually apply when they are equal to or more protective than the published federal regulations.

In the United States, the Resource Conservation and Recovery Act (RCRA) is the controlling federal law for both municipal solid waste and hazardous waste landfills. RCRA enforcement authority is delegated to the states; they are required to have equal or more protective regulations than those contained in federal rules and regulations. RCRA contains many specific requirements regarding the construction, operation, and closure of a landfill, including surface water requirements; groundwater contamination and monitoring; closure system assessment and monitoring; closure criteria; and postclosure care requirements. The remediation of old landfills is generally addressed under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) with RCRA considered as an Applicable or Relevant and Appropriate Requirement (ARAR). Even though the federal rules and regulations contain specific design requirements, they also allow flexibility and use of innovative designs that are protective of public health and the environment. Koerner and Daniel (1997), US EPA (1991), Weand et al. (1999), and ITRC (2003) discuss federal rules and regulations.

1.4.1 INNOVATIVE TECHNOLOGY

Federal regulations for landfills are uniquely different from those for other remediation efforts. They contain design requirements for landfill cover elements; however, regulations for other remediation efforts do not contain design requirements. In the past, both federal and state regulators insisted upon strict application of these landfill cover design requirements, thus allowing little or no latitude for design and construction innovation.

However, there is long-standing law and policy that supports landfill cover innovation and allows designs that are different from the requirements stated in the rules and regulations (Weand et al. 1999). Congress acknowledged the need for innovation in the Superfund Amendments and Reauthorization Act of 1986 (Public Law 96-510 known as SARA): "*The Administrator is authorized and directed to carry out a program of research, evaluation, testing, development, and demonstration of alternative or innovative treatment technologies … which may be utilized in response actions to achieve more permanent protection of human health and welfare and the environment.*"

EPA's Office of Solid Waste and Emergency Response (OSWER) Policy Directive 9380.0-25 defines EPA's support of innovative technologies, and it expresses

EPA's frustration with the difficulty of getting innovative technologies approved and implemented in the field (US EPA 1996). Overall, this is a critical directive because it states EPA's explicit support for innovative technologies. The directive gives helpful information to the remedial project manager (RPM) on how to build a consensus for innovative technology at a particular site.

The EPA and the Environmental Council of the States jointly prepared an agreement to pursue regulatory innovation (US EPA 1998). The agreement encourages and facilitates the exploration of ideas that are potentially more cost-effective or have a better environmental impact. This agreement powerfully reinforces the commitment by the EPA and the states to find innovative regulatory solutions and to avoid being constrained by outdated or overly restrictive regulations. The agreement emphasized that regulatory innovation activity should start with the states because the states are generally delegated RCRA authority and they need to support and pursue regulatory relief.

1.4.2 The Current Situation

The technology used in the landfill cover portion of landfill remediation is changing, and alternative covers are coming into use (ITRC 2003; US EPA 2003). The states are actively supporting innovation as demonstrated by the ITRC's technical and regulatory guidance for design, installation, and monitoring of alternative final landfill covers (ITRC 2003). Accordingly, the application of rules and regulations is changing, thus creating the need for design, construction, and maintenance technology for alternative final landfill cover.

1.5 PURPOSE

Evapotranspiration (ET) is the sum of evaporation of water from the soil surface and plant transpiration. This book explains an innovative landfill cover that relies on ET and other natural forces to provide the benefits required of a landfill cover. The book includes the ET cover concept, its verification, design, construction, maintenance, and allowable leakage through landfill covers.

Although this book deals with landfill covers, the ET cover concept applies equally well to other waste disposal facilities, lagoons, spill sites, spoil piles, mineland restoration, or other facilities needing a final cover. It is well suited to use on bioreactor landfills because it is easy to build it to provide the added water needed to speed the waste decay process. The principles are similar in each case to that described here for landfills.

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2 Landfill Remediation with Covers

This chapter describes the application of covers (also called caps) as components of landfill remediation. Other components—including landfill gas collection and disposal, leachate collection and treatment, hydraulic control of groundwater, and remediation of contaminated groundwater and surface water—are discussed at length by numerous authors (e.g., US EPA 1991; Dunn and Singh 1995; McBean et al. 1995; Koerner and Daniel 1997; Gill et al. 1999; Weand et al. 1999).

Landfill covers are used at various times during a site's active life. At modern landfills, a thin soil layer or other cover is placed over the waste at the end of each day to control odors, prevent litter movement by wind, and keep rodents, birds, and insects out of the waste. Intermediate soil covers protect inactive areas of an active landfill. McBean et al. (1995) present a more complete discussion of daily and intermediate landfill covers.

Landfill remediation includes a final cover; it remains in place as a part of the containment system. This book focuses on final covers; they are the most frequently required, and are often the most complex and costly component of landfill remediation. In the context of remediation within this book, the word *cover* means a final landfill cover.

This chapter contains a review of requirements for remediation, risk-based remediation, the site-specific environment, conventional and alternative covers, and cover selection.

2.1 REQUIREMENTS FOR LANDFILL COVERS

There are fundamental scientific and technical reasons for placing a cover on a landfill. Regulations control the selection and design of landfill covers; however, they are based on specific environmental concerns and have a technical basis. Landfill covers provide several environmental benefits, but they have three primary goals:

- Minimize infiltration into the waste and percolation from the waste to groundwater
- Isolate the wastes from receptors and control their movement by wind and water
- Control landfill gases

These three goals are common to all landfill cover designs; their implementation may include conventional covers based on regulatory requirements. However, alternative landfill covers also satisfy these goals and may provide a more protective, longer-lasting, and less costly solution.

Landfill covers are intended to remain in place and protect the environment for an extended period, perhaps centuries; therefore, they should be durable and self-renewing. Landfill covers should satisfactorily control infiltration of precipitation into the waste because it has potential to carry soluble wastes downward to groundwater. Covers that meet the infiltration requirement usually satisfy the second requirement, that is, that the waste should be isolated from receptors and its movement controlled.

Gas collection may be required to dispose of explosive and toxic landfill gas generated by the biodegradation of organic matter and other chemicals in the waste. This is especially true for landfills with covers that include barrier layers because they trap and accumulate gas; thus, they usually need gas collection and disposal systems. The long-term operation and maintenance of an active or passive gas collection and disposal system, if required, are significant financial burdens for the landfill owner.

The migration of landfill leachate into an aquifer is important because it may cause significant groundwater contamination and the need for expensive remediation. However, recent work demonstrates that natural attenuation may control the extent of groundwater contamination caused by some contaminants. Leachate from a landfill that enters the groundwater contains organic material; it, in turn, produces anaerobic conditions in the groundwater under and down gradient from the landfill. The anaerobic groundwater conditions degraded important contaminants. Therefore, controlled leaching of landfill waste may be beneficial in some cases (Hicks et al. 2002), altering the requirement to minimize infiltration to groundwater. In any case, it is necessary to control leachate to meet site requirements.

2.2 RISK-BASED/PERFORMANCE-BASED REMEDIATION

Previously, regulatory preference for use of design parameters contained in regulations limited or precluded the application of alternative landfill covers and designs for landfill remediation. Currently, the regulatory control of landfill covers is changing to allow consideration of alternative technologies. Risk-Based/Performance-Based (RB/PB) evaluation of landfills is a process that applies engineering and science to the selection among remediation alternatives and allows better decisions. There is already a strong regulatory basis for this process, and it is in use for other types of remediation efforts (Gill et al. 1999).

An RB/PB landfill evaluation is a technical approach to selection of protective remedial options based on the specific conditions at a landfill. Using an RB/PB evaluation allows the landfill owner to determine the technical performance requirements for a cover at a particular site.

The RB/PB landfill evaluation process follows four well-defined steps:

1. Identify releases: On the basis of known waste materials and environmental sampling, identify the actual and potential releases associated with a particular landfill, including
   - Surface materials
   - Gas generation
   - Leachate production
   - Groundwater and surface water contamination
2. Assess exposure: Determine the exposure pathways to potential receptors, and whether the pathway is complete for each actual or potential release, including
   - Direct contact
   - Airborne contamination
   - Surface or groundwater contamination
3. Assess risk: Estimate the risks associated with each completed source–pathway–receptor combination.
4. Establish site-specific performance requirements: Determine the specific performance requirements for each action needed to address the risks identified, including
   - Cover requirements to eliminate direct contact
   - Required control of infiltration to adequately control risks from potential leachate
   - Collection and treatment of gas, if necessary
   - Control of groundwater contamination
   - No further action if no significant risks were identified

The landfill owner may use any landfill remediation method, including alternative covers, which meets the performance requirements after they are fully accepted. This process allows the owner to select the most technically sound and cost-effective landfill remediation for a particular landfill.

2.3 FACTORS THAT INFLUENCE REMEDIATION

Both selection of cover type and its design are dependent on specific site characteristics. Site characteristics that have a dominant influence on covers include climate, soils and plants, landfill characteristics, hydrogeology, gas production, seismic environment, and reuse of landfill areas.

2.3.1 CLIMATE

Precipitation (rain, snow, and sleet), solar radiation, air temperature, wind, and relative humidity are the main climatic factors that affect landfill covers. Precipitation amount and distribution in time has a direct bearing on infiltration of water into the cover and, potentially, into the buried waste. Climatic factors influence ET, which controls soil water content and percolation through the cover soil. Climate may also influence moisture content and temperature of the waste, which in turn controls waste degradation rate. Climatic factors that control soil erosion include precipitation amount and intensity, as well as wind.

The commonly reported annual or monthly averages of climatic variables do not provide sufficient information with which to evaluate a site. Daily and seasonal climatic variation controls daily amounts of deep percolation into the waste. For example, if the majority of precipitation falls during the season when vegetation is dormant, the potential for infiltration through the cover is greater than if the precipitation falls during seasons of active plant growth. A rainy day following a rainy day is more likely to produce water movement through the cover than a rainy day following a dry day.

There is a strong influence from daily or even hourly climatic patterns, for example,

- Precipitation during one or two cloudy and cool days may result in greater infiltration potential than the same total amount of precipitation spread over several days with periods of ET interspersed between the rain events.
- A single, relatively small rainfall event during or immediately following snowmelt when vegetation is dormant has the potential to cause deep percolation.

2.3.2 LANDFILL AND WASTE CHARACTERISTICS

The operating history, wastes, and physical construction of the landfill all affect the remediation options that may be used. For example, some of the characteristics that affect cover design include the type of waste deposited, whether or not the landfill has a liner, the age of the landfill, whether the landfill is active or inactive, and the amount of leachate produced by the waste.

The type of wastes disposed in a landfill leads to its classification as (1) municipal (consisting of typical household wastes), (2) hazardous, (3) radioactive, or (4) mixed waste (nonradioactive mixed with radioactive). The waste classification directly affects the cover design because of both the technical and the regulatory requirements.

As a landfill ages, the degradation of the waste and the pressure of overlying materials lead to compression and settling of the waste, sometimes by as much as 33% (Suter et al. 1993; Sharma and Anirban 2007). Landfill subsidence is likely to be severe for landfills containing deep deposits of fresh waste. The resulting subsidence of the overlying cover can cause cracks in clay barriers, separation of geomembranes (GMs), and slope changes that adversely affect surface water drainage and erosion. Landfills that are old, when covered, are less likely to experience excessive surface subsidence.

2.3.3 HYDROGEOLOGY

The distance between the bottom of a landfill and the water table is an important determinant of the probability that groundwater has been or may be contaminated. If the landfill has no liner but rests on impermeable bedrock, shale, or clay located above the water table, or if the depth to groundwater is great, then an unlined landfill may pose little threat to groundwater. If waste is in contact with groundwater, a surface cover cannot provide a complete remedial solution for the site. The quality and quantity of native groundwater at the site are important because they control potential use and thus potential need for protection from contamination. Therefore, the geology of the site and the lithology of geologic units between the waste and permanent groundwater are important considerations.

2.3.4 GAS PRODUCTION

Decay of wastes and volatilization of waste components in landfills may produce sufficient toxic and explosive landfill gas to warrant gas control systems under the cover. Most conventional, barrier-layer covers need an expensive gas control system because the barrier may trap the gas produced, even at low rates, and may accumulate dangerous volumes of explosive or poisonous gas. Innovative covers, such as the ET cover, contain no barriers that might collect gas. They allow landfill gas to pass through the cover soil into the atmosphere.

Although gas production in a landfill can continue for a long time, high rates occur over relatively short periods, perhaps up to 10 years after the landfill becomes inactive (McBean et al. 1995). Old landfills with no cover in place for 20 years or more may not need the expense of a gas collection system when covered. For example, a survey of less than half of all Air Force landfills revealed that 144 landfills were both inactive for more than 20 years and not remediated in 1998–1999 (Hauser et al. 1999); they are unlikely to produce significant amounts of gas.

2.3.5 SOILS AND PLANTS

The availability of appropriate local soils is an important consideration in any landfill design. Conventional covers need local soils for both the foundation and the surface layers. The soil used in an ET cover should meet the requirements for the site and support robust vegetative growth. For example, ET covers may be impractical where readily available soils have inadequate water-holding capacity.

The growth habits and properties of plants native to the site are important considerations. For example, in some regions, only warm season grasses are practical for use on covers, but in others, it is possible to establish both warm and cool season grasses together on the cover. The combination of warm and cool season grasses is usually more effective than single-season covers because the combination extends the time with significant plant transpiration.

2.3.6 SEISMIC ENVIRONMENT

Earthquakes are a significant threat to public safety and structures. The ground shaking associated with earthquake activity has potential to damage landfill containment structures in many ways, including landslides on the cover, rupture of geomembrane-barrier layers, cracking of clay-barrier layers, breakage of conduit lines (gas control and drainage systems, electrical controls, etc.), and changes in drainage slopes.

Matasovic et al. (1998) studied the performance of landfill covers and liners during six major earthquakes in California between 1969 and 1994. Cover performance was good to excellent at all of the landfills, with the damage limited to cracking of cover soils. Within seismic hazard zones, landfill designs should be evaluated using site-specific seismic risk assessment criteria. Richardson and Kavazanjian (1995) wrote an extensive treatment of this aspect of landfill design.

2.3.7 Reuse of Landfill Areas

Land reuse is an important consideration in landfill cover selection and design. Landfills are warehouses for waste material built to preserve waste for an unknown length of time; that basic requirement controls possible reuse of landfill sites. All alternate uses for a landfill site are secondary to the primary use for waste preservation. Human activity on a final landfill cover is potentially dangerous, creates the need for careful design, and may result in large cost to reduce potential injury to people.

Some apparently beneficial uses may conflict with primary cover purposes. For example, irrigation on golf courses causes deep percolation of water below the plant-rooting zone. Golf courses on landfill covers pose immediate problems because one of the principal objectives of a landfill cover—to minimize infiltration—probably cannot be achieved under normal golf course irrigation (Hauser et al. 2000).

2.4 COVER SELECTION

Previously, because federal landfill regulations contained design requirements, almost all landfill covers were barrier-type because they met the requirements of the regulators. However, as stated in Section 1.4, the situation has changed and it is now practical to utilize the landfill cover technology that is most appropriate for a particular site. Both federal and state regulators currently support alternative technologies (ITRC 2003; US EPA 2003). An RB/PB landfill evaluation, as described in Section 2.2, allows application of the best engineering and science knowledge to select the most appropriate cover type for a particular site. Where an alternative cover is appropriate, it may provide longer and more effective containment than previously used barrier covers, and save millions of dollars in construction and maintenance cost.

The following 10-step process is applicable to the closure of all landfills. It may be iterative, and each step may have significantly different emphasis at a particular site.

1. Determine risks at the specific landfill using RB/PB methods (Section 2.2).
2. Determine site-specific performance requirements dictated by the risks at the site.
3. Select the most appropriate conventional or alternative technologies.
4. Elicit wide regulatory and public participation.
5. Present the proposed technology to the Remedial Advisory Board and the public.
6. Complete any required modeling, design criteria, and feasibility testing.
7. Conduct peer reviews of the decision process and remediation design.
8. Formally document the selection of the technologies in the record of decision document (ROD).
9. Complete the design and monitoring plan.
10. Construct all of the remediation components and gather monitoring and performance data.

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3 Conventional and Alternative Covers

This chapter describes the properties of landfill covers that are in widespread use and alternatives to these conventional covers. An important part of this chapter is a summary of performance measurements for landfill covers; they provide guidance regarding allowable leakage through landfill covers.

3.1 CONVENTIONAL LANDFILL COVERS

Most landfill covers in place today are conventional, barrier covers because both state and federal regulatory officials have readily accepted them in the past. They include one or more barrier layers within the cover and they meet the presumptive requirements for containment. The intention is that the barrier should oppose the forces of nature and prevent water from moving downward in response to the force of gravity. A common misconception is that the barrier layers are "impermeable"; this is seldom, if ever, true. The goal is that the conventional, barrier landfill cover should provide protection for decades or centuries; however, they have actually been tested for a fraction of their intended life.

This chapter provides an overview of barrier covers. Several authors provide in-depth discussion of conventional landfill covers (US EPA 1991, 1993, 1996; McBean et al. 1995; Ankeny et al. 1997; Koerner and Daniel 1997; Gill et al. 1999; Weand et al. 1999).

3.1.1 RCRA SUBTITLE C, BARRIER COVER

Conventional RCRA Subtitle C covers employ barrier technology and typically include five or more layers above the waste (Figure 3.1; US EPA 1991; Koerner and Daniel 1997). The top layer consists of cover soil that supports a grass cover to provide wind and water erosion control. The second layer is a drainage layer; its purpose is to remove water that accumulates above the barrier layer. The barrier layer consists of either a single low-permeability barrier or two or more barriers in combination. The gas collection layer permits removal and safe disposal of gas trapped under the barrier. The foundation layer of variable thickness separates the waste from the cover and establishes the surface slope.

3.1.1.1 The Cover Soil Layer

The primary function of the surface layer is to control wind and water erosion by supporting an adequate vegetative cover, and to protect the other layers. The soil should have adequate physical and chemical properties to store sufficient water for plant use and to provide the necessary nutrients for plant growth.

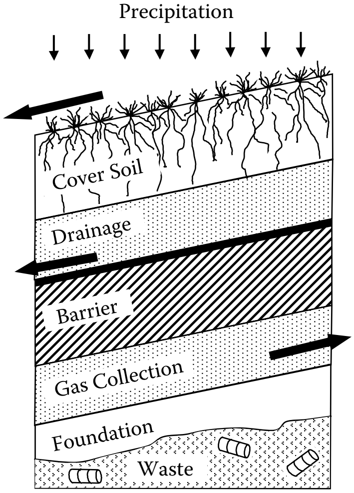

FIGURE 3.1 Cross section of a conventional RCRA landfill cover.

The cover soil layer is usually about 0.6 m (24 in.) thick; the required thickness depends on the climate, soil properties, and vegetation type. In cold climates, the cover soil may be thicker to protect the barrier layer from freezing.

The specific requirements at a site may necessitate additional components in the cover soil layer. For example, a surface sublayer containing a gravel and soil mixture may control wind erosion in desert regions, or a layer of cobble-size stone placed near the bottom of the cover soil layer may prevent animal intrusion into the waste.

3.1.1.2 The Drainage Layer

The cover soil does not stop all precipitation; consequently, precipitation passes through it into the drainage layer. A drainage layer built of highly permeable material should quickly remove water that passes through the cover soil. Rapid drainage removes the hydraulic head on the underlying barrier layer, thus reducing infiltration through the barrier. Drainage also improves slope stability by reducing pore water pressure in the layers above the barrier. The most common materials used for the drainage layer are sand, gravel, and manmade geosynthetic materials. An effective drainage layer is a required component of a barrier cover.

3.1.1.3 The Barrier Layer

The barrier layer is the central element of landfill covers using barrier technology. The barrier layer may be a single material or a combination of two or more. The barrier minimizes percolation of water from the overlying layers into the waste by opposing the natural flow of water downward in response to gravity.

Compacted clay layers (CCLs) are the most commonly used barrier layers; they are typically about 0.6 m (24 in.) thick. Federal regulations require a saturated hydraulic conductivity (K) that is equal to or less than 1×10^{-7} cm/s. Normally, CCLs contain naturally clay-rich soils; both desiccation and freezing can greatly increase the K value of clay barriers.

Other materials are used as barrier layers. Geosynthetic clay layers (GCLs) are manufactured rolls of bentonite clay held between geotextiles or bonded to a geomembrane (GM). The K value of most sodium bentonite GCLs is near 1×10^{-9} cm/s. GMs used as barrier layers in landfill covers are called *flexible membrane covers* (FMCs). The most common materials for FMCs in final covers include high-density polyethylene (*HDPE*), linear low-density polyethylene (*LLDPE*), polypropylene (*PP*), and polyvinyl chloride (*PVC*).

Barrier layers incorporating two barriers are normally more effective than a single barrier. A typical "composite" barrier includes a GM on top of CCL or a GCL.

3.1.1.4 The Gas Collection Layer

The decomposition of wastes and evaporation of organic compounds within a landfill produces gases, some of which are toxic, corrosive, or flammable. Aerobic biological processes occur when oxygen is available to the waste, generally immediately after its disposal and produce mostly carbon dioxide. After oxygen depletion in the waste zone, anaerobic bacteria become dominant and waste decay produces both carbon dioxide and methane gas along with lesser amounts of hydrogen sulfide, nitrogen, and hydrogen. In addition, volatile organic compounds (VOCs) contained in the deposited waste or produced by chemical reactions within the waste may be present in landfill gas.

The presence of explosive or toxic gases underground presents a potential problem to nearby buildings and to personnel working near the landfill. Gases follow preferential flow paths both upward and laterally and either ultimately vent to the atmosphere or accumulate under natural or artificial barrier layers. Collection and disposal of the gas generated under the cover utilizes either active or passive systems. Any cover that employs a barrier layer is likely to need a gas control system because the barrier will probably trap and accumulate explosive or poisonous gas below the cover.

3.1.1.5 The Foundation Layer

The foundation layer establishes the desired surface slope and separates the waste from the cover. Use the least expensive locally available material that will provide a stable working surface above the waste.

3.1.2 RCRA SUBTITLE D, BARRIER COVER

RCRA Subtitle D covers are modified barrier-type covers (Figure 3.2); an alternate name for them is compacted-soil, barrier covers. From the surface downward, these covers include a grass cover; topsoil layer; soil compacted to yield a K value of 1 × 10^{-5} cm/s, and a foundation layer above the waste. Usually, soil found at the site is compacted to form the barrier. The subtitle D cover meets the federal criteria for Municipal Solid Waste Landfills, 40 CFR, Part 258.60, Closure Criteria; it is suitable for dry climates. It is a barrier cover because it relies on compaction to create a layer of soil with reduced hydraulic conductivity. However, the topsoil layer is often no more

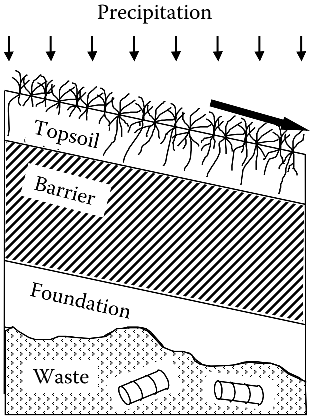

FIGURE 3.2 Cross section of a conventional subtitle D landfill cover.

than 0.15 m (6 in.) thick. Freezing, drying, or root intrusion into the barrier layer may increase its hydraulic conductivity (K) and change the covers' performance.

3.2 ALTERNATIVE BARRIERS FOR COVERS

The alternative barriers discussed in this section are new approaches for designing barrier layers and not complete cover systems. They are at this time primarily experimental systems.

3.2.1 CAPILLARY BARRIER

The capillary barrier is an alternative to conventional-barrier layers. The capillary barrier (Figure 3.3) utilizes two layers: a layer of fine soil over a layer of coarser material (e.g., sand or gravel). A geotextile over the coarse layer will control intrusion of fines into the coarse layer. The barrier is the discontinuity in soil pore size found at the interface between the coarse and fine soil. Capillary force causes the layer of fine soil overlying the coarser material to hold more water than if there were no change in pore size between the layers. Lateral drainage, evaporation, and plant transpiration remove water stored in the soil above the barrier. Stormont (1997), Gee and Ward (1997), Nyhan et al. (1990), Breshears et al. (2005), and Ankeny et al. (1997) tested it in experimental installations. A plant cover to remove water stored in the fine soil is part of a capillary-barrier cover.

A capillary barrier is effective if the combined effect of ET, soil water storage, and lateral diversion exceeds the infiltration from precipitation, thereby keeping the system sufficiently dry so that breakthrough does not occur. This barrier can fail if too much water accumulates in the fine-soil layer or if the desired large change in pore size is missing in spots. Experimental field systems failed although they allowed less infiltration than a fine soil cover alone (Nyhan et al. 1990; Nyhan et al. 1997; Warren et al. 1996). Gee and Ward (1997) tested a full-scale capillary-break cover having 2 m of loose high-quality soil above the interface and found no leakage during a 2 year period in an arid climate.

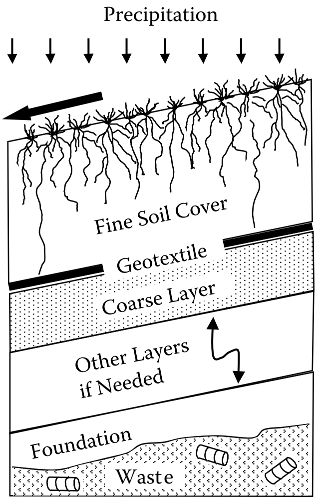

FIGURE 3.3 The capillary barrier in a landfill cover.

By placing the interface between the soil and gravel on an incline, lateral flow at pressures less than atmospheric can occur. Stormont (1996) found that alternating fine and coarse layers were effective over lateral distances of 7 m (23 ft) on a 10% slope. He also found that a single capillary-barrier layer failed under the conditions of his tests.

The capillary-barrier system may be better than conventional clay hydraulic barriers because it is not subject to desiccation and cracking. It may be preferred where soils with high water-holding capacity are unavailable or expensive and in dry climates.

3.2.1.1 Capillary Barriers without Vegetation

Nyhan et al. (1997) and Nyhan (2005) described an interesting experiment in which the soil surface remained bare; therefore, evaporation alone removed water from the soil profile. Because evaporation is smaller than plant transpiration and effectively removes water from a relatively shallow soil depth, this arrangement placed great stress on the capillary barrier. Nyhan (2005) incorrectly labeled the cover the "evapotranspiration" cover. Because there is no transpiration, they are more correctly called *evaporation covers*.

With thick soil covers and 15 or 25% surface slope, no water percolated through these covers as deep percolation. With thin soil covers and slopes as flat as 5%, up to 10% of the precipitation appeared as deep percolation below the cover. Seven years of measurement demonstrated less average deep percolation than the 3.7-year measurement period (Nyhan et al. 1997; Nyhan 2005).

The research plots were located at Los Alamos, New Mexico, in a dry climate. The aridity of the climate and high potential evaporation rate probably contributed to their qualified success.

3.2.1.2 Dry Barrier

As illustrated in Figure 3.4, the dry barrier, sometimes called the *convective air-dried barrier*, is similar to the capillary barrier except that wind-convective or power-driven airflow through the layer of coarse material helps remove water that may infiltrate into that layer (Ankeny et al. 1997). Dry barriers may be suitable for landfills in hot, arid climates where capillary barriers alone may fail.

3.2.2 ASPHALT BARRIER

In arid climates, clay barriers are likely to fail because of desiccation. Gee and Ward (1997) demonstrated that asphalt barriers may replace compacted clay in landfill covers. Levitt et al. (2005) reported the failure of an asphalt cap placed on the surface over waste material in a dry climate. Substantial amounts of water moved through the cover over 37 years. The asphalt cap was cracked; in addition, a collapsed area and adverse slopes collected water on the surface of the cap.

Because oxygen, ultraviolet radiation, and frost heave damage asphalt, asphalt barriers should be protected with soil cover as demonstrated by Gee and Ward (1997). It is important to ensure adequate drainage from the surface.

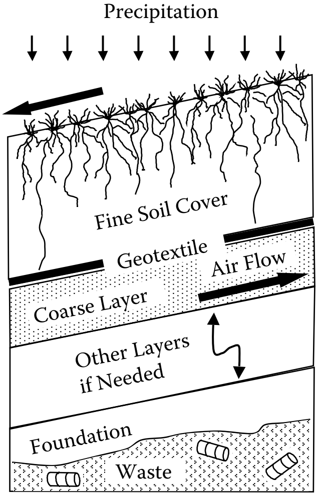

FIGURE 3.4 The dry barrier in a landfill cover.

3.3 ALTERNATIVE COVERS

Because of the water-holding properties of soils and the fact that most precipitation returns to the atmosphere via ET, a reliable and natural process, it is possible to devise landfill covers that meet the requirements for remediation without a barrier layer. These covers usually employ a layer of soil on top of the landfill where grass, shrubs, or trees grow for the purpose of controlling erosion and removing water from the soil water reservoir. They utilize the natural soil water reservoir to temporarily store infiltrating rainfall in the soil until ET removes it.

3.3.1 The MSR Cover

Schulz et al. (1997) tested a cover described herein as the *modified surface runoff* (MSR) cover for discussion purposes in this book (Figure 3.5). The soil was fine textured and suitable for plant growth. Panels or "rain gutters" diverted part of the rainfall off the plot; they planted Pfizer junipers between the panels as plant cover. Their MSR cover was successful.

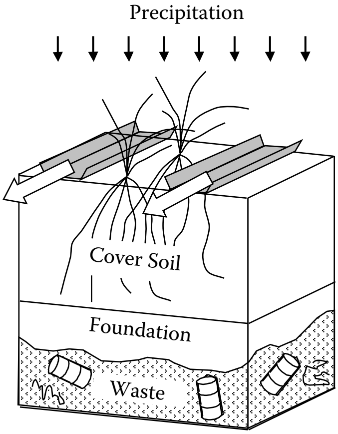

FIGURE 3.5 Modified surface runoff cover.

Karr et al. (1999) reported the results of a 21-month evaluation of the MSR cover in Hawaii ending in March 1998. All of their treatments, including a standard RCRA cover, allowed deep percolation below the cover. At least two adverse conditions affected the results: (1) the treatment designed to divert 40% of precipitation actually diverted only 22% to surface runoff; and (2) the soil in all plots was compacted to 95% of "optimum" Proctor density.

Soil density equal to 95% of "optimum" increases soil strength and significantly reduces root growth. High soil density destroys the large soil pores, which results in reduced water-holding capacity and severely limits oxygen movement through the soil when wet. Low soil oxygen may also substantially reduce root growth. The effect of high soil density is more severe for a fine- than a coarse-textured soil because the soil pores in a compacted, fine-textured soil are smaller. These factors (explained in Chapter 5) may have substantially reduced the effectiveness of the MSR cover tested in Hawaii.

Chittaranjan (2005) reported results of additional study of the MSR experiment reported by Karr et al. (1999). His measurements began in 1999, and he found that vegetation reduced the effectiveness of the rain gutters used to divert rainfall as runoff.

3.3.2 Vegetative Covers

These covers employ a layer of soil on top of the landfill on which grass, shrubs, or trees grow to control soil erosion and percolation of precipitation into the waste

(Figure 3.6). The soil serves as a reservoir to store precipitation until the natural process of ET can remove it (Anderson 1997). The soil in a typical "vegetative" cover is compacted, which may significantly reduce root growth (Chapter 5) and as a result causes excessive deep percolation through the cover.

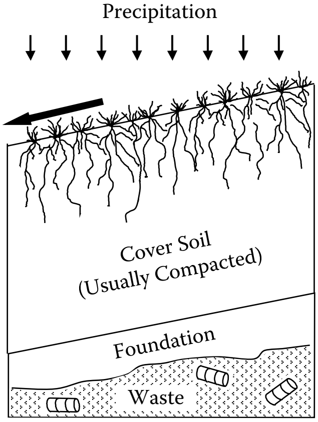

FIGURE 3.6 Cross section of a vegetative cover.

3.3.3 INFILTRATE–STABILIZE–EVAPOTRANSPIRE COVER

Blight (2006) defined the "infiltrate–stabilize–evapotranspire" (ISE) landfill cover and presented performance measurements during an 18-month period. He defined the ISE cover as a layer of compacted soil over the waste and having no vegetation on the surface. He proposed the ISE cover for use in water deficit areas where annual evaporation exceeded precipitation; he stated that such areas covered about 65% of the Earth's surface. A primary objective for the ISE cover is to promote waste decay and stabilization in dry climates; thus, the goal is to wet the waste with percolating precipitation.

Because it has no vegetated cover, water is removed from the compacted soil and the underlying waste by evaporation only. The absence of vegetated cover will require expensive control measures and regular maintenance to prevent soil erosion by wind and water.

3.4 PERFORMANCE OF BARRIER COVERS

Successful design and management of waste containment structures require knowledge of the true performance characteristics of each part of the system. Although barrier layers are sometimes referred to as "impermeable," in practice this is seldom, if ever, true.

Table 3.1 contains performance measurements for conventional-barrier landfill covers, including compacted soil, compacted clay, "US EPA" barrier cover with bare soil, and composite-barrier covers. The data are arbitrarily divided into two groups: arid (less than 300 mm annual precipitation) and other or wetter sites. The test with longest duration measured performance for 14 years and the shortest included a single year of measurements. Short records, and particularly those with less than a 3-year duration, do not adequately sample the climate at the site; however, they provide other useful information about landfill cover performance.

3.4.1 COMPACTED SOIL

Compacted soil covers are the simplest and least expensive conventional covers; a common name for them is the subtitle D cover (Figure 3.2). The regulations in the United States specify a maximum saturated hydraulic conductivity of 1×10^{-5} cm/s

TABLE 3.1
Measured Performance of Barrier Landfill Covers Utilizing Compacted Soil, Compacted Clay, and Composite Barriers

Reference	Location	Test Duration (year)[a]	Average Annual		
			Precipitation (mm)[b]	Leakage	
				(mm)	(%)[c]
Compacted-Soil, Barrier Cover					
Dwyer 2001	Albuquerque, NM	3.0	247	5	2
Albright et al. 2004	Altamont, CA	2.0	343	2	1
Warren et al. 1996	Hill AFB, UT	3.8	539	109	20
Albright et al. 2004	Albany, GA	3.0	1191	118	10
Compacted-Clay, Barrier Cover					
Albright et al. 2006b	Apple Valley, CA	2.9	188	8	4
Warren et al. 1996	Hill AFB, UT	3.8	539	Trace	Trace[d]
Albright et al. 2006b	Cedar Rapids, IA	4.0	815	72	9
Melchior 1997, 20% slope	Hamburg, DE	8.0	865	65	8
Melchior 1997, 4% slope	Hamburg, DE	8.0	865	81	9
Albright et al. 2006a	Albany, GA	2.25	1056	267	25
"US EPA" Barrier Cover with Bare Soil Surface[e]					
Nyhan et al. 1997	Los Alamos, NM	3.7	462	0	0
Composite-Barrier Cover					
Albright et al. 2004	Boardman, OR	2.0	130	0	0
Albright et al. 2004	Apple Valley, CA	1.0	148	0	0
Dwyer 2001 (GM/CL)	Albuquerque, NM	3.0	247	<1	<1
Dwyer 2001 (GM/GCL)	Albuquerque, NM	3.0	247	2	1
Albright et al. 2004	Polson, MT	3.0	311	<1	<1
Albright et al. 2004	Marina, CA	3.0	322	23	7
Albright et al. 2004	Altamont, CA	2.0	343	2	1
Albright et al. 2004	Omaha, NE	2.0	518	5	1
Albright et al. 2004	Cedar Rapids, IA	1.0	791	21	3
Melchior 1997, 20% slope	Hamburg, DE	8.0	865	1	<1
Melchior 1997, 4% slope	Hamburg, DE	8.0	865	1	<1
Melchior 1997, 4% slope	Hamburg, DE	8.0	865	4	<1
Loehr and Haikola 2003	Northeastern United States	14.0	1320	26	2

[a] Measurements for full years are shown when available.

[b] Annual precipitation includes irrigation, if any.

[c] Leakage rate expressed as percentage of annual precipitation.

[d] Clay became progressively wetter and was saturated at the end of the test.

[e] Compacted, clay–tuff mixture with low permeability; no vegetation on surface.

for barrier soil in these covers (US EPA 1991,1996). That rate would allow 315 mm/year of deep percolation if the barrier layer were continuously wetted with a hydraulic gradient of 1. Subtitle D covers are widely accepted for use as final landfill covers in arid and semiarid locations.

In an arid climate, Dwyer (2001) placed 150 mm of topsoil over 450 mm of compacted native soil. He measured percolation equal to 2% of precipitation during a 3-year period. In the near-desert climate of Albuquerque, New Mexico, evaporation from the soil surface should remove most precipitation from the soil within a week or less. This compacted soil cover leaked a surprising amount given the near-desert conditions and low precipitation at the site.

Albright et al. (2004) measured percolation rates, for 2 or 3 years, through two covers that were similar to subtitle D covers. At Altamont, California, a dry site, the cover was about 380 mm of clay soil over a 600-mm-thick CCL; the average percolation for 2 years at that dry site was less than 1% of annual precipitation. At Albany, Georgia, a wet site, the cover was about 600 mm of soil over 700 mm of compacted clayey sand; the average percolation for 3 years was 10% of annual precipitation.

At a semiarid site, Warren et al. (1996) used a single layer of compacted topsoil 900 mm deep; they measured 20% of rainfall as deep percolation. The soil was compacted at all of these sites, but the soil at Warren's site was compacted to a high density (1.86 Mg/m^3) and it leaked a surprising amount in that dry climate.

Benson et al. (2007) reported changes in compacted soils similar to subtitle D covers at 10 sites. The climate at these sites varied from hot, dry desert to humid and cold. The resulting as-built hydraulic conductivities (K) varied from 8.6×10^{-8} to 3.1×10^{-5} cm/s for the various soils used. After 2 to 4 years of service, the K value of the compacted soils increased to 10^{-5} to 10^{-3} cm/s. The K value for some increased by a factor of 10,000.

The compacted-soil, barrier cover allowed substantial leakage, in wet or dry climates; it has four deficiencies:

- The topsoil layer has limited water-holding capacity because it is thin.
- There is no drainage layer.
- Few roots penetrate the compacted soil mass between cracks, thus limiting extraction of water from the compacted barrier layer.
- Soil freezing and drying, and other factors, increase the K value of the barrier soil up to 10,000 times its as-built value.

3.4.2 COMPACTED CLAY

The term *compacted clay* here defines an RCRA cover with a single compacted clay barrier layer and a drainage layer (Figure 3.1).

The regulations specify a maximum saturated hydraulic conductivity of 1×10^{-7} cm/s for clay barriers (US EPA 1991,1993); that rate allows 32 mm/year of deep percolation, if the barrier is continuously wetted with a hydraulic gradient of 1. The liners under landfill waste were the first application of compacted clay barriers. In that environment, they are generally successful because they tend to remain wet, are under constant compacting pressure, and seldom if ever freeze. However, similar compacted clay barriers used in landfill covers may dry, and they are subject to freezing, or to plant root activity. These factors render clay barriers less effective when used in covers. Suter et al. (1993) reviewed failure mechanisms for compacted soil covers in landfills; they concluded that "*natural physical and biological processes can be expected to cause [clay] barriers to fail in the long term.*" Table 3.1 contains measurements of deep percolation through six experimental compacted clay-barrier covers.

The precipitation at Apple Valley, California, was typical of desert climate (Table 3.1). Because evaporation exceeds the measured precipitation at that site, the leakage into the waste of 4% of precipitation is not expected.

Warren et al. (1996) reported only a trace of leakage in a semiarid climate; however, they noted that the soil water content of the clay barrier after 3.8 years was at the saturation value and increasing. Melchior (1997) reported that in a cool, wet climate clay barriers leaked 8 or 9% of precipitation; he noted that at the end of an 8 year experiment, leakage rates were increasing.

Albright et al. (2006a) measured the performance of a compacted clay-barrier cover in southern Georgia; the climate is subtropical and wet. After 4 years of service, they observed numerous cracks in the clay barrier and roots growing in the cracks. Leakage through the cover was small prior to a short drought during the first year of service, but increased substantially after the drought. The authors concluded that soil drying during the drought created the dense network of soil cracks. Leakage through the cover was increasing at the end of the test. The measured increase in hydraulic conductivity was from 10^{-7} to 10^{-4} cm/s during the short service life.

Albright et al. (2006b) measured performance of compacted clay-barrier covers at three sites during 2 to 4 years. The climate at the sites was desert in California, humid in Iowa, and subtropical, wet in Georgia. The as-built hydraulic conductivity of the clay barrier layers varied between 1.6×10^{-8} and 4.0×10^{-8} cm/s. During the short test period, the hydraulic conductivity of the barriers increased between 106 and 765 times the as-built value. In addition to these three sites, the authors cited measurements at four other locations. They concluded that "large increases in the hydraulic conductivity of clay barriers with time are not uncommon."

Some of the experimental measurements of performance for compacted clay-barrier covers were too short to demonstrate their probable long-term performance. However, all of them allowed annual leakage varying between trace amounts and 25% of annual precipitation. The compacted clay-barrier covers leaked in both desert and wet climates. Even though they are prone to leak, compacted-clay barriers have been widely accepted for use as final landfill covers.

3.4.3 "US EPA" BARRIER COVER WITH BARE SOIL SURFACE

Nyhan et al. (1997) tested an interesting concept. Even though the sum of evaporation from the soil and plant transpiration is substantially larger than evaporation alone, they built a barrier cover without plants on the surface. They compacted a mixture of clay and crushed tuff to create the barrier layer in a cover that resembled an EPA-defined RCRA cover. During their 3.7 year test period, it allowed no deep percolation, presumably because the barrier functioned as intended (Table 3.1). They did not report the reason for the good performance. One may speculate that the good performance resulted from a superior mix of materials in the barrier or from less drying of the barrier layer because there were no plants on the surface. Less drying of the compacted barrier should substantially reduce the amount of barrier-layer cracking and serve to maintain its desired low hydraulic conductivity.

3.4.4 Geomembrane Barriers

Geomembrane (GM) barriers are also prone to leak. Board and Laine (1995) found 26 holes in the GM of a 1.6 ha (4 acres) liner. Crozier and Walker (1995) examined seven GM installations and found holes ranging in size from pinholes to 2 m gashes; the average number was five per hectare (two per acre). They traced most leaks in GMs to holes left by construction; however, they did not measure leakage rate.

3.4.5 Composite Barriers

Composite barriers, for example compacted clay covered by a GM (Figure 3.1), are accepted as the best barrier covers. They are costly to build; however, they performed better than the single barriers tested in this group of experiments (Table 3.1).

The composite-barrier covers at the two driest sites produced no leakage; however, the test duration was only 1 or 2 years and the sites are located in deserts. The two sites at Albuquerque leaked even though the site is arid.

At Marina, California, the average percolation was 7% of precipitation in spite of the dryness of the local climate. The maximum single-year percolation rate for the sites tested by Albright et al. (2004) was 36 mm/year in the third year of the test at the dry Marina site.

Melchior (1997) reported that three experimental composite covers leaked, on average, between 0.2 and 0.4% of annual precipitation in a humid climate. He measured a maximum single-year leakage of 5.2 mm.

The measurements by Loehr and Haikola (2003) are worthy of emphasis because they measured leakage through the cover of a large working landfill for 14 years. They show that after the initial period of drainage resulting from water storage in the waste during landfill construction, a composite-barrier cover leaked 2% of precipitation (Table 3.1).

Dwyer (2001) and Albright et al. (2004) created one puncture in the GM in their composite-barrier test covers; one puncture resulted in a larger incidence of leaks per unit area than expected for good construction practice. Even with good construction practice, some holes are likely in the GM barrier. In a full-scale composite barrier-type cover, a single hole in the GM near the bottom of a long slope has potential to funnel a very large volume of water into the waste. In a full-scale cover, the holes may be located anywhere. At each test site, the holes in the covers were not located at the bottom of the slope, limiting leakage through them. Thus, the measurements by Dwyer (2001) and by Albright et al. (2004) demonstrate that composite-barrier covers are likely to leak.

The measurements from these independent investigations show that all composite barriers tested at sites with more than 240 mm of annual precipitation leaked. Generally, the leakage rates were small; however, at one site, it was greater than 7%

of annual precipitation and at another it was 3%. The 14-year test in a wet climate demonstrates that a real cover, working under good conditions for the technology, leaked about 2% of precipitation.

3.5 PERFORMANCE OF ALTERNATIVE COVERS

Several investigators built and tested alternative covers that utilize plants to remove water from the cover. Many of them leaked even in dry and desert climates; this section examines possible causes. Capillary-barrier covers are an experimental alternative for barrier covers; however, they depend on the interaction between vegetation and the soil water reservoir for success. They are, therefore, included in this section.

3.5.1 Capillary-Barrier Covers

The capillary barrier covers relied on a capillary "barrier" to increase the water-holding capacity of fine-textured soil, and plants to remove the water from the cover.

3.5.1.1 Vegetated Surface

Table 3.2 contains measurements of performance for capillary-barrier landfill covers both with and without vegetation on the surface. Success with the capillary-barrier cover requires that water temporarily stored in the soil above the barrier be removed to provide storage space for the next precipitation event. Most experiments employed a vegetated surface because the combination of evaporation and plant transpiration is much larger than evaporation alone.

Gee and Ward (1997) measured no deep percolation at Hanford, Washington. Nine of the capillary barrier tests had annual precipitation amounts greater than 400 mm; Gee and Ward's (1997) experiment was the only one in that group to report no deep percolation. They stated that the soil density in their test plot was 1.38; that density would allow good plant root growth. The soil over their barrier was also deep. Either the soil in the others was compacted or soil density information was not available, except for Los Alamos, where the soil cover was thin.

Warren et al. (1996) measured 12 and 15% of annual precipitation as leakage through two capillary barriers during more than 3 years at Hill Air Force Base (AFB), Utah, a semiarid site. Their cover soils were compacted to a very high soil density. During the third and final year of the measurements at Hill AFB, the capillary barriers with grass, and grass and shrub cover produced about 120 and 180 mm of deep percolation, respectively.

Six of the test plots contained compacted soil and each of them leaked, including two located in a dry climate at Albuquerque. The cover at Hamburg was compacted and the cover soil was relatively thin for such a wet site; it leaked 11% of annual precipitation.

Albright et al. (2004) measured percolation rates through capillary barriers at six sites in the United States. At three arid locations, they measured no deep percolation; however, the average percolation at Marina was 16% of annual precipitation at that dry location.

TABLE 3.2
Measured Performance of Capillary-Barrier Landfill Covers

Reference	Location	Soil Depth (m)	Test Year[a]	Annual Precipitation (mm)[b]	Annual Leakage (mm)	Annual Leakage (%)[c]	Soil Density (Mg/m^3)
Vegetated Capillary-Barrier Cover							
Khire et al. 1999	Wenatchee, WA	0.15	2.5	224	2	<1	N/A[d]
Albright et al. 2004	Helena, MT	1.65	3.0	233	0	0	N/A
Dwyer 2001	Albuquerque, NM	1.42	3.0	247	1	<1	Compacted[d]
Dwyer 2001	Albuquerque, NM	1.05	3.0	247	<1	<1	Compacted
Albright et al. 2004	Monticello, UT	1.70	3.0	298	0	0	N/A
Albrigh et al. 2004	Polson, MT	1.10	3.0	311	0	0	N/A
Albright et al. 2004	Marina, CA	1.50	3.0	322	53	16	N/A
Gee and Ward 1997	Hanford, WA	2.00	2.0	469	0	0	1.38
Albright et al. 2004	Omaha, NE	1.06	2.0	518	27	5	N/A
Albright et al. 2004	Omaha, NE	1.36	2.0	518	16	3	N/A
Warren et al. 1996	Hill AFB, LA-1	1.50	3.8	539	64	12	1.86
Warren et al. 1996	Hill AFB, LA-2	1.50	3.8	539	80	15	1.86
Nyhan et al. 1990	Los Alamos, NM	0.71	3.0	579	8	1	1.4
Breshears et al. 2005	Los Alamos, NM	0.71	10.3	482	14	3	1.4
Melchior 1997	Hamburg, DE	0.75	8.0	865	95	11	Compacted
Bare Soil Capillary Barrier, 5% Land Slope							
Nyhan et al. 1997	Los Alamos, NM	.15/.76[e]	3.7	462	47	10	Compacted
Nyhan 2005	Los Alamos, NM	.15/.76[e]	7.0	444	8	2	Compacted
Nyhan et al. 1997	Los Alamos, NM	0.6 l[f]	3.7	462	26	6	Compacted
Nyhan et al. 1997	Los Alamos, NM	0.6 cl[g]	3.7	462	15	3	Compacted

(continued on next page)

TABLE 3.2 (continued)
Measured Performance of Capillary-Barrier Landfill Covers

[a] Test duration, years—measurements for full years are shown when available.
[b] Annual precipitation includes irrigation, if any.
[c] Leakage rate expressed as percent of annual precipitation.
[d] Soil compacted and/or density not stated.
[e] 0.15 m loam mix/0.76 m crushed tuff over medium gravel.
[f] 0.6 m loam mix/.76 m fine sand over medium gravel.
[g] 0.6 m clay loam mix/0.76 m fine sand over medium gravel.

These 15 measurements of the performance of capillary barriers show that they frequently leaked. Covers with a thin soil cover produced more leakage than those with thick soil covers. The likely cause of leakage in many cases appears to be soil compaction that may have restricted root growth. The single test with adequate soil density and a thick soil cover allowed no leakage.

3.5.1.2 Bare Soil Surface

Nyhan et al. (1997) and Nyhan (2005) reported measurements of capillary-barrier covers having no vegetation growing on the soil (Table 3.2). Table 3.2 contains the measurements from their plots with 5% land slopes. They reported measurements for land slopes of 10, 15, and 25%; the increased slopes had less leakage and some of them produced none. All of their covers produced significant volumes of interflow, indicating that the capillary barrier functioned in a small plot, although it was occasionally overwhelmed and produced leakage. In spite of the handicap of no water extraction by plants from the soil, these covers demonstrated that the capillary barrier could work for small plots. Stormont (1996) found that larger plots with plants leaked where the accumulated lateral drainage above the capillary break overwhelmed the system.

3.5.2 Vegetated Covers

The vegetated covers relied on plants to dry the cover soil.

3.5.2.1 The MSR Cover

The MSR cover exceeded the requirement for keeping the underlying waste dry at Beltsville, Maryland (Table 3.3; Schulz et al. 1997). The authors saturated 880 mm of soil in one of their test cells. That MSR cover removed all precipitation and the stored groundwater; it dried the soil to the bottom of the cell in 4 years. The MSR cover succeeded because the impervious cover intercepted 91% of rainfall and in spite of poor rooting conditions created by the elevated soil density (1.6 Mg/m^3).

TABLE 3.3
Measured Performance of Modified Surface Runoff (MSR) and Vegetation Only Landfill Covers

Reference	Location	Soil Depth (m)	Test Year[a]	Annual			Soil Density (Mg/m^3)
				Precipitation (mm)[b]	Leakage (mm)	Leakage (%)[c]	
			Modified Surface Runoff (MSR) Cover				
Schulz et al. 1997	Beltsville, MD 20%	3.80	9.0	>1000[d]	0	0	1.60
Schulz et al. 1997	Beltsville, MD 40%	3.80	9.0	>1000[d]	0	0	1.60
Karr et al. 1999	Oahu, HI 20%	0.60	1.7	606	14	2	Compacted[e]
Karr et al. 1999	Oahu, HI 40%	0.60	1.7	606	13	2	Compacted
			Vegetated Cover				
Albright et al. 2004	Boardman, OR	1.22	2.0	130	0	0	N/A[e]
Albright et al. 2004	Boardman, OR	1.84	2.0	130	0	0	N/A
Albright et al. 2004	Apple Valley, CA	1.20	1.0	148	0	0	N/A
Dwyer 2001	Albuquerque, NM	1.05	3.0	247	<1	<1	1.70
Albright et al. 2004	Sacramento, CA	1.08	3.0	293	34	12	N/A
Albright et al. 2004	Sacramento, CA	2.45	3.0	293	3	1	N/A
Albright et al. 2004	Altamont, CA	1.00	2.0	343	2	<1	Compacted
Breshears et al. 2005	Los Alamos, NM	0.20	10.3	482	15	3	1.4
Nyhan et al. 1990	Los Alamos, NM	0.20	3.0	579	35	6	1.4
Karr et al. 1999	Oahu, HI	0.60	1.7	606	39	6	Compacted
Albright et al. 2004	Cedar Rapids, IA	1.80	1.0	791	157	20	Compacted
Albright et al. 2004	Albany, GA	1.30	3.0	1191	118	10	Compacted

[a] Test duration, years—measurements for full years are shown when available.

[b] Annual precipitation includes irrigation, if any.

[c] Leakage rate expressed as percentage of annual precipitation.

[d] Precipitation not stated; average annual precipitation in the area exceeds 1000 mm.

[e] Soil density not available or soil compacted, but density not stated.

In Hawaii, the MSR cover allowed some leakage (Karr et al. 1999; Chittaranjan 2005). The cover depth was only 0.6 m. In addition to inadequate thickness, the cover soil was compacted to 95% of standard Proctor density. In spite of the adverse conditions in Hawaii, both treatments allowed less than 2.5% of precipitation to move through the cover as deep percolation (Table 3.3). In a following study using the same plots, Chittaranjan (2005) found that up to 30% of precipitation appeared as deep percolation for several large events. As explained in Section 3.3.1 and Chapter 5, excessive soil compaction may have adversely affected the performance of the MSR cover in Hawaii.

The MSR cover has potential to control infiltration from precipitation if the cover is correctly designed and constructed. However, the runoff diversion structures used as barriers to precipitation are small roofs; they are likely to have high construction and maintenance costs. The MSR cover, described in these tests, does not meet the requirement for self-renewal to assure long cover life.

3.5.2.2 Vegetation-Only Landfill Covers

Albright et al. (2004) tested eight alternative vegetated covers that they described as "monolithic" *(i.e., a thick layer of finer-textured soil overlain by topsoil).* At the Cedar Rapids, Iowa and Albany, Georgia, sites' deep percolation was 20 and 10% of precipitation, respectively. The soil was compacted at both sites, and the vegetative cover included trees. The thinner soil cover at Sacramento, California (1.08 m), used sandy clay soil with poor water retention properties; deep percolation was 12% of precipitation. At the Altamont site, the cover included compacted soil and produced deep percolation in spite of the dry climate. The remaining three sites were in desert environments and had no deep percolation (Table 3.3).

Although the covers tested at Los Alamos had desirable soil density, the soil covers were very thin, thus limiting their water-holding capacity. They apparently leaked because the soil thickness was inadequate.

Five of the conventional "vegetated" covers tested used a compacted soil layer; two had desirable soil density and the soil density for the others was not available. Performance was poor for all of the covers with compacted soil. Three covers with compacted soil and annual precipitation greater than 600 mm leaked between 6 and 20% of annual precipitation. Chapter 5 discusses the reasons for likely failure of vegetated covers planted on compacted soil.

3.5.3 ASPHALT REPLACED BY VEGETATED COVER

Levitt et al. (2005) measured the water balance to a maximum depth of 20 m under an asphalt cover and under the vegetative cover that replaced it. They found that during 37 years with the asphalt cover in place, water accumulated deep in the covered profile and a perched water table developed under the cover. They replaced the asphalt cover with a vegetated cover having only 15 cm of topsoil over crushed and compacted tuff varying in thickness from zero to 2 m. They report that during the first 4 years after installing the vegetated cover, the soil below the cover dried significantly.

3.5.4 ISE Cover

Blight (2006) measured performance of an ISE cover during an 18 month period when 864 mm of precipitation fell. He stated that the measurements showed the viability of the ISE cover concept.

Blight (2006) cited earlier reports that showed deep drying of waste in a dry climate. At Cape Town and Johannesburg, landfills with temporary cover of beach sand and pervious silty sand to a depth of 300 mm, the waste seasonally dried to a total depth of 7.5 and 16 m, respectively. The waste dried to the bottom of the fill at each site at the end of the dry season.

3.5.5 Common Elements of Vegetated Cover Failure

Even though success was expected, a large number of vegetated covers failed to meet expectations for a landfill cover by allowing a significant amount of precipitation to infiltrate through the cover. Anderson (1997) stated that *"failures of earthen barriers as final caps on landfills in arid or semiarid regions likely result from insufficient depths of soil to store precipitation and support healthy stands of perennial plants."*

The vegetated cover site at Sacramento with only 1.08 m of soil cover leaked 12% of the precipitation; its deeper companion leaked only 1% of the precipitation. Both vegetated covers at Sacramento leaked a large amount given the relatively low precipitation at the site. The Los Alamos plots had thin soil covers with low soil density; they leaked up to 6% of precipitation. Both the Los Alamos and the Sacramento plots support Anderson's (1997) statement that inadequate soil water-holding capacity is likely to cause failure for vegetated covers.

All test covers listed in Table 3.3 had vegetated covers whose purpose was to remove water stored in a soil profile. Table 3.3 contains performance measurements for seven experimental, alternative covers stated to have compacted soil in the cover or soil density equal to or greater than 1.7 Mg/m^3; none of them was successful. The data presented in Table 3.3 show that high soil density is likely to produce failure for vegetated covers.

3.6 FOCUS OF THIS BOOK

The ET cover is the subject of this book. It uses soil and plants to control infiltration of precipitation into the waste; however, there are important, major differences between the ET cover and the "vegetative covers" described in this chapter. As a result, the ET cover will perform as expected at most sites where the "vegetative covers" failed.

The ET cover is compatible with and enhances new concepts such as the bioreactor landfill and the ISE landfill that focus on waste decay, landfill stabilization, and reduction of waste to harmless materials. It is also appropriate for use in covering mining waste, contaminated soil, and similar sites.

This book is devoted to explanation of the requirements for ET covers. It also explains the background science and technology or provides references to more complete information. The remainder of the book is devoted to the technology of the ET landfill cover.

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4 Evapotranspiration Landfill Covers

The evapotranspiration (ET) landfill cover is an innovative design with two important characteristics:

- It uses natural systems with no barrier layers.
- Measurements show that the concept was successful in natural systems for decades and centuries.

4.1 DEFINITION

The ET landfill cover works with the forces of nature rather than attempting to control them. It utilizes a layer of soil covered by native grasses, and it contains no barrier layers (Figure 4.1). The ET cover uses two natural processes to control infiltration into the waste: (1) the soil provides a natural water reservoir and (2) natural evaporation from the soil and plant transpiration (ET) empties the soil water reservoir. At most sites, it is easy to build the ET cover to allow small or large percentages of annual precipitation to enter the waste. It is an inexpensive, practical, easily maintained, and self-renewing biological system. The ET cover will remain effective over extended time periods, perhaps centuries.

4.1.1 MINIMUM REQUIREMENTS AND FUNCTION

The ET cover differs from "vegetative" covers because it requires optimization of both cover soil properties and the plants grown on the cover. The "vegetative covers" described in the literature require neither, resulting in failure as described in Chapter 3. The ET cover has the following minimum criteria:

- The soil should hold enough water to minimize water movement below the cover and meet the requirements of the site.
- The soil should support rapid and prolific root growth in all parts of the soil cover.
- The vegetation established on the cover should be native to the site, adapted to the soil in the cover, and compatible with site remediation goals.

Because of these criteria, design and construction methods for ET covers differ from both conventional barrier and recently reported vegetative covers that failed (see Chapter 3).

ET covers need no barrier layers because the soil provides a reservoir that stores and holds infiltrating water. Infiltrating rainfall moves downward as a saturated front, filling the soil pores as it advances deeper into the soil. When the volume of water contained in the saturated front is all stored in pores at or below the field water capacity for that soil, downward movement becomes very slow.

Theoretical considerations and research measurements, with evaporation controlled at the surface, show that soil water may continue to move downward for a long time after wetting, but at a slow and exponentially decreasing rate (Hillel 1998). The actual conditions on rangeland, pasture, a cultivated field, or on an ET cover are different from the "covered soil" conditions of the research site. On soils with bare surfaces, water evaporates from the surface soon after rain stops, thus establishing upward gradients for water flow. Plants growing on the surface remove soil water faster than evaporation alone. The upward hydraulic gradient established by even a small amount of soil drying reverses the direction of soil water movement, and soil water begins to move upward in response to natural hydraulic gradients established by drying of the soil. This process reduces the rate of downward soil water movement after the end of precipitation to a very small amount in 1–48 h, depending on the soil. For practical purposes of plant growth and protection of landfill waste, soil water is then stationary until it begins to move upward in response to evaporation or water extraction by roots. The infiltrated water is stored within the soil mass until evaporation from the surface or plant roots removes it. This basic process makes all plant and animal life on our planet possible. As it does not rain every day, plants depend on stored soil water for sustenance during rainless periods; the process has functioned for a long time.

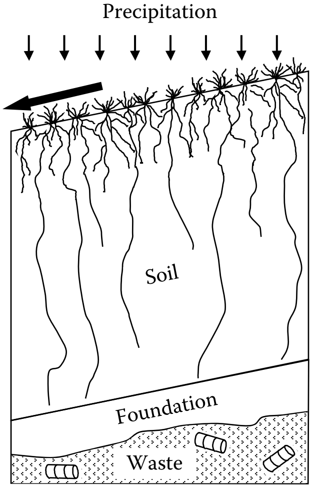

FIGURE 4.1 Cross section of an ET landfill cover.

If more water infiltrates through the surface than the soil can hold at field capacity, some of it will move through the soil profile and appear as deep percolation. Good design and construction practice controls percolation to meet site requirements.

4.1.2 SOIL WATER STORAGE AND PLANT ROOTS

The soil water reservoir is a major feature of an ET landfill cover; it should be composed of the largest possible volume of soil pores. It is desirable that much of the soil pore volume be contained within the midsize pores because they hold much water against the force of gravity, yet plants easily and quickly remove water from them. Two important ingredients that control soil's water-holding capacity are soil particle-size-distribution and bulk density.

An ET cover controls infiltrating water by storing it in the soil water reservoir. In order to have reservoir capacity available when precipitation events occur, it is necessary that the vegetation remove the stored water rapidly and maintain the soil in the driest condition possible. Water removal from the soil reservoir is dependent on a large mass of healthy plant roots growing in all parts of the soil mass that contain water. For practical purposes, plant roots must grow to the water in the soil, because water movement to plant roots is limited to a small distance in the soil (see Chapter 5). The soil should provide near-optimum conditions for plant root growth; fortunately, optimum soil conditions are easy and inexpensive to create.

4.2 DIFFERENCES

Conventional landfill covers (see Chapter 3) employ technology and construction practice proved in road and dam construction, building foundations, reservoir liners, and similar activities. That technology serves well in the applications for which it was developed and when applied to design and construction of liners placed under the waste. However, it produces failures when applied to an ET landfill cover.

The ET landfill cover applies different science and technology. Some requirements for ET covers are opposite from the technology adapted to conventional covers. For example, soil used as a construction material is commonly compacted to the highest density that is practical in the field. However, that approach when applied to the "vegetative" covers (see Chapter 3) resulted in poor-to-unacceptable performance. The soil in an ET cover should have low density.

4.3 CONCEPT BACKGROUND AND PROOF

The principles and technology that form the basis for the ET landfill cover are well understood, and field measurements are available to test the concept. The measurements prove the ET landfill cover concept over periods of years, decades, and even millennia.

This chapter cites measurements from short-term experiments, decades-long experiments, and the consequence of water movement during millennia. The long-term measurements included measured water balance under grass during three decades and field measurements at other sites that demonstrated water movement within soil profiles during millennia. The measurements assessed the effect of unusually wet periods, fires, drought, and other natural events. These data demonstrate that the ET cover can minimize movement of precipitation into stored wastes by using natural forces and the soil's water-holding capacity. Figures 4.2 and 4.3 show the location of the measurements discussed here; they include hot, cold, wet, and dry climates.

4.3.1 WATER BALANCE BY SOIL WATER MEASUREMENTS

Some of the proof-of-concept measurements rely on soil water measurements. Because there is no watertight bottom under these soil profiles, some individuals claim that soil water measurements do not provide accurate estimates of water balance or deep percolation. This claim may be true for thin soils located in wet climates or under unnatural environmental conditions.

Irrigation engineers have long used soil water measurements to estimate plant water use under surface irrigation on level basins. The soil in irrigated fields is at or near field capacity several times during each growing season. Jensen (1968) stated,

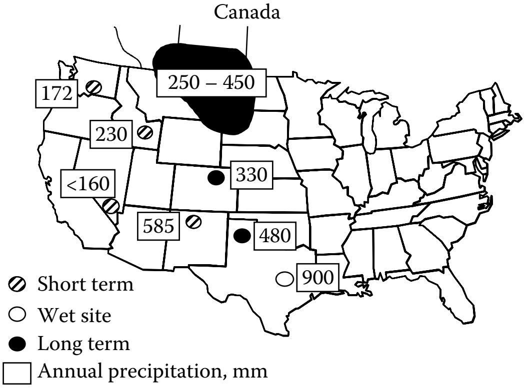

FIGURE 4.2 Field verification sites.

"The most common method of determining water requirements of agricultural plants under natural environmental conditions for 5- to 20-day periods is by soil moisture depletion. This method has been used extensively in irrigated areas of the world and in the western United States for more than 70 years." Jensen (1967), Jensen and Haise (1963), and Jensen and Sletten (1965) used soil water measurements to estimate ET from heavily irrigated sites. Their measurements are widely used in irrigation design and are similar to results of measurements using other methods (Jensen et al. 1990). They demonstrated that water balance estimates for irrigated crops derived from soil water content measurements are valid.

FIGURE 4.3 Soil water-balance sites.

Important proof-of-concept measurements were made in the Great Plains on the deep soils of that vast region. Under natural field conditions found in the Great Plains, the water content of the soil near the bottom of the potential root depth is small and often near the wilting point year-round. Under these conditions, the unsaturated hydraulic conductivity of soils in the lower part of the profile is diminishingly small. Therefore, the flow rate through these dry layers in the lower part of the field soil profile is, for practical purposes, zero, and the water balance is defined by change in soil water content and precipitation.

4.3.2 EXPERIMENTAL PROOF

Short-term field experiments tested the ET cover concept at four dry sites having significantly different climate and soil resources and measured the performance of the ET cover concept in a wet climate. Measurements of water balance at five sites in the central and northern Great Plains are available for a 30-year period and both soil water and lysimeter measurements over 33 years are available for a native grass site in Colorado. Measurements demonstrated the result of many centuries of water movement for a site in the southern Great Plains and for a large region in the northern Great Plains.

4.3.2.1 Short-Term Experiments

There were seven experiments located at four sites in New Mexico, Idaho, Washington, and Nevada (Figure 4.2). The investigators evaluated water movement through soil covers for 4–17 years (Nyhan et al. 1990; Anderson et al. 1993; Waugh et al. 1994; Anderson 1997; Andraski 1997; Forman and Anderson 2005; Fayer and Gee 2006). These experiments sampled annual precipitation amounts from less than 160 to 585 mm per year. They demonstrated that covers utilizing soil and natural vegetation could minimize or prevent percolation of precipitation into the waste even though the soil at some of these sites was not optimum for an ET cover.

4.3.2.2 Wet Climate and Modified Soil

Measurements are available for one wet site in east central Texas (Figure 4.2), where average annual precipitation was 900 mm, and the soil resource was of poor quality. Chichester and Hauser (1991) and Hauser and Chichester (1989) measured soil water balance and soil chemistry for 6 years. Precipitation at the site was greater than the long-term average during 5 of the 6 years of measurement.

They measured performance of grass grown on soils built from poor-quality local subsoil and the undisturbed soil at the site. The eroded undisturbed soil at the site had little topsoil, contained dense clay layers of low permeability, and had high density beginning at a depth of 0.2 m in the profile. The clay layers in the undisturbed soil were sufficiently dense to limit root growth. The mixed subsoil plot simulated an ET landfill cover built from local soil. The subsoil plot was a mixture of several soil layers from the local eroded soil; the soil mixture included the dense clay.

The site in east central Texas (Figure 4.2) demonstrated the performance of soil modified in a similar fashion to that of an ET landfill cover built from the poor-quality soil–subsoil mixture. The mixed and amended subsoil produced forage yields equal to that of the undisturbed soil. Hauser and Chichester (1989) measured both soil water content and soil salt movement; these two measurements independently measured the depth to which precipitation penetrated into the soil profile. Infiltrating water penetrated below 1.8 m on the undisturbed soil, but only about 0.6 m deep on the mixed subsoil plot. The mixed subsoil had low soil density and allowed prolific root growth; therefore, the grass removed precipitation from the soil rapidly, thus limiting downward water movement. These measurements demonstrated success with poor-quality soil in a wet climate.

4.3.3 LONG-TERM PROOF

It is good that short-term experiments validated the concept. However, one expects a landfill cover to function as planned for decades or centuries; therefore, long-term proof of the concept is required.

4.3.3.1 Great Plains Water Balance

The classic paper by Cole and Mathews (1939) contained the results of water balance measurements from five locations in the Great Plains (Figure 4.3) extending over the years 1907–1936. Two locations provided continuous water balance measurements from native sod, and the others had partial records for native sod. In addition, they measured soil water content under winter or spring wheat at each location. Wheat is a grass plant, and it was grown every year (continuous wheat). Natural precipitation was the only source of water at all sites.

Soil water measurements were complete for native sod grown on a silty clay loam soil for 21 years at Mandan, North Dakota, and on a very fine sandy loam soil during 25 years at North Platte, Nebraska. Cole and Mathews (1939) stated that for both sites, water did not penetrate to depths beyond the roots of the native sod. Their measurements also show that water did not move below the root zone of continuous wheat at Havre, Montana; Hays, Kansas; and Colby, Kansas, where record lengths were 21–28 years.

The review of measurements presented by Cole and Mathews (1939) demonstrated no evidence that water moved below the root zone of native grass or continuous wheat at these five locations. Either cool or warm season native plants grew throughout most of the year on native sod; thus, they quickly removed water from the soil. Winter wheat provided a more rigorous test of the concept than native sod because continuous wheat utilized a 3-month-long fallow period during which water accumulated in the soil profile. In spite of the fallow period between harvest and planting of the succeeding crop, they measured no water movement below the root zone of continuous wheat.

The water balance measurements reported by Cole and Mathews (1939) represent a large region (Figure 4.3). They measured water balance each year at each site under both native grass and cultivated wheat during 21 to 28 year periods. The length of their measurements is important. They found that no water moved below the root zone of wheat or grass during the decades of measurement.

4.3.3.2 Pawnee National Grasslands

Sala et al. (1992) reported measurements of the soil water balance under native grassland in Northeastern Colorado (Figure 4.2). The mean annual precipitation at the site during the 33 year study was 327 mm. The soil at the site is sandy loam in texture; therefore, it has only moderate water-holding capacity. The authors concluded from both field soil and field lysimeter measurements that it is unlikely that the soil profile within the potential rooting depth of native range grasses would ever be completely filled with water. Sala et al. (1992) stated, "*No deep percolation beyond 135 cm was recorded during the 33-year period.*"

This is an important test site because soils with high water-holding capacity are not available at all landfill sites. The soil at the site has relatively low water-holding capacity; however, the measurements demonstrated that no water moved below the rooting depth of native grasses.

4.3.3.3 Saline Seep Region

The saline seep region found in the Northern Great Plains of the United States and southern Canada (Figure 4.2) provides opportunity to evaluate water movement in soils of a vast region. The saline seep region covers parts of Montana, Wyoming, South Dakota, and North Dakota in the United States, and Alberta, Saskatchewan, and Manitoba in Canada. The hydrogeology of the region was measured and described by Ferguson and Bateridge (1982), Halvorson and Black (1974), Doering and Sandoval (1976), Luken (1962), and Worcester et al. (1975). The soils that formed over shale after the retreat of the glaciers provide a natural "lysimeter" covering millions of hectares.

Ferguson and Bateridge (1982) described the soils, plants, and hydrology associated with saline seeps. They state that the glacial till soils of the Northern Plains developed from debris left by the ice ages 12,000–14,000 years ago on top of ancient marine shales. Native short grass covered the surface and the natural subsoil contained large amounts of soil salts beginning at depths of 0.5–1 m below the land surface.

Saline seeps first appeared about 30 years after cultivation of dryland crops began in the region. Figure 4.4 is a conceptual cross section of soils in the saline seep region. Summer fallow with spring wheat or winter wheat was widely practiced; it prevented all plant growth for more than a year, thus allowing water to move below the root zone of the crop during wetter-than-normal years. Field investigations in Montana show that about 90 Mg/ha of salt moved downward with water percolating below the root zone of dryland crops (Ferguson and Bateridge 1982). Figure 4.5 shows measurements of the typical soil salt content estimated by electrical conductivity of the soil under both native grass and cultivated dryland. These data show that percolating water removed significant quantities of salt from the subsoil under cultivated land, but not from soils under native grass.

Doering and Sandoval (1976) observed that the excess soil water accumulated on cultivated land moved downward to natural layers of low permeability, then laterally to produce saline seeps at the base of slopes or other outcrops (Figure 4.4). In contrast, excess soil water did not accumulate in soils covered continuously by native grass. Halvorson and Black (1974) stated, *"Native grasslands generally support some actively growing vegetation throughout most of the growing season, reducing*

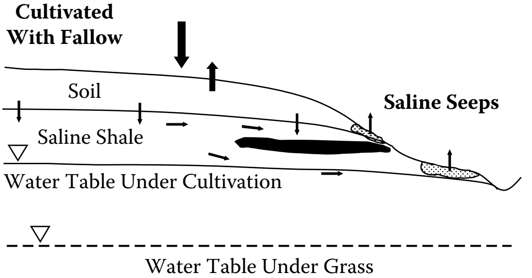

FIGURE 4.4 Conceptualized cross section of a saline seep.

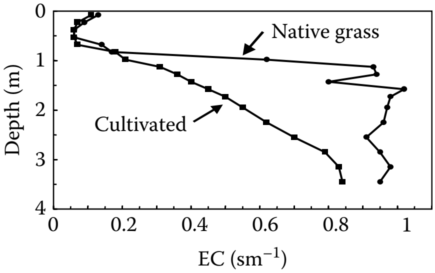

FIGURE 4.5 Electrical conductivity of soil in saline-seep area of Montana. (Drawn from data in Ferguson, H. and Bateridge, T., *Soil Sci. Soc. Am. J.,* 46, 807–810, 1982.)

the chance of precipitation percolating beyond the root zone. As a result, saline seeps are generally absent on rangeland."

In summary, no water moved below the root zone of native grass. The following process created the saline seeps (see Figure 4.4):

1. The root zone of both grass and wheat was within the nonsaline surface soil. During occasional wet years, water percolated below the root zone of wheat during the fallow period and dissolved salt from the saline subsoil.
2. The percolating saline water raised the water table under wheat and caused groundwater to flow laterally.
3. Where the groundwater was near the soil surface down gradient from wheat, plant water extraction and evaporation from the soil surface concentrated salts in the surface soil and formed the saline seeps.
4. Where native grass grew on the land surface, no water percolated below the root zone, the water table was stable and deep, and no saline seeps emerged.

The saline seep region (Figure 4.2) provides a good example of how soils, plants, climate, and water interact during centuries. An ancient sea left saline shale deposits that now lie below the modern soil. The soil–plant–climate system was in balance under native grass and allowed no precipitation to move below about 0.9 m (Figure 4.5). The native grass consumed water stored in the surface soil during each year, and none moved into the shale as demonstrated by the salt profile in the shale and the lack of saline seeps near native grass. The ecosystem of the saline seep region developed in a cold, dry climate with long winters during which plants used little soil water. Evaluation of the saline-seep region demonstrated that native grass prevented significant water movement through the thin soil profile during 12,000 years, because the ice sheet melted in that region.

4.3.3.4 Texas High Plains

Aronovici (1971) measured soil water content, chloride, and salt movement in soil profiles under native grasslands, dryland wheat and sorghum, and irrigated wheat and sorghum. His measurements extended from the surface to the 15 m depth at a site near Amarillo, Texas (Figure 4.2). Mean annual precipitation is about 480 mm at

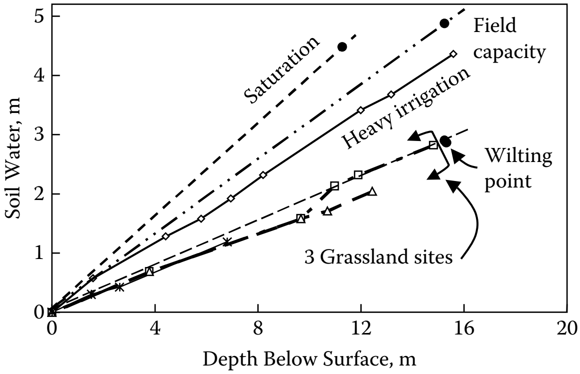

FIGURE 4.6 Cumulative soil-water content in Pullman clay loam soil and underlying Pleistocene sediments. (Drawn from data in Aronovici, V. S., *Percolation of Water through Pullman Soils, Texas High Plains,* Bulletin B-1110, Texas A&M University, College Station, TX, 1971.)

that Southern High Plains location. The Pullman clay-loam soil at the site has a high shrink-swell capacity and cracks extensively when dry. Prairie dogs and other small burrowing animals historically populated it and excavated holes in the soil. The soil throughout the 15 m depth contained many root and wormhole casts ranging in size from less than 1 to 5 mm (Aronovici 1971). The soil offered numerous preferential flow paths from the surface to the 15 m depth.

Figure 4.6 contains cumulative soil-water content measurements, by Aronovici 1971, in Pullman clay-loam soil and the underlying Pleistocene sediments. He stated that two of the three sampling sites under grass were unusually dry at depth, thus creating high soil strength that prevented sampling to the intended depth of 15.2 m. The soil water content under grass was below the plant wilting point beginning at 1 m below the surface and extending to the 15 m depth.

The data shown in Figure 4.6 for “heavy irrigation” were from a plot that was irrigated for 20 years; during 14 of those years, it was heavily irrigated in level borders. This condition offered the maximum potential for deep percolation below the root zone and wetted the soil and underlying Pleistocene sediments to near the field capacity to the 15.2 m depth.

Soil chemistry offered a way for Aronovici (1971) to make an independent determination about water movement downward through the soil profile. Chloride and electrical conductivity data show large accumulations of the chloride ion and salts from 0.9 to 1.8 m under native grass (Aronovici 1971). For example, Figure 4.7 shows significant deposits of calcium plus magnesium measured for the Pullman soil under native grass at the site. The high-salt layer between 0.9 and 1.8 m under native grass is a result of natural processes. It is common for soil profiles in arid and semiarid regions to contain soil layers that are high in salt. Precipitation amount at the site determines their depth below the land surface. Precipitation dissolves soil salts from surface soil layers and transports them downward in the soil. Plants remove water, but little salt from each soil layer; therefore, over time, salt accumulates at the bottom of the soil-wetting front. This process is a strong indicator of past leaching potential

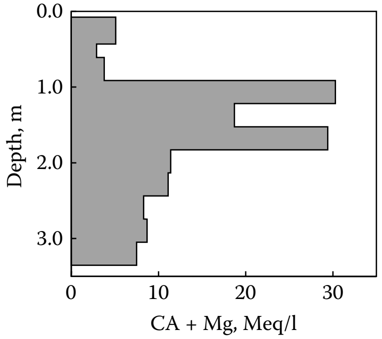

FIGURE 4.7 Calcium plus magnesium content of soil at the grassland site, Bushland, Texas. (Drawn from data in Aronovici, V. S., *Percolation of Water through Pullman Soils, Texas High Plains,* Bulletin B-1110, Texas A&M University, College Station, TX, 1971.)

at the site. Salt accumulation in the soil demonstrates that little or no water moved below the depth of accumulation. In this case, little or no water moved below the 1.8 m depth.

The chloride ion is a good indicator of recent water movement in a soil profile because it is highly soluble and moves with percolating water. Figure 4.8 shows that on grassland, chloride accumulated below the 0.8 m depth, indicating that water movement stopped near that depth. The chloride in the upper 4 m of the profile fell from the historical value of 10 meq/L under grass to about 5 meq/L or less under heavily irrigated land. The large accumulation of chloride ion in the sediments below 11 m suggests that the 11–15-m depth is the extent of leaching under irrigation during the 20-year period (Figure 4.8).

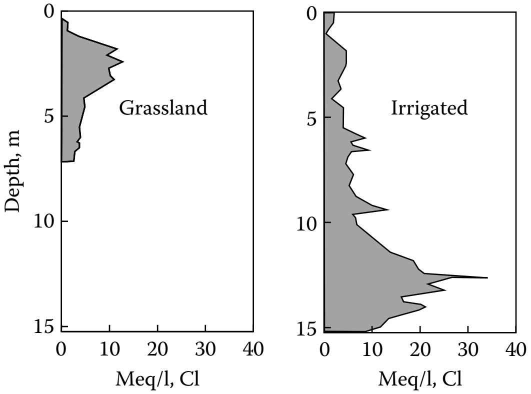

FIGURE 4.8 Distribution of chlorides in Pullman soil and underlying Pleistocene sediments, Bushland, Texas. (Drawn from data in Aronovici, V. S., *Percolation of Water through Pullman Soils, Texas High Plains,* Bulletin B-1110, Texas A&M University, College Station, TX, 1971.)

Aronovici (1971) measured soil water content directly and independently verified the conclusion with soil chemistry. He concluded, "*There has been little or no deep percolation on native or revegetated grassland within historic time where natural surface drainage occurs.*"

The soils at the Texas High Plains site are different and the climate at the site is wetter than both the saline seep region and the grassland site in eastern Colorado. Important features of the soil on the Texas High Plains include the dense clay layers contained within the upper 1.2 m of the root zone. The upper 1 m of soil has high shrink-swell capacity and cracks extensively when dry; it contains wormholes, animal burrows, and other openings. The dense, limiting layers in the upper 1.2 m of soil have hydraulic conductivity of about 0.03 m/day when wet, and limit the intake of irrigation or rainfall.

The parent material of the Texas High Plains site is Pleistocene sediment. The root zone below 1.2 m is primarily porous, partially cemented Pleistocene material including cracks, large pores, wormholes, animal burrows, and other openings. Schneider and Jones (1983, 1988) demonstrated that water moves easily through the porous parent material. They measured the water intake rate of the Pleistocene sediment and found that it was 0.4 m/day, 10 times the value for the surface layer. The highly permeable material extended from the 1.2-m depth to the water table at 55 m.

Soil layers within the upper root zone have elevated density; they reduce root growth, thus reducing the rate of water extraction by plants from the bottom of the soil profile. Roots grow in the partially cemented Pleistocene material, but it is not known if the soil strength limits total root mass.

The natural soil is fertile, but less than perfect for an ET landfill cover. High-density soil layers reduce root growth, and preferential flow pathways are present throughout the soil and the underlying permeable sediments. Hydrologic measurements demonstrated that native grass prevented significant water movement through the soil profile over thousands of years.

4.4 RECOVERY FROM FIRE

Fire may remove the vegetation from an ET landfill cover. It is a natural part of grass ecosystems on the Texas High Plains and the Saline Seep Region; however, there was no evidence that water moved below the root zone of grass at either site.

Fire removes the aboveground portion of the plants in a grass ecosystem, but kills few plants in the cover. Most of the native grass plants whose tops were burned begin growing from the plant crowns and roots immediately. Following the first rain after a fire, many species of plants spring up from the seed store in the soil.

Tree cover may or may not recover rapidly after a fire, depending on the severity of the fire, tree size and age, and other causes. Forbs and grass may replace trees for a few years following fire.

Porro (2001) simulated the effect of fire with a severe and artificial condition that is unlikely to occur in nature. He measured the effect of heavy irrigation on soil covers built in a cold desert site where no plants grew on the soil surface during the 3-year measurement period. He saturated the soils to initiate drainage from each profile. The average annual precipitation during the 3-year measurement period was

232 mm. However, within 2 years of soil saturation, evaporation from the soil surface restored the capability of the soil columns to function as intended.

Although fire may cause other damage to a landfill, it is unlikely to impair the ability of an ET landfill cover to control soil water movement.

4.5 COST COMPARISON

Hauser et al. (1999) reported that construction of conventional landfill covers built for the air force cost between $319,000 and $571,000 per acre of surface covered. They also reported firm cost estimates by consulting engineers, and indicated that construction of ET covers for similar landfills would cost less than half as much as conventional covers.

The ET cover is less costly to build than conventional covers because it needs no barrier layers and no drainage layers. Hauser et al. (2001) performed detailed construction cost estimates for conventional RCRA and ET covers for the southern Great Plains. They found that construction costs for an ET cover varied from 35 to 72% of the costs for conventional covers. Typically, ET cover construction should cost less than half of a conventional cover.

Because the ET cover is self-renewing, its maintenance costs are small. If a depression, crack, or hole develops on an ET cover, repair is simple and inexpensive; it requires only filling with soil to reestablish grade and replanting the grass cover. Repair of a conventional cover is more difficult and more expensive.

4.6 ADVANTAGES AND DISADVANTAGES

The ET cover is an effective, natural, self-renewing cover that typically meets the requirements for a cover at a site and costs about half as much as conventional covers. It is suitable for use at most sites. The ET cover is suitable for remediation of municipal and industrial landfills, mining waste, or contaminated soil and waste piles.

The ET landfill cover may satisfy differing site requirements. It applies when the requirements for a cover demand little or no movement of precipitation into the waste. At the other extreme, its design and construction is flexible and it can allow a small or a large percentage of average annual precipitation to enter the waste in order to meet the requirements for a bioreactor landfill. Table 4.1 summarizes advantages and disadvantages of ET covers.

4.6.1 ADVANTAGES

Because the ET cover is natural and self-renewing, it is less prone to failure. These natural attributes also lead to a long service life. It meets site-specific cover requirements, and it is well adapted for use on bioreactor landfills. A cover that is less prone to fail is also more protective of the environment and public health. At most sites, it will have low costs for both construction and maintenance.

Gas control is easy to install during construction or afterward. Conventional horizontal collection pipes or vertical pipes may be used. Because there is no barrier

TABLE 4.1
Advantages and Disadvantages of ET Landfill Covers

Advantages	Disadvantages
Meets site-specific cover requirements	Requires site-specific design
Natural, self-renewing system	Requires adequate soil resource nearby
Less prone to fail	Reuse restricted
Long life	
More protective	
Easily repaired	
Well adapted to bioreactor landfills	
Low construction and maintenance cost	
More options for gas control	

layer to protect, drilling and installation of vertical gas control wells through the ET cover does not threaten the integrity of the cover. The ET cover allows several options for gas control, if needed, either during or after cover construction.

4.6.2 DISADVANTAGES

Each site needs a site-specific design because climate, soil, plant cover, and site requirements are unique for each site. The U.S. EPA regulations contain design parameters for conventional covers, but not for ET landfill covers. It is impractical to move cover soil for long distances; therefore, adequate soil should be located near the site.

Land used as a landfill was, for practical purposes, previously dedicated to the single purpose of preserving waste; therefore, the options for reuse are limited for any landfill. The use of an ET landfill cover may alter the potential reuse choices; however, the primary restrictions are the same for all cover types.

4.7 CONCEPT USE

This chapter describes confirmation of the ET landfill cover concept at 13 locations; however, it is necessary to use the concept at sites far from the measured sites described here. Successful ET covers utilize soils and plants combined in a system that will control precipitation and meet all cover requirements for a particular landfill. ET cover design is best accomplished with the aid of a suitable comprehensive model to evaluate the numerous interactions among soils, plants, and climate in a site-specific design.

Successful use of the ET cover concept at a specific site requires that we (1) understand factors that control performance of an ET cover and (2) apply suitable design and construction methods. Chapters 5 and 6 explain basic technology; Chapters 7 through 11 explain pertinent design and construction considerations.

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5 Basic Technology

Each evapotranspiration (ET) landfill cover should satisfy the requirements of the site; this requires integration of concepts and principles from soil and plant science as well as engineering fields. Because there are several potential combinations of the technology, it is possible to provide a cover that meets the unique situation at a particular site.

Robust plant growth is necessary to satisfy the requirements for a landfill cover, but some factors may limit plant growth and effectiveness. Fortunately, it is relatively easy and economical to remove, control, or manage limitations to plant growth in constructed soils such as in a landfill cover. However, removal of limitations requires knowledge of soil properties, the principles of plant growth, and their interactions with other factors.

This chapter explores basic concepts that govern success of the ET landfill cover; it does not cover each scientific topic in detail. Soil water balance and hydrology are basic technology and they incorporate basic scientific principles; they are discussed separately in Chapter 6. Appendix A contains a reference bibliography to assist the reader in finding additional information, if needed.

5.1 SOIL

Table 5.1 contains a list of soil properties that are important to the success of ET landfill covers, and this book contains a discussion of the most important of these. Hillel (1998), Marshall et al. (1996), Carter (1993), and SSSA (1997) more fully describe soil properties.

If necessary, the landfill owner may change the plants growing on an ET cover after the cover is complete. The landfill owner may improve soil with fertilizer, lime, or compost after cover construction; however, changing soil physical properties or nutrient-holding capacity after construction is complete is very costly. It is important to understand the soil.

5.1.1 SOIL PHYSICAL PROPERTIES

Soil physical properties are important to successful application of the ET landfill cover, but construction of an ET landfill cover modifies the physical properties of the soil used to create the cover. Soil modification during construction may either (1) improve the soil or (2) damage the soil and reduce the opportunity for success.

TABLE 5.1
Important Soil Properties and Factors

Basic Properties	**Other Properties**	**Factors**
Particle size distribution	Available water capacity	Water content
Bulk density	Field capacity/wilting point	Temperature
pH	Tilth	Oxygen in soil air
Soil salinity	Soil strength	Bacteria
Soil sodium content	Aeration properties	Fungi
Kind of clay mineral	Available nutrient supply	Toxic substances
Total porosity	Fertility	Ammonia
Percentage large pores	Cation exchange capacity	CO_2 from decaying OM
Humus content	Hydraulic conductivity	Methane

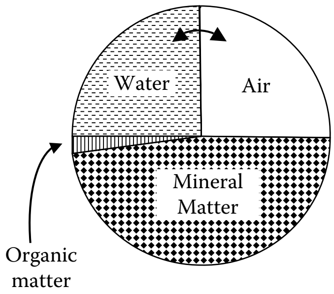

FIGURE 5.1 Schematic composition (by volume) of a typical medium-textured soil; the solid matter constitutes 50% and the pore space 50% of the soil volume. The arc demonstrates that as water content changes, air content changes in response.

Soil is composed of solids, liquid, and air. The solid phase includes inorganic products of rock weathering, organic products of the flora and fauna that inhabit the soil, and highly weathered minerals such as clay. The organic matter content of fertile soil may be near zero or up to 5% of the mineral matter of the solid phase for most soils; peat soils are an exception and their organic matter content can be near 100%. However, peat covers small areas of the Earth, and when drained oxidizes rapidly; thus, it should not be used in ET covers. Figure 5.1 illustrates the relative volume of each component for a typical fertile soil.

5.1.1.1 Solids

The solid particles are highly irregular in shape and size. Their size is measured by the sieve opening through which they pass or for fine materials, by their settling velocity in water. The U.S. Department of Agriculture (USDA) standardized particle-size descriptions for agricultural use; their system is useful for describing soils in which plants grow and it is used throughout this book.

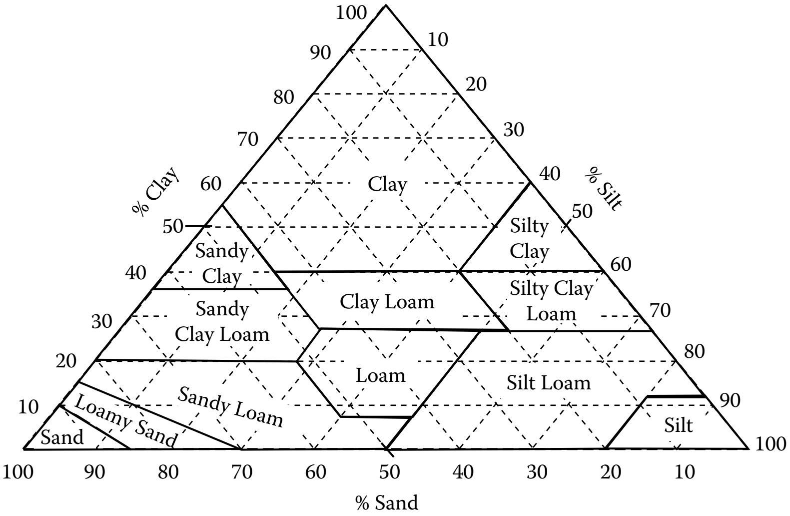

FIGURE 5.2 The soil textural classes. (Drawn from data in SSSA, *Glossary of Soil Science Terms,* Soil Science Society of America, Madison, WI, 1997.)

Soil material contains particles smaller than 2 mm; however, some soils contain stones and particles larger than 2 mm. Soils containing gravel and rock may be useful construction material, but they may be unsuitable for use in ET cover soils. Stones and particles larger than 2 mm reduce the water-holding capacity and dilute the nutrient-supplying capacity of the soil. Only material smaller than 2 mm is included as soil when evaluating ET cover soils.

The USDA soil classification defines the particle sizes of soil material as follows: clay less than 0.002 mm, silt between 0.002 and 0.05 mm, and sand between 0.05 and 2 mm. The relative proportions of the various separates (particle sizes) that make up a soil define soil texture. Figure 5.2 shows the textural triangle and names of the conventional textural classes (SSSA 1997).

5.1.1.2 Liquid

The liquid component of soil is principally water, but it contains materials dissolved from the soil; thus, it is soil solution although in common practice it is usually called soil water. Soil water and air are contained within, and fill the soil pore space (Figure 5.3). Large pores favor movement of water and air, both of which are necessary for good plant growth. The force holding water contained within large soil pores is small; however, the force holding water contained in small pores may be very large. The forces holding part of the soil water are so great that plants cannot effectively remove it.

Soil water below the water table exists at a positive hydrostatic head, and its pressure is taken as zero, or atmospheric, at the water table. Soil water held in soil above the water table exists at a negative pressure potential relative to the atmosphere. The negative pressure of soil water in the vadose zone is called matric potential, matric suction, capillary potential, and soil water suction; the terms are used interchangeably. The negative pressure of soil water is explained by analogy with the negative pressures observed in small capillary tubes inserted into pure water. Even though no uniform, tubular capillary shapes exist in the soil (Figure 5.3), the analogy serves well to describe water pressure in unsaturated soil. There are both capillary and adsorptive forces between water and the soil matrix; they bind the water to the soil and produce the negative matric potential. As the soil dries, the water films within the soil become thinner, resulting in progressively more negative pressures within the remaining water.

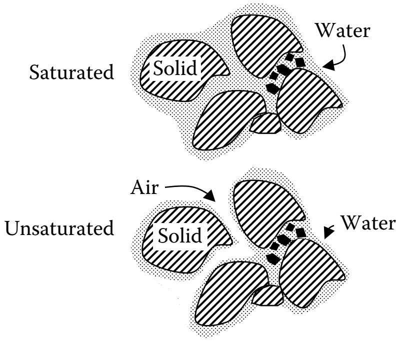

FIGURE 5.3 Conceptualized, saturated, and unsaturated soil.

Soils high in total salts tend to produce soil solution with high osmotic potential. High osmotic potential significantly reduces the availability of soil water to plants, and it increases the negative force or pressure against which plants must work to remove water from the soil. The sum of the osmotic potential and matric potential determines the negative force needed within the plant to remove water from the soil. Osmotic potential reduces the amount of water that plants can withdraw from the soil, and some dissolved solids may produce toxic effects on plant growth.

Immediately after rainfall or irrigation, the soil solution is dilute; however, as plants withdraw water from the soil, the solution is concentrated. Therefore, plants may grow satisfactorily in soils with low-to-moderate salinity when the soil is wet, but they cannot remove water to the conventional wilting point determined by matric suction. Thus, soils with elevated salt content may significantly reduce the effectiveness of ET landfill covers even though plants may survive on the cover. (For additional information on water and plants, see Stewart and Nielsen 1990.)

5.1.1.3 Air

The largest soil pores drain freely by gravity, thus providing space for the soil air, which is held primarily in the largest pores, although some air is contained or trapped in small pore spaces, where it may be surrounded by water. The source of soil air is atmospheric air, but plant respiration, chemical reactions, and microbial activity modify its properties within the soil mass. Diffusion between the atmosphere and the soil air is important in replenishing it. Drainage of large pores following rainfall or irrigation draws fresh air into the soil, and wind turbulence enhances air exchange between the soil mass and the air.

5.1.2 SOIL WATER

Soil water content is expressed as percent by wet or dry weight of the soil mass or as volumetric water content (SSSA 1997; Hillel 1998). Units of volumetric water content are commonly cm^3/cm^3; during ET cover evaluation and design, they are easily converted to millimeter, centimeter, or meter of water per unit depth of the soil.

Soil-water content expressed as volumetric water content is preferred for ET cover design and evaluation because it is compatible with other hydrologic and engineering units.

5.1.2.1 Soil Water-Holding Capacity

The water-holding properties of ET cover soils are important to success. Soils that hold much water will achieve the desired water control with a thinner layer of soil than those with low water-holding capacity. Important water-holding properties include the permanent wilting point, field capacity, and plant-available water content; they are defined by the Soil Science Society of America (SSSA 1997). It is important to understand the scientifically correct definitions, but the following approximations of the volumetric soil water content for each are sufficiently accurate for engineering design:

- Wilting point—the laboratory-measured water content at −1.5 MPa (about −15 atm) pressure
- Field capacity—the laboratory-measured water content at −0.03 MPa (about −1/3 atm) pressure
- Plant-available water capacity (AWC)—volumetric water content, estimated by the difference between field capacity and wilting point

The AWC for soils may range from about 7 to 25% by volume; the range for many soils acceptable for use in ET covers is between 10 and 20% by volume. Table 5.2 contains estimates of water-holding characteristics for soil having 2.5% organic matter, no salinity or gravel and requiring no soil density adjustment. The estimates were calculated by the *Hydraulic Properties Calculator* (Saxton 2005; Saxton and Rawls 2005).

Table 5.2 contains estimates derived from particle-size distribution of soils typical of widely differing textural classes. During early planning and preliminary engineering design, approximations of water-holding properties are adequate. Soil properties are available in USDA soil reports or they may be estimated from soil texture by methods similar to those described by Saxton (2005) and by Saxton and Rawls (2005). However, properties of soils intended for use in the cover should be measured, and the measured values should be used in the final design.

5.1.2.2 Soil Water Pressure

Most plants can survive saturated soils for only short time periods, a few hours to a few days, depending on temperature and other factors. Phreatophytes can grow in saturated soils having zero or positive water pressure.

Water held in soils supporting most plants exists at negative pressure for most of the time. The negative pressure may be less than –30 atm in dry soil. The water held in plants is also at negative pressure and plant water pressure may be below −40 atm. In order for plants to extract water and the associated nutrients from soil, they must exert a more negative pressure at the root–soil interface than exists in the soil in which they grow. Plants grow best when plant and soil water pressures are relatively

TABLE 5.2
Estimated Water-Holding Characteristics for Typical Soils

Texture Class	Sand (%W)	Clay (%W)	W P[a] (%v)	F C[b] (%v)	Sat.[c] (%v)	AWC[d] (%v)
Loamy sand	80	5	5	12	46	7
Loam	40	20	14	28	46	14
Silt loam	20	15	11	31	48	20
Silt	10	5	6	30	48	25
Sandy clay	60	25	17	27	43	10
Silty clay	10	35	22	38	51	17
Clay	25	50	30	42	50	12

Note: Numbers calculated by the "Soil Water Characteristics Hydraulic Properties Calculator" published on the Web and available to the public.

[a] Wilting point.

[b] Field capacity.

[c] Saturation.

[d] Plant-available water-holding capacity.

Source: From Saxton, K. E., Soil water characteristics, hydraulic properties calculator, Agricultural Research Service, USDA, http://hydrolab.arsusda.gov/soilwater/Index.htm (accessed March 3, 2008), 2005; and Saxton, K. E. and Rawls, W. J., Soil water characteristic estimates by texture and organic matter for hydrologic solutions, Agricultural Research Service, USDA, http://users.adelphia.net/~ksaxton/SPAW%20Download.htm (accessed March 3, 2008), 2005.

near zero in a well-aerated soil, in that condition, large soil pores are filled with air and the water content is near field capacity. The physics of water movement in the unsaturated soil of an ET landfill cover is different from that below the water table, where pressures are positive and hydraulic conductivity of a particular soil mass is constant.

The relationship between soil water pressure and water content is a unique function for each soil, and there are large differences between these relationships for different soils. Water-holding properties of soils are controlled by several factors, the most important being particle-size distribution, but clay minerals, soil density, and organic matter are also important. Figure 5.4 illustrates the relationship between soil water content and soil water pressure calculated for two soils with the *Hydraulic Properties Calculator* (Saxton 2005).

Table 5.3 contains soil properties and estimates by the *Hydraulic Properties Calculator* for the soils illustrated in Figure 5.4 (Saxton 2005; Saxton and Rawls 2005). Soil organic matter was 1%, salinity was 0.0 ds/m, and gravel content was 0.0% for both soils.

Examination of Table 5.3 and Figure 5.4 reveals interesting facets of soil physics. At the wilting point and field capacity, respectively, the water content of the clay loam soil is 2.9 and two times greater than for the sandy loam soil. The plant-available

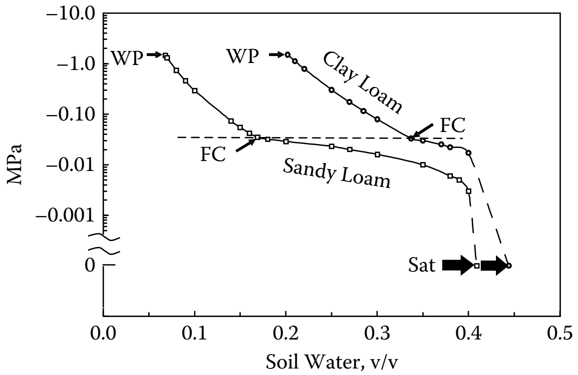

FIGURE 5.4 Water pressure as a function of water content for two soils, showing wilting point (WP), field capacity (FC), and saturation (Sat.).

TABLE 5.3
Calculated Water Content, Water Pressure and Hydraulic Conductivity for Two Soils Described in Figures 5.4 and 5.5

Soil and Particle-Size Distribution (% by wt.)	Property	Water Content (v/v)	Water Pressure (MPa)	Hydraulic Conductivity (cm/day)
Sandy loam	Wilting point	0.07	−1.5	0.0000001
(sand: 60%, silt:	Field capacity	0.17	−0.03	0.004
30%, and clay: 10%)	Saturation	0.41	0	90
Clay loam	Wilting point	0.20	−1.5	0.000006
(sand: 33%, silt:	Field capacity	0.34	−0.03	0.06
33%, and clay: 33%)	Saturation	0.44	0	8

Note: Numbers calculated by the "Soil Water Characteristics, Hydraulic Properties Calculator" published on the Web and available to the public.

Source: From Saxton, K. E., Soil water characteristics, hydraulic properties calculator, Agricultural Research Service, USDA, http://hydrolab.arsusda.gov/soilwater/Index.htm (accessed March 3, 2008), 2005; and Saxton, K. E. and Rawls, W. J., Soil water characteristic estimates by texture and organic matter for hydrologic solutions, Agricultural Research Service, USDA, http://users.adelphia.net/~ksaxton/SPAW%20Download.htm (accessed March 3, 2008), 2005.

water capacity, however, is only 1.4 times greater for the clay loam than for the sandy loam soil. The drainage from a saturated condition to the field capacity is 2.4 times greater for the sandy loam than for the clay loam soil. For soil water content between field capacity and wilting point, a small change in water content produces a large change in soil water pressure for both soils; thus, even a small amount of soil drying at the surface can create upward soil water gradients.

5.1.3 HYDRAULIC CONDUCTIVITY OF SOIL

The physics of water movement within the soil is important for an understanding of the principles that govern the performance of an ET landfill cover. The modern understanding of water movement in unsaturated soils has been under development for at least 150 years, and the development of new concepts continues in the modern era. Darcy (1856) provided the earliest known quantitative description of water flow in porous mediums. The basis for modern equations for both saturated and unsaturated soil water flow is Darcy's equation.

The actual flow pathways for water in either saturated or unsaturated soil are so irregular and tortuous that it is impossible to describe flow in microscopic detail; therefore, flow is described macroscopically. The discharge rate, Q, through a column or defined soil mass is the flow volume, V, per unit time, t. Q is directly proportional to the cross-sectional area of flow, A, and to the change in hydraulic head, ΔH, across the flow length, and inversely proportional to the flow length, L:

$$Q = V/t \propto A(\Delta H/L)$$

The change in hydraulic head is the total head relative to a reference level, at the inflow boundary, H_i, minus the total head relative to the same reference level at the outflow boundary, H_o. Therefore, ΔH is the difference between these heads:

$$\Delta H = H_i - H_o$$

Obviously, flow is zero when $\Delta H = 0$.

The change in head in the direction of flow ($\Delta H/L$) is the "*hydraulic gradient*," and it is the force driving the flow. The volume of flow through a unit of cross-sectional area of soil per unit of time, t (Q/A), is called the flux density (or simply the flux) and is indicated by q. Therefore, the flux is proportional to the hydraulic gradient:

$$q = Q/A = V/At \propto \Delta H/L$$

The proportionality factor, K, is called the "*hydraulic conductivity*":

$$q = K(\Delta H/L) \tag{5.1}$$

Equation 5.1 is known as *Darcy's law* after Henry Darcy, a French engineer (Darcy 1856).

Darcy's law was developed for saturated flow through sand filters; however, it is applied to both saturated and unsaturated flow. In either application, it has limitations. Darcy's law applies only to laminar flow; therefore, it may not accurately describe high-velocity flow in gravel or other coarse material. At low gradients in fine materials (e.g., clay), Darcy's law may appear to fail. Darcy's law is applicable mainly to relatively homogeneous and stable systems of intermediate scale and pore size. It has proved highly useful in many estimates of both saturated and unsaturated flow in soils. However, it is now widely employed far beyond the use for which it was

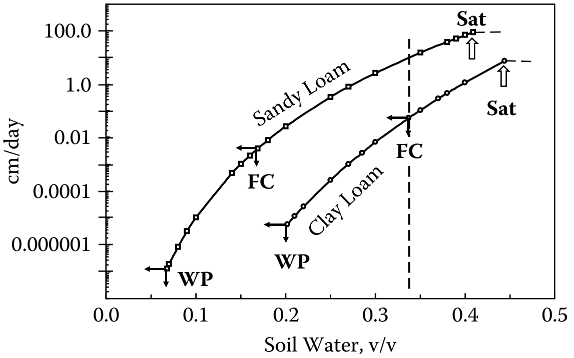

FIGURE 5.5 Hydraulic conductivity as a function of water content for two soils, showing wilting point (WP), field capacity (FC), and saturation (Sat).

developed. In spite of these limitations, it is still the best unifying theory available for water flow in soils and generally produces reliable estimates.

The currently used equations for water flow in unsaturated soil are based on Darcy's law and the assumption that soils are similar to a bundle of capillary tubes. Given these assumptions, water flow can be approximated by the Hagen–Poiseuille equation (Marshall et al. 1996). Although it is obvious that the pore space in soil is not the same as a bundle of capillary tubes, the assumed concept has proved highly useful and is currently used in mathematical descriptions of water flow in soil.

Figure 5.5 illustrates the relationship between soil water content and hydraulic conductivity for the same soils illustrated in Figure 5.4 and shown in Table 5.3. The hydraulic conductivity relationships differ greatly between soils; they depend on particle-size distribution, soil structure, and on other factors. Figure 5.5 and Table 5.3 present calculated values of hydraulic conductivity for two soils of differing texture. The hydraulic conductivity of saturated soils is constant; however, in unsaturated soils, it varies over several orders of magnitude as soil water content changes. The shapes of the curves differ between the wetting and drying cycle of soils in the field; the difference is called hysteresis. Hysteresis is not illustrated in Figures 5.4 and 5.5.

5.1.4 SOIL WATER MOVEMENT

The illustrative data in Figure 5.5 reveals the mechanism that allows the ET landfill cover to control water within the cover soil. The soil water content in the wetted soil layers drains to the field capacity quickly when rainfall ends because of the high values of K for saturated and near-saturated soils (Figure 5.5). At field capacity, the sandy loam and clay loam soils depicted have hydraulic conductivities (K) of 0.004 and 0.06 cm/day, respectively. The gravitational force tends to move the water downward, but the possible rate of water movement downward in the soil is very small for small values of K. The K value decreases rapidly in response to small additional soil drying (Figure 5.5).

Examination of Table 5.3 and Figure 5.5 reveals interesting facets of soil physics. At saturation, the K value for sandy loam soil is 11 times the value for clay loam; however, at field capacity, the relationship reverses: the *K* value for clay loam is 15 times greater than for sandy loam (Table 5.3 and Figure 5.5). The differences between the two soils are more pronounced at lower water contents. The *K* value for either soil at field capacity is small and decreases by several orders of magnitude as soil water content approaches the wilting point.

Theoretically, and as measured in the field, soil water never stops moving (Hillel 1998). In field or laboratory experiments, investigators measuring water movement for long times prevent evaporation from the soil surface. However, surface drying begins soon after rainfall ends on an ET landfill cover, and even a small amount of soil drying at the surface can reverse the hydraulic gradient and may effectively stop drainage from the soil profile. Therefore, for practical purposes water is held in suspension within the soil in less than 2 days after rainfall ends for most soils.

During landfill cover design, hydraulic conductivity relationships may be needed to model water flow in the finished landfill cover soil. The landfill cover soil is likely to be a mixture of several layers of soil and will be disturbed during placement in the cover; thus, its hydraulic properties should be estimated or measured on a disturbed and mixed soil sample. Appropriate methods for measuring soil properties are readily available in methods published by the SSSA (Dane and Topp 2002).

Cost constraints or other factors may make it necessary to estimate the hydraulic conductivity relationship rather than measure it. Several authors have developed methods for estimating the hydraulic conductivity functions from simpler and more easily measured soil parameters. For example, Savabi (2001) employed methods described by 12 different authors to estimate hydraulic conductivity in his model evaluation of the hydrology of a region in Florida. Van Genuchten et al. (1991), Zhang and van Genuchten (1994), and Othmer et al. (1991) each developed computer code to estimate hydraulic functions for unsaturated soils. The revised *Hydraulic Properties Calculator* is easy to use (Saxton 2005; Saxton and Rawls 2005).

5.1.4.1 Water Movement to Plant Roots

The ET landfill cover should quickly remove stored water from all the soil mass in the cover after precipitation. That requires a large, dense mass of plant roots.

The movement of water from soil to plant roots is a critical part of the ET landfill cover performance. When the soil is wet near a plant root, water moves rapidly to the root because the soil hydraulic conductivity is high. The plant consumes the soil water closest to the plant root first, thus drying the soil near the root. As the soil near the root dries, the rate of water movement to the root decreases rapidly because of the reduction in hydraulic conductivity of the soil near the root. As a result, a single plant root can effectively dry only a small volume of soil. Where soil conditions are good for root growth, plants can produce a large mass of roots that explore all the wet soil quick enough to maintain a high water extraction rate.

When the soil mass dries, and the plants are in water stress, many or perhaps most of the small feeder roots that extract soil water die. When the soil is again wetted, new roots must replace those that died. Within a particular soil mass, roots may grow and die more than once per season. As a result, it is necessary to provide soil physical conditions that allow rapid and prolific plant root growth.

Soils with high density often contain cracks. It is normal for roots to grow in the cracks, but the high soil density between the cracks limits or prevents root growth into the soil blocks between cracks. The roots within the soil cracks can extract soil water from the surface of the dense blocks between cracks. As a result, plants can extract some water from dense cracked soils, but they cannot effectively remove water from most of the soil mass.

5.1.4.2 Preferential Flow

The SSSA (1997) defines preferential flow as *"the process whereby free water and its constituents move by preferred pathways through a porous medium."* However, a group of Swiss research workers stated, *"[I]t is fascinating how the expression 'preferential flow' has been adopted by various scientific communities without having been properly defined"* (Fluhler et al. 2001). Two national symposiums on preferential flow examine numerous concepts pertaining to the topic in 95 papers published by the American Society of Agricultural Engineers (ASAE) in 1991 and 2001. At this time, there is consensus on a few, but not all, factors related to preferential flow and no adequately tested models with which to predict its effect on water movement during engineering design. Fluhler et al. (2001) explain that preferential flow depends on the saturation of the soil.

Preferential flow can occur through soil cracks, wormholes, macropores in the soil, root networks, burrows, and other large openings. However, preferential flow is possible only if the water in the large pores exists at atmospheric or greater pressure. In most instances, this requires that two conditions be true: (1) a large opening in the soil extends to the soil surface, for example, a crack in a clay soil; and (2) water is ponded over the opening on the surface.

Preferential flow of water through soil cracks, wormholes, or animal burrows may offer a means for precipitation to move deep into the soil and bypass the active root system. However, this requires that water be ponded above an opening to a preferential flow pathway. On landfill covers, the land surface is smooth, thus allowing little water to pond on the surface. Animals and worms commonly block the flow of water from the surface into their holes. Gee and Ward (1997) reported the results of irrigated lysimeter tests of landfill covers performed at an Animal Intrusion Lysimeter Facility; they stated that *"the presence of small-mammal burrows does not appear to have a significant influence on the deep percolation of water through the barrier.*" Under grass, growing on soil built with adequate density for an ET cover, soil cracks are closely spaced and small; they close rapidly in the surface soil during rain. There is limited opportunity for water to enter cracks in the soil on an ET landfill cover.

Preferential flow is cited as a mechanism for failure of vegetative landfill covers. Although the concept has theoretical merit, field observations indicate that it has little or no impact on performance of ET covers with properly constructed covers.

In each of the long-term tests cited in Section 4.3, the following conditions were present: cracking soils, wormholes, ant tunnels, and both large and small animal burrows. The soil contained preferential flow paths for hundreds of years. However, in each case, these preferential flow pathways produced no apparent effect on water movement through the soil profile (Cole and Mathews 1939; Luken 1962; Aronovici 1971; Halvorson and Black 1974; Worcester et al. 1975; Doering and Sandoval 1976; Ferguson and Bateridge 1982; Sala et al. 1992).

Preferential flow is unlikely to contribute significantly to water flow in an ET landfill cover for the following reasons:

- The soil placement and cover construction process thoroughly disrupts continuous pathways through the soil, for example, ancient root networks and wormholes.
- Landfill covers have a continuous slope of 2% or greater and allow no ponds on the surface.
- Burrowing animals protect their burrow from surface runoff by a diversion dam or mound; in addition, their presence is discouraged on landfill covers.
- Measurements and historical evidence presented in Chapter 4 demonstrated that in spite of known pathways for preferential flow, water did not penetrate below the root zone of native grasses.

5.1.5 SOIL CHEMICAL PROPERTIES

All plants need an adequate amount of nutrients. Rapid water use by plants is essential for successful use of the ET landfill cover. Rapid water use by plants requires robust plant growth, which in turn requires sufficient soil nutrient supply and satisfactory soil pH. Plant growth, and thus water use, may be reduced by inadequate amounts of only one plant nutrient. The water use by plants can be no greater than allowed by the most limiting plant nutrient found in the soil.

The soil nutrient store and the plant-available nutrients should be adequate to support robust plant growth via nutrient cycling, both immediately and for decades into the future. Because it is likely that maintenance of the cover will have low priority in the future, the soil should contain an ample store of nutrients and have the capacity to capture and release to plants, nutrients recycled from decaying vegetation on the cover.

5.1.5.1 Soil pH

Soil pH is the pH of a solution in equilibrium with soil under defined conditions. Low soil pH receives great attention because it is widespread in arable soils and, for many conditions, it is practical to correct low soil pH. Soils with excessively high pH are difficult or impossible to remediate. *"Soil pH is probably the single most informative measurement that can be made to determine soil characteristics"* (Thomas 1996). He describes soil pH and its standard measurement.

Plants grow best in soils with neutral pH in the range of 6–7.5. For example, nitrogen is readily available at soil pH 5.8 and greater, whereas availability of phosphorus may be limited for pH below 6.2 or greater than 8.5. Merva (1995) more fully explains the relationship between soil pH and availability of several nutrients to growing plants.

Thomas (1996) presents useful values for soil pH. Soils with pH greater than 7.6 normally contain adequate to abundant calcium; however, pH below 5.5–6.0 indicates possible need for lime addition. Soil pH values of 2 or 3 indicate free acid in the soil and may result in excessive cost to remediate them; plants will not grow in these soils without amendment. At pH values below 5.5, toxic amounts of aluminum may be present in the soil. Soils with pH values of 7.6–8.3 are probably calcareous; adapted plants grow in them but other plants may suffer zinc and iron deficiencies. Where pH is 8.3 or higher, the soil solution may contain excess sodium, and at pH above 9, the soil probably contains excess sodium, which disperses both clay and organic matter resulting in "black alkali soils." Few, if any, plants grow in these soils.

5.1.5.2 Soil Nutrients

Soil nutrients are the elements essential as raw materials for plant growth and development. The nutrient used in the largest amount in plant growth is nitrogen, followed by phosphorus and potassium. Sulfur, magnesium, and calcium are required plant nutrients, but in smaller amounts. Important trace elements include iron, manganese, boron, chlorine, iodine, zinc, copper, and molybdenum (Sauchelli 1969).

If the native soils at the landfill site contain adequate nutrients for good plant growth, it is likely that they will hold and provide adequate nutrients for plants growing on an ET cover with minimal maintenance. Fertilization of soils deficient in nitrogen, phosphorus, or potassium nutrient supply is usually successful and relatively inexpensive.

The mere presence, as indicated by laboratory measurements, of large amounts of essential plant nutrients in soil does not assure robust plant growth. Soils of the western United States containing excess calcium may also contain large amounts of phosphorus, which may be relatively unavailable to plants because, in these soils, it may form compounds that are relatively insoluble.

Iron is a trace element for plant growth; however, it offers an important example of nutrient availability. Iron is an abundant element in primary and secondary minerals found in most soils. However, iron may be relatively unavailable to plants in alkaline or calcareous soils, where it may have low solubility. Conversely, soils with low pH may contain sufficient iron in solution to be toxic to plant growth (Loeppert and Inskeep 1996).

Water percolating below the plant rooting depth may leach nutrients from the soil profile, and soils with low pH tend to suffer the greatest leaching losses. As a result, soils available for use in building ET covers may be deficient in plant nutrients in regions where annual precipitation is high. For example, permeable acid soils of the eastern United States may have experienced significant natural leaching and thus contain an inadequate nutrient supply. Potassium may be deficient in leached soils, particularly those that are acidic. Leached soils may need chemical amendment to satisfy plant nutrient needs.

5.1.5.3 Cation Exchange Capacity

The cation exchange capacity (CEC) of a soil is an important measure of its capacity to hold and exchange nutrients with the soil solution. Cation exchange sites are located on the edges of fine soil materials, primarily clay and soil organic matter. The clay content dominates the CEC properties of most soils because soil organic matter is less than 5% of the soil mass for most soils and is rarely higher than 3 or 4%. High values of CEC are preferred for soils used in ET landfill covers to provide an ample store of plant nutrients.

The CEC of soil is the sum of exchangeable bases plus total soil acidity at a specific pH (usually 7 or 8). CEC values are expressed in centimoles of charge per kilogram of exchanger (cmol/kg); however, older literature may use the numerically equivalent milliequivalents per gram (meq/g; SSSA 1997). Standard methods are available for its measurement (Sumner and Miller 1996).

The total number of exchange sites is large even for soils with low CEC capacity; however, only a fraction of the sites actively exchange ions for plant use at any time. As a practical result, productive soils are those with large values of CEC.

Clay minerals differ greatly in their typical CEC values, ranging from 3–15 for kaolinite to 80–150 cmol/kg (meq/g) for smectite (montmorillonite) (Grim 1968). The clay fraction of most soils is a mixture of clay minerals; thus, the CEC of the clay usually lies between these limits. Because clay is a fraction of the typical soil mass, the CEC values of soils are typically much less than for clay minerals alone.

Mathers et al. (1963) measured soil properties for seven soils of the Southern Great Plains; their data provide an example of CEC values and its variability between soils. Three soils located in the semiarid environment of the Texas High Plains and adjoining "South" Plains, of West Texas provide examples of soil CEC content and its variability. The Pullman silty clay loam soil was located near Amarillo, Texas; the Amarillo fine sandy loam soil was located near Lubbock, Texas; and the Gomez fine sandy loam soil was located near Midland, Texas. The depth-weighted clay content of the upper 4 ft (1.2 m) of each soil was 40, 23, and 16%, respectively, for Pullman, Amarillo, and Gomez soils. Figure 5.6 presents the CEC for soil layers within the Pullman soil profile and for its clay fraction to the 1.35 m (53 in.) depth. The variability of CEC values between soil layers in natural or undisturbed soils may be greater than shown by the measurements for Pullman soil shown in Figure 5.6.

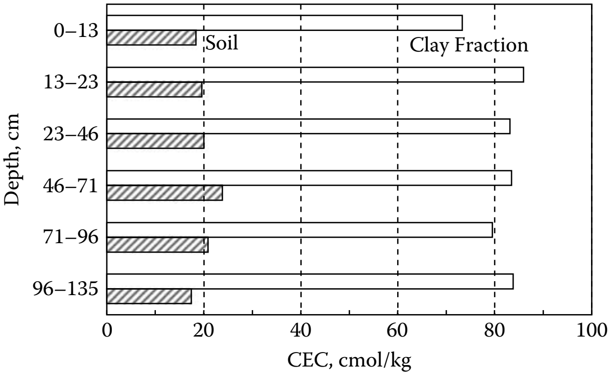

FIGURE 5.6 Cation exchange capacity (CEC) for soil layers and the respective clay fraction in Pullman silty clay loam soil. (Drawn from data in Mathers, A. C., Gardner, H. R., Lotspeich, F. B., Taylor, H. M., Laase, G. R., and Daniell, R. E., *Some Morphological, Physical, Chemical and Mineralogical Properties of Seven Southern Great Plains Soils,* ARS 41–85, Agricultural Research Service, USDA, Beltsville, MD, 1963.)

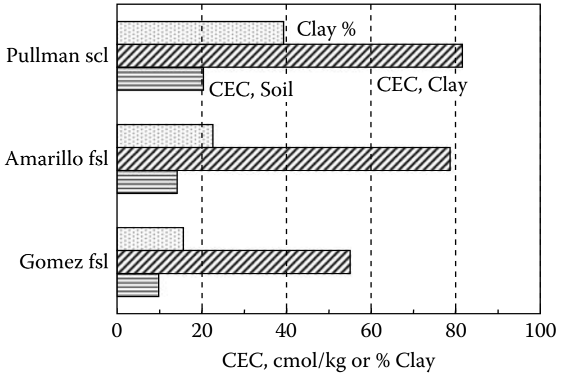

FIGURE 5.7 Depth-weighted average clay percentage, and cation exchange capacity of whole soil and clay fraction to the 1.1 m (45-in.) depth. (Drawn from data in Mathers, A. C., Gardner, H. R., Lotspeich, F. B., Taylor, H. M., Laase, G. R., and Daniell, R. E., *Some Morphological, Physical, Chemical and Mineralogical Properties of Seven Southern Great Plains Soils,* ARS 41–85, Agricultural Research Service, USDA, Beltsville, MD, 1963.)

Figure 5.7 presents depth-weighted average values in the upper 1.1 m (45 in.) of the profile for soil clay percentage, and CEC values for the soil clay and the whole soil for Pullman, Amarillo, and Gomez soils. The clay content was significantly different among these soils, resulting in differences in CEC values between them. The kind of clay mineral present also affected the CEC values. Montmorillonite dominated the clay mineral content of the Pullman and Amarillo soils; however, the Gomez soil minerals included illite and kaolinite with only minor amounts of montmorillonite. As a result, both smaller clay content and kind of clay mineral resulted in small values of CEC for the Gomez soil.

5.1.5.4 Soil Humus

Humus is an important component of soils; it is composed of organic compounds in soil exclusive of undecayed organic matter. Manure, compost, and grass clippings are organic matter, but they are not humus. Many years or decades may be required to create humus in soil. Humus decays slowly; it provides significant additional CEC, and improves soil structure. The organic matter of naturally formed and undisturbed soils is primarily humus.

A common misconception is that a large amount of humus is necessary for good plant growth; this is seldom true. Plants can grow well in fertile soils that contain little humus, such as soils of the southern Great Plains and the 11 western states where soil organic matter content is commonly less than 2% of the soil mass. The dark soils found in cold moist regions, such as the Corn Belt, the northeastern states, and Canada typically contain large amounts of humus; it contributes to the fertility of these soils. Soil layers containing natural humus are valuable; they should be preserved and used carefully.

The addition of organic material to soil to improve its properties may improve soil tilth and fertility, temporarily. However, it may not be worth the expense in a landfill cover because most of the added material oxidizes and disappears in a relatively short time, after which soil properties revert to those of the original soil material. In most situations, little of the added organic material is converted to long-lasting humus.

5.1.5.5 Harmful Soil Constituents

Landfill cover soils should be free of harmful constituents, such as synthetic chemicals, oil, and natural salts. The salts of calcium, magnesium, and sodium may occur naturally, and can create high salinity in the soil solution. Soil salts may raise the osmotic potential of the soil solution high enough to prevent plants from using all of the soil water. In addition to its contribution to soil salinity, sodium can cause deflocculation of clay particles, thereby causing hard soil crusts as well as poor soil tilth, structure, and aeration. Stewart and Nielsen (1990) discuss soil salinity and sodicity in detail.

5.1.6 SOIL PROPERTIES AND ROOT GROWTH

Successful ET covers employ robust plant growth, and rapid, complete removal of soil water from the soil cover. In order to meet this requirement, the soil should support fast and robust root growth to facilitate removal of stored water from the soil cover.

5.1.6.1 Soil Tilth and Other Factors

Good soil tilth is a requirement for robust root growth. Soil tilth is *"[t]he physical condition of soil as related to its ease of tillage, fitness as a seedbed, and its impedance to seedling emergence and root penetration"* (SSSA 1997). Several factors affect soil tilth, including particle-size distribution, water content, aggregation, soil chemistry, and bulk density. There are no useful direct measures of soil tilth; however, the effect of tilth on root and shoot growth as it may affect ET cover performance may be evaluated by other measurements. Soil strength and bulk density are closely related to tilth and they control quality of soil in an ET landfill cover; they are discussed in separate topics below.

Aggregation is the process that binds primary soil particles (sand, silt, and clay) together, usually by natural forces and substances derived from root exudates and microbial activity. Aggregation of soil particles is important; however, it is a complex property. Most soils with little or no aggregation are similar to concrete and allow minimum root growth. Repeated wheel traffic or excessive tillage destroys soil aggregates. Once destroyed, it is difficult to create new soil aggregates. Provisions for low soil strength and density, as discussed in the following text, promote adequate soil aggregation in a finished ET cover soil.

The size and distribution of soil particles tend to control the size and distribution of soil pores. Sandy soils naturally tend to have larger pores in which plant roots can grow; they usually have good aeration, but low water-holding capacity. Clay soils tend to have smaller pores; however, aggregated soils with high clay content provide excellent soil material for an ET landfill cover. Loam soils often provide superior material for ET landfill covers.

Oxygen is required in the root respiration process, and it must be available to roots from the soil air. Soil physical properties, and particularly bulk density, affect oxygen and soil air movement and availability to roots. Low or high soil pH can limit or stop root growth. Ammonia generated by large amounts of fresh plant or animal biomass incorporated into the soil can temporarily stop root growth. Saline conditions caused by high concentrations of fertilizer in bands or layers can also limit or stop root growth.

The film *Cotton Root Growth* available from the American Society of Agronomy graphically illustrates several soil conditions that are unfavorable to plant root growth (referenced in Appendix A).

5.1.6.2 Soil Strength and Density

Soil strength is related to tilth. One of the major potential obstacles to robust root growth is high soil strength (Taylor et al. 1966; Taylor 1967; Rendig and Taylor 1989; Raper and Kirby 2006). Several factors determine soil strength, including water content, bulk density, particle-size distribution, and possibly others (Jones 1983). Fortunately, where soil density is controlled within a desirable range, soil strength is normally adequate for good root growth. Soils with optimum soil density for plant growth usually have adequate tilth.

5.1.6.3 Soil Density

Soil bulk density is the mass of dry soil per unit bulk volume (Hillel 1998); the units for bulk density are Mg/m^3 or gm/cm^3. It is easy to measure and relatively easy to control soil density during ET landfill cover construction. Soil bulk density greater than 1.5 Mg/m^3 reduces root growth; values above 1.7 Mg/m^3 may effectively prevent root growth (Monteith and Banath 1965; Taylor et al. 1966; Eavis 1972; Jones 1983; Gameda et al. 1985; Timlin et al. 1998). Grossman et al. (1992) summarized 18 laboratory studies and found that root growth was only one-fifth of optimum for soil bulk density greater than 1.45 Mg/m^3 except for three soils in which root growth was restricted at soil bulk density of 1.3 Mg/m^3.

Particle-size distribution in the soil combines with soil density to control root growth. Roots grow in some sandy soils with elevated density, but their low water-holding capacity discourages their use in ET landfill covers. Jones (1983) demonstrated that plant root growth is reduced (1) at soil bulk density greater than 1.5 Mg/m^3 for most soils and (2) to less than 0.2 optimum root growth for all soils containing less than 70% sand and having bulk density greater than 1.6 Mg/m^3.

Sharpley and Williams (1990) used the work of Jones (1983) to develop functions relating soil sand content, bulk density, and plant root growth, and they used them in the successful EPIC computer model. The solid lines in Figure 5.8 show the functional relationship between soil sand content and bulk density developed for use in the EPIC model. The success of the EPIC model suggests that this approach is a realistic way to estimate the effect of soil strength on plant root growth.

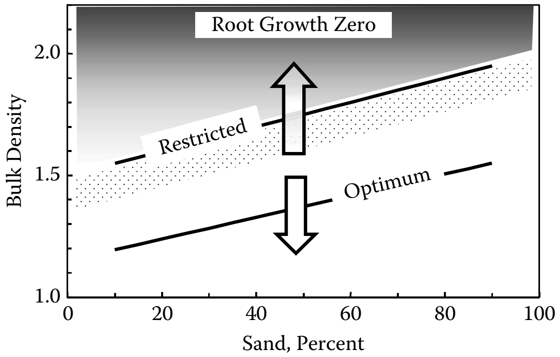

FIGURE 5.8 Limits for plant root growth imposed by soil bulk density and sand content. (Drawn from data in Jones, C. A., *Soil Sci. Soc. Am. J.*, 47, 1208–1211 1983; and Sharpley, A. N. and Williams, J. R., Eds., *EPIC—Erosion/Productivity Impact Calculator: 1. Model Documentation*, USDA, Washington, DC, 1990.)

In addition to inhibiting root growth, high values of soil bulk density result in low soil water-holding capacity because pore space is limited in dense soils. Soil compaction and the resulting high soil density destroy the large soil pores, which results in reduced water-holding capacity and limited oxygen movement through wet soil. Oxygen diffusion to roots in high-density soils may be so low that roots cannot survive, particularly when the soil is wet and many pores are filled with water. Wetting a dense soil reduces its strength substantially, thus potentially favoring root growth; however, wetting the dense soil may reduce oxygen diffusion rates low enough to kill roots. The effect of high soil density is more severe for a fine- than a coarse-textured soil because the soil pores in a compacted, fine-textured soil are smaller.

Fine-textured soils contain large amounts of clay and silt and have high water-holding capacity. When soil density is properly controlled, these fine-textured soils retain an adequate volume of large soil pores and produce good ET landfill cover soil.

Soil bulk density should be controlled during ET landfill cover construction to optimize soil properties for root growth. Soil densities between 1.1 and 1.5 Mg/m^3 ensure robust root growth in most soils.

5.1.7 Soil Modification

Within limits, soil may be modified to improve ET cover performance. Modification may include tillage, addition of nutrients as fertilizer, or pH modification with limestone. It is easy to amend some chemical properties of soils, for example, low pH, or deficiencies of nitrogen, phosphorus, or potassium. Other chemical properties may be more costly or impractical to amend. Physical soil properties are difficult or impractical to amend after severe damage. Therefore, it is better to select soils with desirable properties and handle them properly to maintain them in good condition for plant growth when used in an ET landfill cover.

5.1.7.1 Natural Changes of Physical Properties

Freezing and thawing increases saturated hydraulic conductivity of soil; therefore, it is natural to assume that freezing and thawing can correct soil structure problems created by excessive compaction. However, Sharratt et al. (1998) present evidence that adverse effects of soil compaction by steel wheels was not remediated by a century of freezing and thawing under native grass cover in Minnesota. They cite other short- and long-term research that demonstrated similar long-lasting adverse effects of high soil density on plant growth.

Raper and Kirby (2006) discussed natural alleviation of compaction. They point out that freezing and thawing of soil does not produce long-lasting alleviation of high soil density resulting from vehicle compaction because the soil quickly returns to its original compacted condition. They provide evidence that soil compaction resulting in increased soil density below 40 cm is particularly resistant to change by natural processes. They state that subsoiling, when correctly carried out, can remediate most compacted soils; but if it is incorrectly applied, it may cause additional damage to the soil.

5.1.7.2 Chemical and Physical Modification

Agricultural interests have successfully amended existing soil chemical and physical properties; their experience demonstrates the power of knowledge of soil properties. In the agricultural setting, cost of soil amendment severely limits possible solutions because the return to profit from sale of agricultural products is small. For practical purposes, the cost of soil amendment is a relatively small expenditure for ET landfill covers because of the normal, large construction costs for landfill covers.

Deep plowing mixes topsoil with subsoil, reduces the density of the soil in the profile, and improves water intake rate. Soils modified by deep plowing to achieve lower soil density, produce more plant biomass, store more plant-available water in the soil profile than the native soil, and allow increased rooting depth and root density (Taylor 1967; Unger 1979). Moreover, plants use water quickly and efficiently from soils modified by deep plowing. The benefits of deep plowing remain effective for decades (Musick et al. 1981; Unger 1993; Allen et al. 1995); the possible life of good soil properties should extend to centuries with good care during maintenance.

Four field-scale soil covers built with subsoil or minespoil having poor chemical and physical properties, produced equivalent or better forage production than undisturbed soil because they were properly modified during placement (Hauser and Chichester 1989; Chichester and Hauser 1991). They controlled soil density to near the optimum for plant growth, modified soil pH by addition of lime, and added fertilizer to supply plant nutrients. The improvement in physical and chemical properties of both soils during placement was critical to success.

Both chemical and physical modification of soil properties may be more complete during construction of a landfill cover than in the examples provided above. Therefore, modification of ET cover soils has potential for maximum effectiveness. Control of ET cover soil properties has potential to enhance cover performance and adds relatively little to total construction cost; it is discussed in Chapter 11.

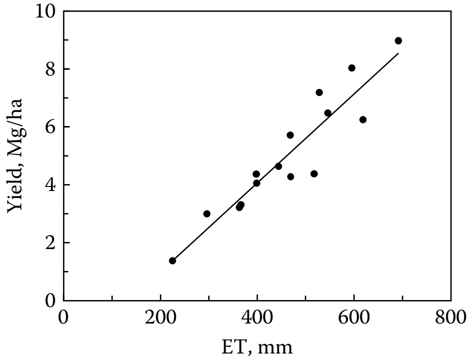

FIGURE 5.9 Relation between the yield of grain sorghum and plant water use under limited irrigation or dryland production. (Drawn from data in Stewart, B. A., Musick, J. T., and Dusek, D. A., *Agron. J.,* 75, 629–634, 1983.)

5.2 PLANTS

The performance of an ET landfill cover is optimum when the only limitation to plant growth is soil water content. Plants naturally consume water and nutrients rapidly when they are available and growing conditions are good. Healthy plants dry the soil cover and minimize percolation through the cover.

Aboveground biomass in the ET cover is an indicator of the effective use of water from the soil because biomass production and plant water use are linearly related for most situations. For example, Figure 5.9 shows the relation between yield of grain sorghum and ET by the crop (Stewart et al. 1983).

Several factors may limit plant growth, including soil properties, incorrect species selection, soil and air temperature, humidity, disease, and insect attack. More than one limitation may be in effect at any given time, and there may be interactions among limiting factors.

5.2.1 PLANT SELECTION

ET landfill covers should include a diverse mixture of grass species that are native to the site. Native plant mixtures evolved under the conditions of the site and, therefore, they are predisposed to survive there and successfully perform as desired. During any particular year, one or more species may encounter less than optimum conditions for growth. However, as natural systems “abhor a vacuum,” other species in a native grass mixture thrive and dry the soil profile. Native grass mixtures are particularly well adapted to rapid regrowth after fire or drought.

Grass cover is preferred because it provides optimum erosion control and an extensive fibrous root system. However, woody plants are appropriate at some sites. Perennial species are preferred at most locations, although annuals should be used where they are the predominant native species; for example, in central and southern California, annual grasses dominate the native grasslands. The growing season of individual species within a native grass mixture often differ, and may extend the season for active soil water use from the cover soil beyond that for a single species.

Native species evolved at the site; as a result, they are hardy and persistent. They utilize resources efficiently and produce near the maximum possible biomass and water use that is possible under the conditions at the site. Native plants developed under both favorable and unfavorable conditions at the site, yet they survived for centuries. They survived extended drought, insect attack, disease, periodic fire, and other adverse factors.

Many introduced species threaten existing ecosystems; some are official noxious weeds. Some introduced species will displace native species and form a monoculture; such a cover is vulnerable to unexpected insect or disease attack (Schuman et al. 1982). Introduced plants may have been hardy in the place where they developed; however, there is often no proof that they will be equally hardy at a different site. Introduced species may be highly susceptible to disease or an insect found occasionally at the site. Introduced species may invade the site.

A mixture of native species will provide protection during periods when natural factors cause individual species to grow poorly. The mixture should include several grasses and forbs. Although seeds of cultivated plants have short lives in the soil, native plant seeds remain viable in the soil for many years and, if present, provide a source for natural landfill cover renewal. Native grasses and forbs will create a seed bank in the soil if the plants in the cover produce mature seeds during each year.

The seeds of native grasses and forbs may be difficult to get because they are difficult to grow and harvest. There are, for almost all locations in the United States, selections derived from native plants that will be available and are often highly satisfactory. Native grasses perform best if they have a few native forbs in the planting. Some of the broad-leaf forbs are legumes, and if inoculated, will supply needed nitrogen to the grasses. The forbs, although small in total number and total biomass, make a major contribution to the health and natural renewal of the grass cover. Seeds of forbs are often difficult to get, but planting even one legume species will substantially improve the probability for success. Native grasses and forbs not planted may invade the site after establishment and add species diversity.

5.2.2 SOD AND BUNCH GRASSES

Sod-forming grasses produce dense ground cover and leave little bare ground; they may be established from seed or vegetatively. Individual plants spread by lateral creeping stems or rhizomes to establish new plants in the space between plants. The creeping stems grow laterally from the plant near the ground. The rhizomes grow under the soil surface and appear to be part of the root system. New plants form along the lateral stems and rhizomes and produce a dense interconnected cover of grass. A dominant characteristic of sod grasses as compared to bunch grasses is the density and completeness of ground cover achieved by sod-forming grasses. Sod-forming grasses provide excellent soil erosion control and can withstand concentrated water flow to depths of 2–3 ft (60–90 cm) on steep slopes. Figure 5.10 shows Bermuda grass, an introduced sod-forming grass, that is now widely distributed in warm climates.

FIGURE 5.10 Bermuda grass, a low-growing, sod-forming grass. (Photo courtesy of USDA Natural Resources Conservation Service.)

Bunch grasses grow as individual plants, and they spread by germination of seeds to establish new plants. Some of them spread vegetatively; in that case, the crown of the bunch grass produces a ring of new plant material on the outer edge of the crown, thus increasing the size of the bunch. Where water supply is limited, the grass plants (bunches) are widely separated, leaving bare ground between them. The roots, however, spread laterally and utilize all the soil water between plants. At arid sites, bunch grasses provide adequate water erosion control if plant litter and stems cover the ground between bunches. Following fire, erosion control by bunch grasses is reduced until new growth emerges. In humid regions, bunch grasses usually grow so close together that they overlap and provide excellent water and wind erosion control. Figure 5.11 compares bunch grasses in an arid climate with those growing in a humid climate.

A good mixture of grasses may include both bunch and sod-forming grasses because a primary goal for the vegetation is the most complete ground cover possible. The selection of species should follow as closely as possible the native plant distribution at the site.

5.2.3 Trees and Shrubs

Trees and shrubs can effectively remove soil water from the cover soil. Shrubs and trees are native vegetation in some areas; however, even in these areas, native grasses are suitable for an ET cover. A properly constructed ET cover soil will provide excellent conditions for grass production in any area.

The claim is sometimes made that trees use more water than grass. Several factors that control plant water use from the soil are similar between grass and trees:

- Source of energy to evaporate water is the sun.
- Stomata in the leaves controls water flow through most plants.
- Stomata control the evaporation of water from the leaves of most plants to maintain optimum leaf temperature (Wanjura et al. 1992; Evett et al. 1996).

FIGURE 5.11 Bunch grasses growing in an arid climate (*left*); and in a humid climate (*right*). (Photo courtesy of USDA Natural Resources Conservation Service.)

It is unlikely that trees planted in a forest will consume significantly more water than grasses unless they provide green growing vegetation for a longer time during the year. There is one notable exception: large trees growing in isolation may use more water than grass on an ET landfill cover when winds provide significant advective energy.

Some shrubs and trees produce allelopathic materials that suppress plant growth under and near the tree. The soil under trees and shrubs may be bare because of water consumption and interception of light by the tree. In either case, bare soil or sparse ground cover under and around trees and shrubs may create a soil erosion hazard.

The rooting depth of plants may be important for ET cover applications. Even though some trees and shrubs have taproots that may penetrate deeply, their primary root activity is in the same upper soil layers occupied by grass roots.

5.2.4 SELECTING NATIVE PLANT SPECIES

Local agricultural extension agents employed by the USDA or a state, are excellent sources of information regarding plants native to the site. The yearbook of agriculture entitled *Grass (*USDA 1948) is an excellent source of information about grass plants for each region of the United States.

A recent reference including both native and introduced grasses is the USDA book on grass varieties (Alderson and Sharp 1994). The USDA Plant Database (USDA-NRCS 2006) provides useful descriptions of plant species. They also created a Web site that is useful in planning an individual site called Vegetative Practice Design Application (VegSpec 2006).

State highway departments maintain recommendations for plant cover on right-of-way property. State highway departments select plants for right-of-way for their ability to survive on thin, infertile soils and under harsh environments. Although these recommendations are good for roadway embankments and right-of-way, they are unlikely to match the needs of plants growing on an ET landfill cover. Plants selected from USDA recommendations should perform much better on ET landfill covers.

Almost all plants experience a dormant season when they use little water. Some or all of the plants selected for the cover should actively grow and use water during the season with greatest precipitation. Native plant species usually grow during the season of greatest precipitation. Cool- and warm-season native grasses may successfully grow together at many sites. The combination of cool- and warm-season grasses substantially increases the length of the growing season and the soil-drying action of the grass cover.

5.3 PLANT ROOTS

ET landfill covers are highly dependent on the action of plant roots, so it is necessary to understand the role of roots in the system and their requirements because plant roots control water removal from the soil; they control success. Several factors affect water removal from soil by plant roots, and roots serve many complex functions (Rendig and Taylor 1989; Klepper 1990), including the following:

- Roots provide the plant with water and nutrients absorbed simultaneously from deep and shallow soil layers, from moist and partially dry soil, and from soil zones of different biological, chemical, and physical properties.
- Roots provide anchorage for the plant.
- Fleshy roots store nutrients.
- Some plants develop adventitious shoots after damage to the main root.

Roots and shoots (aboveground plant parts) are interdependent. Shoots are the source of organic metabolites used in growth and maintenance, and roots are the source of inorganic nutrients and water. Pruning, clipping, or mowing the top of a plant reduces root mass.

Plants remove water, nutrients, and oxygen from the soil via the plant root system. Plant feeder roots (the smallest roots) extract the water, plant nutrients, and oxygen from the soil and the soil atmosphere. When soil layers dry, plants become stressed, the mass of aboveground shoots may be reduced, and roots may die. When conditions for robust plant growth return, it is necessary for the plant to replace dead roots quickly; that requires a favorable soil environment.

In order for the ET cover to be effective, the plants should maintain the soil in the driest possible condition at all times, resulting in significant loss of plant root mass, several times during each season. After rainfall, it is important that the plants produce new roots in the wet soil as quickly as possible. Native plants naturally tend to grow new roots rapidly because through competitive selection during the evolutionary process, only those plants capable of rapid root and shoot growth survived to become part of what we define as "native plants." It is possible, with little or no additional construction expense, to produce ET cover soils with few restrictions to root growth, thus allowing optimum plant performance.

Roots grow rapidly if soil conditions are favorable; this requires that the soil have low soil strength, adequate fertility, and that the soil atmosphere contain adequate levels of oxygen. Low soil strength requires low bulk density. As stated earlier, low soil density is vital to success, affects other soil conditions, and is easy to control during ET cover construction and maintenance activities.

5.3.1 ROOT DISTRIBUTION WITHIN THE SOIL

The distribution and density of living plant roots in soil controls the drying of each soil layer. Figure 5.12 illustrates general root distribution patterns that are possible during a growing season for a soil with good tilth. When all layers are adequately wetted, roots often develop as shown for condition 1 early in the growing season; the majority of the roots are near the surface in the upper 15–30 cm. Plants extract water and nutrients in greatest quantity from the uppermost soil layers when they are wet; as a result, the natural rooting pattern dries the upper layers first. After surface soils dry, the root distribution, water, and nutrient extraction may shift to a pattern similar to condition 2. After a significant period of drought, when most of the extractable water is deeper in the soil or at the end of the growing season, most of the active roots will be deep in the soil profile (condition 3). As the soil dries during condition 2 or 3, soil water is held at greater negative pressure by the soil; as a result, plants may wilt during part or all of the day, and both water used and active growth rate may be reduced.

Parts of the root system, particularly small feeder roots, die in response to soil drying or other stresses in a particular layer, whereas, at the same time, new roots may be growing rapidly in another soil layer. Soil temperature, soil oxygen, and other factors may limit root density and water use from a particular soil layer. The density of living and active roots in each layer may increase and then decrease more than once during the growing season because of changing conditions. Thus, the distribution of actively growing and functioning roots may change from upper to lower and back to upper soil layers during one growing season in response to soil water content

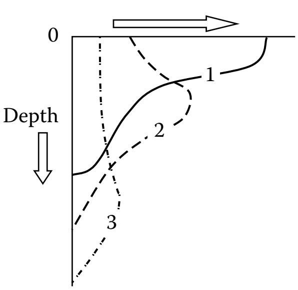

FIGURE 5.12 Possible distribution of living roots at different times during the growing season for a soil with good tilth.

changes caused by precipitation and ET (Russell 1977; Klepper 1990; Merva 1995). Generally, the potential maximum root mass in each layer decreases with depth. Where the soil in an ET landfill cover is near the desired optimum in each layer, root growth will be adequate at depth to extract water from the entire soil profile.

Soil water flows to roots (Section 5.1.4); however, soil water-holding properties severely limit the distance that it can effectively move. After only a small amount of soil drying near the root, the rate of water movement slows by orders of magnitude. It is, therefore, vital that soil conditions allow rapid growth of new roots so that they may quickly grow into all areas of moist soil after a storm. Under favorable conditions, root axes may grow 2 cm/day and root laterals may grow 0.5 cm/day; however, some investigators report growth rates up to 6 cm/day (Russell 1977). It is highly advantageous to maintain soil tilth in a condition that allows maximum rates of growth for plant roots.

5.3.2 ROOT GROWTH RATE AND MAXIMUM DEPTH

Under optimum conditions, plant roots grow fast; however, during most of the time, limiting factors reduce the rate of root growth below the optimum for the plant in question. Limitations on root growth result in limitations on the ability of the plant to extract water and plant nutrients from the soil. Factors that may limit root growth include (Rendig and Taylor 1989) the following:

- Unsatisfactory soil pH
- Soil strength and physical factors
- Soil temperature
- Salinity of the soil solution (caused by excess Ca, Mg, Na, and other salts)
- Soil water content
- Soil oxygen
- Air-filled porosity in the soil
- Chemical toxicity (e.g., pH, Al, Be, Cd, Pb, Cu, Cr, Fe, Hg, Zn, NH_3, B, and Se)
- Allelopathic toxicants

Most native grasses or associated species have the potential to root to depths of 2 m or more; however, at many natural sites, soil or climate characteristics—not plant potential—limit the rooting depth. The soil conditions within the ET landfill cover soil should be optimized for maximum root growth throughout the full depth of the cover for two primary reasons:

- Roots should grow quickly in all of the wetted soil.
- It is relatively inexpensive to optimize the physical properties during construction.

The plant cover should have potential rooting depth greater than the thickness of the soil cover because it is necessary to have roots in wet soil. Some native species have potential rooting depth greater than 2 m (Sharpley and Williams 1990).

TABLE 5.4
Rooting Depths for Plants Grown in the United States

Common Plant Name	Depth (m)	Common Plant Name	Depth (m)
Cultivated Grasses		**Other Crops**	
Barley	2.0	Alfalfa	2.0
Corn	2.0	Clover	2.0
Fescue	2.0	Cotton	2.2
Oats	2.0	Sugar beet	2.0
Orchard grass	2.0	Sunflower	2.2
Rye	2.0	Vegetables, several	0.7–1.5
Sorghum, grain	2.0		
Timothy	2.0	**Trees**	
Wheat, spring	2.0	Mesquite	3.5
Wheat, winter	2.0	Pine	2.0
		Poplar	3.5
Other Grasses		Sweet gum	2.0
Bermuda grass	2.0		
Buffel grass	1.4	**Northern Great Plains**	
Cane, sugar	2.0	Barley, spring	1.3
Gramma, blue	1.4	Bromegrass, meadow	1.3
Gramma, side oats	1.4	Canola, Argentina	1.4
Rangeland grasses	2.0	Canola, Polish	0.9
Switch grass	2.2	Corn	2.0
Wheat grass, western	1.3	Wheat grass, crested	1.3
		Wheat grass, western	1.3
		Wheat, spring	1.3
		Wheat, winter	1.3
		Wildrye, Altai	1.3
		Wildrye, Russian	1.3

Source: From Sharpley, A. N. and Williams, J. R., Eds., *EPIC—Erosion/Productivity Impact Calculator: 1. Model Documentation*, USDA, Washington, DC, 1990, 56–57; and Kiniry, J. R., Major, D. J., Izaurralde, R. C. et al., *Canadian J. Plant Sci.,* 75, 679–688, 1995.

Table 5.4 contains rooting depths measured for plants grown in the United States (Sharpley and Williams 1990) and in the Northern Great Plains (Kiniry et al. 1995). Data for the Northern Great Plains are from measurements made in the Canadian Great Plains and the adjoining northernmost states of the U.S. Great Plains. The rooting depth measured for several plants in the Northern Great Plains was less than that found in other parts of the United States (Table 5.4). There are two possible reasons for the difference: (1) the soil temperature is colder and the growing season is shorter than for most of the United States and (2) the depth of the soil limited root depth at several sites in the Northern Great Plains (Kiniry et al. 1995). Either of these factors could have significantly reduced the observed plant rooting depth. Many natural soils contain layers that reduce, but do not stop, root growth, and other factors may limit rooting depth described in the literature. It is safe to assume that most native grasses can easily send roots to the bottom of a well-built ET cover soil that is 2 m thick.

5.4 OTHER TECHNOLOGY

Other factors affect performance of an ET landfill cover. The following paragraphs describe some of them.

5.4.1 Soil Temperature

Soil temperature exerts strong control over the rate of root growth and may limit top growth. The site design should ensure that the plants selected are adapted to the expected soil and air temperatures. Each plant has an optimum temperature for root growth; soil temperatures either above or below that temperature result in reduced rate of growth. Beyond the high- or low-temperature limits for each plant, root growth stops.

5.4.2 Salinity of the Soil Solution

Salinity of the soil solution may be an important issue. Many salts may contribute to the salinity level of the soil solution. As plants dry the soil, they remove soil water and the salinity of the soil solution increases rapidly. Saline soil solution produces an osmotic effect that reduces or stops water movement into plant roots. The plants remove pure water and only a small amount of salts. As a result, the osmotic strength of the soil solution will increase during soil drying. The resulting concentration of salts in the root zone may become a problem; therefore, salinity of soil used in an ET cover is important.

5.4.3 Soil Oxygen

Soil oxygen is required in the root respiration process that converts carbohydrates to carbon dioxide and water, thus releasing energy needed by the plant for all of its processes. Oxygen moves through the soil by diffusion through air-filled pores and, to a lesser degree, by mass flow through air-filled pores in response to wind forces on the surface. In order to sustain plant life, an adequate supply of oxygen must be available at the roots. When the air-filled pore space in the soil is less than 10% oxygen, some plants are stressed. However, the rate of oxygen movement through the soil is also important. If the air-filled pores are too small or not connected, little or no oxygen can move to the roots.

5.4.4 Air-Filled Porosity

Air-filled porosity in the soil is important because each root requires oxygen and because during rainfall or irrigation these pores become channels for water and air to move rapidly through the soil. Soil pore space includes both large and small pores. Small pores contribute little to the movement of air, but much of the water is stored in small pores. An optimal soil structure includes both large and small pores that are connected so that water and air may move freely. Total pore space and soil bulk density are inversely related; as a result, dense soils have little pore space and less dense soils have more pore space. One adverse impact of soil compaction is the reduction of large pore spaces. Sandy soils generally have large pore spaces, and they are well aerated. Clay soils often contain more total pore space than sandy soils, but most of the pores may be small.

5.4.5 CHEMICAL TOXICITY

A few soils contain enough toxic material to reduce plant growth. Chemical toxicity is a potential limitation to plant growth.

5.4.6 ALLELOPATHIC TOXICANTS

Allelopathic toxicants are chemicals produced by one plant that may kill or limit growth of another plant. These toxicants may remain in the soil from previous vegetation. If, for example, the soil used in the ET cover was covered by salt cedar or juniper in the past, some grasses or trees may grow poorly in that soil for one or more seasons. Allelopathy is an unlikely source of problems because the site manager can control the type of plants grown at the site and can select the soil used in construction.

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6 Climate, Weather, and Water Balance

Climate and weather influence performance of ET landfill covers more than they influence conventional barrier-type covers. The daily weather at a site governs both the input and outgoing parts of the water balance. Climate is the sum of weather events and offers a convenient way to understand atmospheric influence at a particular site.

6.1 CLIMATE AND WEATHER

Table 6.1 contains climate and weather parameters that are important to evaluation or design of ET landfill covers.

Climate is the average course or condition of weather at a place over a period of years, in terms of air temperature, wind speed, and precipitation (Webster 1971). Descriptions of climate may also include other important factors such as direction of prevailing wind and nearness of oceans or large lakes. Climatic data describe the long-term average state of weather for a region or a site. Chapter 2, Section 2.3.1 introduced climate concepts for landfill cover evaluation.

Weather is the state of the atmosphere with respect to heat or cold, wetness or dryness, calm or storm, clearness or cloudiness (Webster 1971); it controls climate. Weather parameters may be measured daily, hourly, or more often.

6.1.1 CLIMATE

Regional climate should be the first consideration when evaluating the suitability of an alternative landfill cover for a site because it costs little. If the regional climate appears compatible with the requirements of the alternative cover, then examine site characteristics to determine whether the site climate is also suitable. Site and regional climate may differ substantially for locations near mountains, in valleys, in the rain shadow of coastal mountains, or near the coast, or for other less obvious reasons.

Use the longest available record to assess climate for a site. The 35 years of annual precipitation records ending in 1993 for Coshocton, Ohio, illustrate the point. The 35 year average annual precipitation is 934 mm; however, one 5 year period averaged 88% and another averaged 115% of the overall average. Annual extremes are even greater; they are 65% and 144% of the 35 year average. Many sites have greater variability in climate. A long record for the site in question is desirable.

If the regional and local climate supports use of the ET cover, further investigation costs are justified. Average values define regional climate; therefore, they do not assess the potential impact of exceptional or extreme weather events. Even though an

TABLE 6.1
Climate and Weather Parameters That Are Important to the Function of ET Landfill Covers

Climate (average of)	Weather (daily, hourly, or other)
Air temperature	Maximum air temperature
Wind speed	Minimum air temperature
Precipitation	Average air temperature
Solar radiation	Wind speed
	Rainfall
	Snowfall
	Sleet and hail
	Dew point
	Solar radiation

initial assessment of climate may be favorable, successful design and use of an ET cover requires an in-depth analysis.

6.1.2 WEATHER

Table 6.1 contains a list of weather measurements that are commonly available to evaluate and design ET covers. Daily values of weather parameters are adequate to evaluate extreme events for landfill cover design. Long-term records available for ET landfill cover design are generally daily values. Daily average air temperature alone has limited usefulness for ET cover design; therefore, use daily maximum and minimum air temperature records for each day when they are available.

At some sites, only maximum and minimum air temperature, wind speed, and precipitation records are available; these are sufficient if the data quality is acceptable and the record is long. Solar radiation and dew point data are often available, at a site, but for a shorter time than for precipitation and temperature. Because solar radiation and dew point measurements usually fluctuate less over time than other weather data at a site, use the short records in concert with longer records of temperature, wind, and rainfall.

It is important to understand the possible accuracy of the data as completely as practicable. Allen (1996) presents procedures and guidelines for assessing integrity, quality, and reasonableness of measured weather data.

Evaluate solar radiation measurements made before 1985–1990 against those made after that date or against records from nearby weather stations, if available. Early solar radiation measurements were subject to error because the calibration of early instruments changed during use. Excellent records exist for the early years at sites where persons collecting the data understood the instruments and exercised due diligence in their operations.

6.1.3 PRECIPITATION MEASUREMENT

Precipitation records are the most basic and important measurements used in assessment and design of ET covers. Precipitation is the largest part of the water balance, and it is the source of incoming water to the landfill surface. Error in the precipitation record used for design will result in similar error in estimates of other performance parameters. The best precipitation records contain errors, and there is no universally accepted definition of true precipitation at a site. The design engineer should use records collected with standard and tested methods and understand the possible size of the errors in precipitation measurement.

6.1.3.1 Accuracy of Precipitation Measurements

Several factors may affect the accuracy of precipitation measurement. Snow amount is difficult to measure and may introduce substantial measurement errors. The American Society of Civil Engineers' (ASCE) *Hydrology Handbook* presents a detailed discussion of precipitation measurement (ASCE 1996). The following list identifies major factors that affect the accuracy of precipitation measurements (Chow 1964; Brakensiek et al. 1979; Schwab et al. 1966):

- Disturbance of the wind field by the gage
- Snow or ice accumulations on the gage
- Trees, buildings, or other objects located close to the gage
- Evaporation from the gage
- Mechanical damage to the gage (dents, leaks, etc.)
- Splash into or out of the receiver funnel
- Water creeping up the measuring stick of a standard gage

Wind is the greatest single cause of error in precipitation measurements. Schwab et al. (1966) report that winds of 10 mph caused a rainfall catch deficit of 17%, but a wind of 30 mph caused a deficit of 60%. Brakensiek et al. (1979) state, *"An ideal [gage] exposure would eliminate all turbulence and eddy currents near the gage."* They also state that wind may cause a –5 to –80% error in precipitation measurement. They reported that errors resulting from other causes were between +1 and –1.5%.

Gage height is important because wind movement affects the gage catch, and wind velocity near the ground is a logarithmic function of height above ground surface. Snow is particularly difficult to measure accurately in the presence of wind because it is so easily moved by air currents. Small raindrops typical of low intensity rainfall are also subject to more movement by wind than are large drops found in higher intensity storms.

The best measurement of rainfall is that obtained at ground level. Rain gages placed in a large hole so that their top is at ground level are called "pit gages." Care should be taken to prevent splash from adjacent ground surfaces into the pit gage. Pit gages may catch up to 15% more rainfall than gages with their tops mounted at standard heights (Neff 1977).

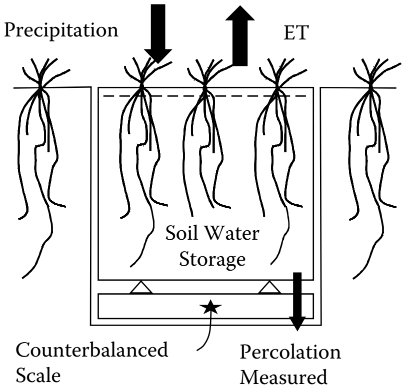

FIGURE 6.1 An automatic weighing lysimeter.

The results of research on the effect of gage height are variable. Allis et al. (1963) reported that a gage mounted 1.8 m (6 ft) above ground surface captured the same amount of rainfall as a standard gage at 75 cm (30 in.). However, the gage at standard height captured 30% more snow than the gage mounted at a height of (1.8 m).

Shields may improve the measurement of snow and rain under windy conditions. Allis et al. (1963), Brakensiek et al. (1979), and Chow (1964) discuss shields and refer to the extensive literature about them.

Field lysimeters can measure all parts of the hydrologic water balance for a site, and they catch precipitation at ground level on a large surface area (Figure 6.1). They accurately measure precipitation (McGuinness 1966; Brakensiek et al. 1979). McGuinness (1966) found that lysimeters at Coshocton measured 6% more rainfall than a standard gage, but 27% more snowfall. Hauser et al. (2005) evaluated measurements by one lysimeter and a rain gage at Coshocton, and by two lysimeters and a rain gage at Bushland, Texas. The lysimeter caught 10% more precipitation than the rain gage at Coshocton. The two lysimeters at Bushland caught 2.5 and 5.8% more precipitation than a nearby rain gage. The most likely cause for the difference between the locations was that Coshocton received substantial snow, but Bushland received little.

6.1.3.2 Standard Rainfall Measurement

Experience and research have produced accepted standards for precipitation measurements. Precipitation measurements using the standard methods are comparable from site to site, and they are accepted for use in design.

A standard rain gage includes a collection tube with a sharp-edged circular orifice at the top to catch precipitation. The U.S. Weather Bureau standardized the diameter of the orifice at 203 mm (8 in.) (Chow 1964; Brakensiek et al. 1979; Schwab et al. 1966). The height of measurement is less well defined; it is normally taken to be either 762 or 1016 mm (30 or 40 in.) above ground surface. The standard measurement height for rainfall in hydrologic research is 762 mm (30 in.) above ground surface (Brakensiek et al. 1979).

6.2 HYDROLOGIC WATER BALANCE

A major requirement of a landfill cover is control of the amount of precipitation that enters the waste. The amount of water that percolates through the cover and may enter the waste is deep percolation (PRK). Deep percolation is a part of a bigger hydrologic system and, because all of the parts are interrelated, it should be

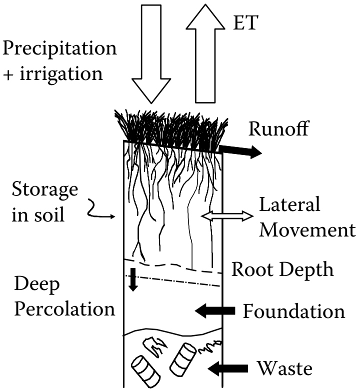

FIGURE 6.2 Water balance terms for an ET landfill cover.

assessed in parallel with the other parts. Therefore, it is necessary to estimate the entire hydrologic water balance for the cover in order to assess its behavior.

The water balance is an accounting of all water entering and leaving an ET landfill cover: a mass balance. The quantity of water on or near Earth is constant; therefore, we may say:

incoming water = *outgoing water* or the following equation:

$$P + I = ET + Q + L + \Delta SW + PRK + error \tag{6.1}$$

where

P = precipitation
I = irrigation, if applied
ET = evapotranspiration (the actual amount)
Q = surface runoff
L = lateral flow
ΔSW = change in soil water (SW) storage
PRK = deep percolation (below cover or root zone)
error = lack of balance in the measured terms

This equation is the hydrologic water balance equation for an ET landfill cover; Figure 6.2 illustrates the relationship between the terms. The incoming water (P + I) should equal the outgoing water (ET, Q, L, ΔSW, and PRK). Where all terms are measured, for example, lysimeter measurements (Figure 6.1), the difference or lack of balance is an expression of measurement error. In typical ET landfill cover design, the error term is unknown.

6.2.1 ACTUAL AND POTENTIAL EVAPOTRANSPIRATION

ET is the sum of evaporation of water from the soil surface and plant transpiration (primarily through the stomata on the plant's leaves). ET is the largest mechanism of water removal in the water balance for an ET cover. The ET term in the water balance equation is the actual value and not the potential value. With current knowledge, it is necessary to estimate potential evapotranspiration (PET) first and estimate the ET for the site as a fraction of PET or estimate the reduction of PET by limiting factors.

PET is the maximum ET expected from a set of climatic conditions; the amount of energy available to evaporate water limits PET (Jensen et al. 1990). PET is the amount of water that would return to the atmosphere if abundant, freely transpiring plant leaves are available and the water supply to the plants is abundant and unrestricted. Allen et al. (2005) recently proposed the equivalent description *"reference crop evaporation."*

ET is less than the PET amount except for short time periods during and after rainfall or snowmelt events. Soil and plant factors that may reduce ET at a site include soil dryness, cold soils, high soil density, poor soil tilth, high soil aluminum caused by low soil pH, limited plant nutrients, soil salinity, soil alkalinity, and limited soil oxygen. Plant disease, insect attack, and other factors may also reduce actual ET below the potential amount.

When evaluating performance of an ET landfill cover, the estimate of actual ET is important. The accuracy with which a model estimates ET is the biggest controlling factor for hydrologic modeling accuracy because (1) ET is the largest term on the right-hand side of Equation 6.1 and (2) water removed from the soil by ET affects or controls the size of the other terms on the right-hand side of Equation 6.1.

6.2.2 SURFACE RUNOFF

Surface runoff (Q) is the second largest part of the hydrologic water balance for ET landfill covers in humid regions. Even at dry sites where surface runoff is small, errors in estimates of Q are important, and especially so if the model estimates significant Q on days with no runoff. Estimates of Q are, therefore, important to the design process at all sites.

Surface runoff can begin only after (1) rainfall or snowmelt fill storage by plant interception and surface ponding and (2) the rainfall or snowmelt rate exceeds the soil infiltration rate. Excellent sources for technical details include Chow et al. (1988), Linsley et al. (1958), and ASCE (1996).

6.2.3 LATERAL FLOW AND CHANGE IN SOIL WATER STORAGE

Lateral flow (L) within the soil layer containing plant roots is small for ET cover situations and may safely be assumed zero. During the course of a hydrologic year, change in soil water storage (ΔSW) is usually small in comparison to the other terms, but it is large on a daily basis and thus important in assessing the impact of critical events.

6.2.4 DEEP PERCOLATION

A primary focus for the design is deep percolation below the ET landfill cover as represented by the rearranged Equation 6.1.

$$\mathrm{PRK} = \mathrm{P} + \mathrm{I} - \mathrm{ET} - \mathrm{Q} - \mathrm{L} - \Delta\mathrm{SW} - \mathrm{error} \qquad (6.2)$$

In keeping with the purpose for landfill covers, deep percolation (PRK) is the primary design criterion. Estimates of PRK are affected by data input errors for P and I and by errors in model estimates for ET, Q, and ΔSW. ET is the largest part of the outgoing water balance for almost all sites. It is important to understand the accuracy of estimates for both ET and Q because errors in these estimates contribute directly to error in estimates of PRK.

Soil water content changes in response to water removal by plants, soil evaporation, and gravitational drainage. During and immediately after rainfall or snowmelt, soil water storage may change rapidly in response to the influx of water from the rain or snowmelt and the removal of water due to drainage by gravitational forces and plant use. Although gravitational drainage is significant, it is effective for a short time and is near zero most of the time. Soil evaporation is important for one to a few days after precipitation; then it rapidly declines to near-zero amounts as the top 250 mm of soil dries. Plant use is the primary mechanism for change in soil water content and continues for a long time or until the soil becomes dry.

Because soil water content strongly affects daily values of ET, Q, and PRK, errors in estimates of change in total soil water content will be included in errors of the PRK estimated by a model. An appropriate model should continuously estimate the amount of soil water in storage for all layers within the soil profile.

The principles of water balance analysis are contained in numerous texts, including Chow et al. (1988), Linsley et al. (1958), and Jensen et al. (1990). Water balance analysis for landfill covers is described by Koerner and Daniel (1997), McBean et al. (1995), ASCE (1996), Weand et al. (1999), Gill et al. (1999), and Hauser et al. (2005).

6.3 MEASURING HYDROLOGIC WATER BALANCE

High-quality measurements of the water balance are expensive, and little high-quality data exist. The quality of hydrologic measurements is assessed by a complete water balance that requires measurement of all terms except error in Equation 6.1. The variability of water balance terms is important; therefore, the duration of water balance records is important.

Figure 6.3 illustrates a high-quality recording monolithic lysimeter located at the North Appalachian Experimental Watershed (NAEW), USDA, Agricultural Research Service, Coshocton. Harrold and Dreibelbis (1958,1967) and Malone et al. (1999, 2000) described the lysimeter; hydrologic measurements began in 1943.

The dimensions of the soil block contained in the lysimeter are 4.27 m (14 ft) long, 1.9 m (6.22 ft) wide, and 2.44 m (8 ft) deep, with the long dimension up- and downhill. The surface area is 8.09 m^2 (0.002 acres). The lysimeter soil block is an undisturbed natural soil profile from the site and includes bedrock in the bottom layers. The lysimeters are deep enough to include bedrock so that drainage from the bottom is natural. Thus, the lysimeters duplicated drainage conditions of the undisturbed surrounding watershed.

The land slope around the lysimeter and on its surface is about 23%. Vegetation similar to that on the lysimeter pair surrounds them to a distance greater than 305 m.

Precipitation and ET are measured by weight changes of the lysimeter. Drainage from the bottom of the soil profile and surface runoff are independently and

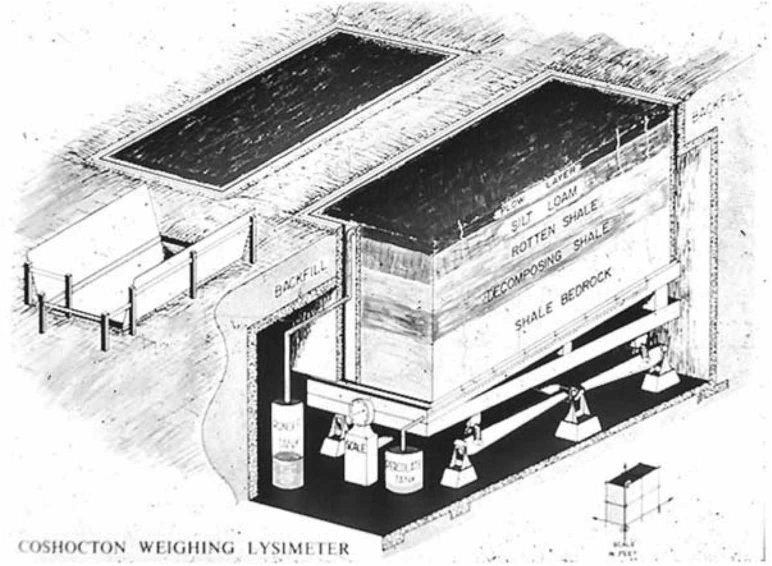

FIGURE 6.3 Weighing and recording lysimeter, Coshocton, Ohio. (Photo courtesy of Dr. J. Bonta, North Appalachian Experimental Watershed, Agricultural Research Service, USDA.)

continuously measured volumetrically. Precipitation and other weather measurements are measured by a weather station operated at the site. Soil water content change is measured by the lysimeter and by periodic and independent neutron meter measurements in the lysimeter soil. Measurements of hydrologic variables made by the lysimeter are automatically recorded.

There are few high-quality, complete measurements of water balance terms. Therefore, it is not possible to use measured data directly in design. However, models may be tested against the available, complete lysimeter data to evaluate their usefulness and accuracy in design.

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7 Potential Application

The evapotranspiration (ET) landfill cover satisfies wide variations in site needs. It applies where the requirements for a cover include little percolation into the waste. At the other extreme, its design and construction are flexible and it can allow a large part of average annual precipitation to enter the waste in order to meet requirements for waste stabilization.

The following chapters (Chapters 8 to 13) discuss the design process. During site assessment, the planning staff and designers need methods to make an informed initial choice of cover type. This chapter focuses on methods to make an initial assessment about whether an ET cover is appropriate for a particular site.

7.1 LIMITED PERCOLATION

Some landfill sites require little percolation of precipitation into the waste; these sites present the greatest challenge for cover performance. Climate is a major determinant of ET cover performance at a given site and the evaporation-to-precipitation ratio is naturally most favorable in arid and semiarid areas. Analysis of readily available climate information provides an inexpensive initial assessment for these landfill sites.

Although interesting, monthly or annual average values of precipitation, temperature, wind, etc., do not produce a satisfactory estimate of the potential for use of the ET landfill cover. Short-term or daily weather events are usually the cause of excess percolation. This chapter presents a method for initial assessment; it is based on estimates of daily weather, including natural daily variability and the resultant size of each term in the water balance at numerous sites. It includes extreme events and their effect on annual or average ET, Q, and PRK during a 100 year period.

7.1.1 EVAPOTRANSPIRATION

PET is an easily calculated upper bound for ET. The PET varies in response to daily weather factors including humidity, air temperature, and solar radiation. PET provides a useful way to evaluate suitability of the ET cover to conditions at a site because it is the upper bound of ET for the site.

The ET is less than PET, except for short times when the surface is wet immediately after precipitation. Natural stress factors applied to the PET result in estimates of ET. Plant stress due to limited soil water supply is a primary limitation to plant growth; it is a useful indicator of the frequency and duration of dry soil in the ET cover during the year.

FIGURE 7.1 Location of 60 PET evaluation sites.

7.1.2 CALCULATIONS

Hauser and Gimon (2001) calculated daily values of PET, ET, and number of days when soil dryness was the most limiting ingredient for grass growth at 60 locations in the United States. The locations included hot, cold, wet, and dry sites (Figure 7.1). Averages from their data form the basis for general regional maps, indicating the possible level of effectiveness of the ET cover for the continental United States.

They used the Environmental Policy Integrated Climate (EPIC) model to estimate PET, ET, and number of days when soil dryness was the most limiting factor for grass growth at each site. The EPIC model and its earlier versions meet the requirements for ET estimation (Sharpley and Williams 1990; Williams et al. 1990; Hauser et al. 2005).

The EPIC model estimates PET for each day, and uses the sum of daily stress factors to estimate ET. One stress indicator is the total number of days when soil water content was the most limiting factor for plant growth during each year (water stress days).

The Penman–Monteith method is the most accurate and robust method available for calculating PET; however, it requires a complete climate data set, including solar radiation, daily wind run, and relative humidity (Jensen et al. 1990). Available data with adequate record length included only daily precipitation and maximum and minimum air temperatures. The Priestly–Taylor and Hargreaves methods estimate PET with acceptable accuracy, if used in regions for which they were developed; they need only the available data (Jensen et al. 1990).

Hauser and Gimon (2001) used the Priestly–Taylor ET estimation method east of 100° west longitude and the Hargreaves method for locations west of that line. They used the EPIC model to estimate daily values of PET, and from the daily values, they calculated annual estimates of PET for a 100 year period.

The EPIC model includes tested climate data for sites near each location. It stochastically generated daily values of weather parameters for each location from monthly mean values of rainfall, temperature, wind data, and associated statistics. The stochastically generated climate data contains extreme events and has statistical properties similar to measured data (Sharpley and Williams 1990; Williams et al. 1990).

TABLE 7.1
Grass Cover and PET Equation Used for Each Region of the United States

Region	Grass Cover	PET Equation
Northeast (west to 100°)	Russian wild rye grass	Priestly–Taylor
Southeast (west to 100°)	Switch grass	Priestly–Taylor
Rocky Mountain region (South to AR–NM border)	Crested wheat grass	Hargreaves
Southwest (east to 100°)	Range grass mixture	Hargreaves
West Coast (east to Sierra Nevada and Cascade Mountains)	Annual rye grass	Hargreaves

TABLE 7.2
Properties of the Soil Mixture Used for PET and ET Estimates

Soil Property	Value
Sand content	14.2%
Silt content	41.7%
Clay content	44.1%
Bulk density	1.4 Mg/m^3
Wilting point	0.18 v/v
Field capacity	0.34 v/v
Soil pH	6.8
Organic carbon	1.4%
Cation exchange capacity	21.0 cmol/kg
Soil thickness	2.0 m
Number of soil layers	10
Hydrologic soil group	D

The plant cover consisted of a monoculture of grass that is adapted to the region and climate of each location. Each grass has the potential to grow roots 2 m or more into the soil and to extract water from that depth. Table 7.1 contains a list of the grasses and PET equations used. Each model estimate used the same soil (Table 7.2).

7.1.3 PET-TO-PRECIPITATION RATIO

The ratio of PET to precipitation is a useful statistic.

$$\text{PET ratio} = \text{Annual PET}/\text{Annual precipitation} \tag{7.1}$$

where

Annual PET = average annual total of daily PET
Annual precipitation = average annual total of daily precipitation

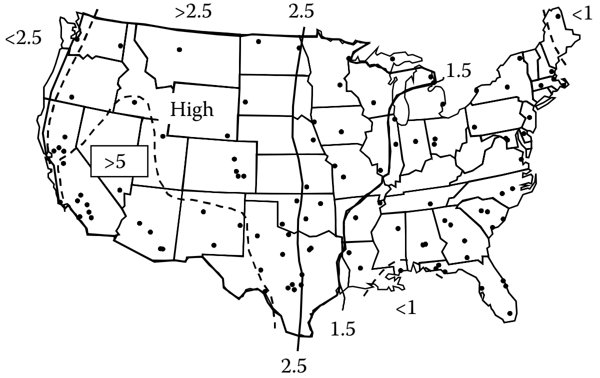

FIGURE 7.2 Average annual PET-to-precipitation ratio.

Where the PET ratio is large, it is likely that an ET cover will satisfy the requirements for a landfill cover because evaporation potential greatly exceeds precipitation. Where the PET ratio is equal to one, evaporation potential is equal to annual precipitation. A PET ratio of 1.2 was chosen as the division point between expected satisfactory and unsatisfactory results.

The PET ratio is greater than 1.2 for most of the United States (Figure 7.2). In small areas along the Gulf Coast, in Northern New England, and in the coldest climates, the PET ratio indicates caution in using the ET landfill cover. However, only 5 of the 60 sites examined had PET ratios less than or equal to 1.2.

The PET ratio is greater than 1.5 for the western two thirds of the country with one exception. The exception is the cold wet strip extending from the Pacific Ocean to the coastal range of mountains, between Canada and San Francisco. Because average annual precipitation is high in these cool coastal areas, the ET cover should be evaluated for each site. It is clear that the ET landfill cover is suitable for use in most of the country.

7.1.4 WATER STRESS DAYS PER YEAR

A primary goal of an ET cover is to keep the soil of the cover as dry as possible to provide ample water storage capacity to hold the water produced by extreme events. On days when the soil of the cover is dry enough to limit plant growth and water use, the potential water storage capacity of the cover is high. After several days of plant water stress, the soil water reservoir will be empty, or nearly so, and will thus be able to hold storm water to its maximum capacity. The number of water stress days per year provides a useful addition to the preliminary selection process. It is not an average; it is determined by extreme events.

As explained earlier, water stress is one of several stress factors. The water-stress-day parameter includes only the days when it was the most limiting factor. Water stress existed on other days when other factors were larger. As a result, EPIC's estimate of water stress days is conservative. Figure 7.3 shows the geographic distribution of water stress days estimated by the EPIC model.

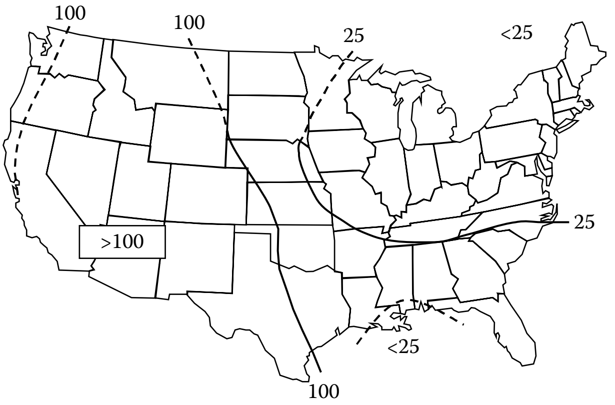

FIGURE 7.3 Average number of water stress days per year.

It is desirable for the soil water reservoir within an ET cover to be empty at least once each year. Water stress during 10 or more days per year indicates that the soil water reservoir was significantly depleted or nearly empty at those times. Ten sites near the Gulf of Mexico or the Atlantic Ocean coasts had about 10 water stress days per year. The site with the shortest growing season tested in the United States was located in northern Maine, and it had 20 water stress days per year.

For all areas where the number of water stress days exceeds 25, it is likely that the water reservoir in the ET cover is nearly empty more than once each year. These data fully support the conclusions based on the PET ratio.

7.2 INCREASED PERCOLATION FOR WASTE STABILIZATION

Where decay and rapid stabilization of waste are important goals for landfill remediation, it is important for precipitation to move through the cover and into the waste to maintain the desired water content. At these sites, it is easy to reduce the thickness of the cover or to use soil with lower water-holding capacity to produce the desired infiltration into the waste.

At dry sites where the need for a physical cover to confine the waste controls the thickness of the cover, additional measures may be required to produce increased percolation through the cover. For example, natural stony soils or fine-textured soil with added gravel will produce greater drainage through the cover than for an equal depth of fine-textured soil. Gravel mixed into the cover soil in a dry region may provide two benefits. First, the cover may allow adequate deep percolation. Second, the grass cover is more robust where coarse material in the soil causes water from a small shower to wet the soil deeper for plant growth, thus leaving less water from the shower in top layers where it may be wasted by surface evaporation.

7.3 APPROPRIATE USE

The ET landfill cover is appropriate for use at almost all sites in the United States, where deep percolation should be limited. Evaluate each site in the coastal areas of

Louisiana, Mississippi, and Alabama, and a narrow strip along the west coast from Canada south to San Francisco, California.

For sites where a significant portion of rainfall should pass into the waste to hasten decay and landfill stabilization, the ET landfill cover is appropriate for use anywhere in the United States.

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8 ET Landfill Cover Design Steps

The design of evapotranspiration (ET) landfill covers fits within the framework normally used for landfill remediation. This chapter includes design information that is specific to ET covers.

Each landfill cover should satisfy site requirements to protect public health and the environment over many decades or even centuries. Federal rules and regulations (USEPA 1991) prescribe the important design requirements for conventional landfill covers, and a model is accepted for their design (Schroeder et al. 1994a,b). As a result, the accepted conventional covers tend to be similar to one another.

The technology that governs performance of the ET cover dictates a unique design for each landfill cover so that it can meet the requirements of the site. Federal rules and regulations provide no guidance for alternative landfill covers. Each ET landfill cover is designed for its location. The four-step risk-based/performance-based (RB/PB) process described in Chapter 2 applies to ET landfill covers and should precede the following six design steps:

1. Site characterization
2. Performance criteria
3. Cover type
4. Preliminary design
5. Site-specific design
6. Final design

Because each site is unique, these design steps may need modification or iteration of the steps for a particular site.

8.1 SITE CHARACTERIZATION

Site characterization includes measurement and description of parameters that are important to the decision process and preliminary ET landfill cover design. It may include information listed in Table 8.1 and Chapter 2, Section 2.3. Characterization may involve two steps. The first is the information needed for site evaluation and preliminary design; it should be relatively brief and inexpensive. The second is for final design and requires additional measurements; it may require substantial amounts of time and expense.

TABLE 8.1
Site Characteristics That Are Important to Evaluation and Design of an ET Landfill Cover

Characteristic	Measured Parameters
Hydrogeology	Geology, permeability of strata, seismic activity, groundwater connection to waste, native groundwater quality and use, domestic or other use of groundwater
Groundwater	Depth, separation from waste, rate and direction of movement, native quality, potential use of native groundwater, current groundwater use, and contaminants both upgradient and downgradient from the landfill
Landfill liner	Lined or unlined, kind of lining, thickness, permeability, and durability
Waste	Kind, age, degradability, toxicity, and radioactivity
Gas production	Current gas production, potential gas production, and gas quality
Climate	Wet, dry, cold, hot, weather extremes, ice and snow accumulations, hurricanes and storms, monthly average precipitation and temperature, length of growing season, and variability of weather
Seismic risk	Seismic risk for the area, geological factors affecting seismic risk to the landfill, and waste properties that affect seismic risk
Soil resource	Quality of soil near site, haul distance, volume available, quality of subsoil, soil salt, alkalinity, contamination, fertility, cation exchange capacity (CEC), pH, organic matter content, and total salt
Plant resource	Native species, annual or perennial, potential rooting depth, growing season, water use, density of ground cover, ease of establishment, availability of seed, and ability to control soil erosion
Site reuse	Rural or urban location, value of surrounding land, and distance to national forest and parks

The measurements of site characteristics listed in Table 8.1 should demonstrate current or potential complete pathways between contaminants in the landfill and receptors. It is important to measure the risks added by the landfill and their relation to remediation activities. For example, landfills located above tight shale formations or other low-permeability materials are unlikely to harm the local groundwater. At the opposite extreme, some old landfills contain waste in contact with groundwater and, therefore, a landfill cover cannot prevent movement of contaminants to groundwater; however, the landfill may need a cover.

8.2 PERFORMANCE CRITERIA

As explained in Chapter 2, all landfill covers should:

a. Control infiltration of precipitation into the waste
b. Isolate the waste and prevent its movement by wind or water
c. Control landfill gases

Federal regulations contain design requirements for the water flow barrier, the drainage layer, the thickness and function of the soil and plant cover, and other parts of conventional covers. As a result, criterion (a) receives little thought when designing conventional landfill covers to meet these regulations because of the presumption that the mandated barrier is adequate.

Allowable infiltration of precipitation through the cover is likely to be the most contentious requirement for most landfill covers. Because an infiltration criterion is needed for each ET landfill cover, all concerned parties should agree upon infiltration and other performance criteria before cover selection begins. Agreement on cover requirements will then allow use of any cover that provides adequate remediation for the site. The ET landfill cover will satisfy requirement (a) at many sites.

Performance criteria (b) and (c) are easily met by ET landfill covers. Most covers that satisfy the infiltration requirement also satisfy criterion (b), that is, isolation of waste and prevention of its movement. The exception may be in a dry climate where an ET cover that is too thin to isolate the waste can control infiltration; in that case, it is easy to increase the thickness.

Because there is no barrier within the ET cover, it is less prone to collect gas generated within the landfill, creating less need for gas collection. It is easy to install conventional gas extraction systems under an ET landfill cover where needed, for example, for fresh waste, the known presence of toxic gases, or where large volumes of methane are expected. In addition, vertical gas extraction wells inserted through a completed ET cover do not threaten cover performance.

An RB/PB evaluation of a landfill is the first step in establishment of performance criteria and precedes the selection of a cover concept. An RB/PB evaluation of a landfill (Chapter 2, Section 2.2) utilizes the site characterization data and allows application of the best engineering and scientific knowledge to selection of performance criteria.

The RB/PB process includes the following steps:

- Identify releases
- Assess exposure
- Assess risk
- Establish site-specific performance requirements

Because site-specific conditions control the requirements for a landfill cover, the RB/PB process is important for selection of remediation criteria.

8.2.1 COVER REQUIREMENTS

Table 8.2 contains basic requirements for success for conventional and ET covers that meet landfill cover demands. Five of the eight requirements for ET covers differ substantially from those for conventional covers. The ET cover needs site-specific design in the same way that other remediation efforts do.

All the factors listed in Tables 8.1 and 8.2 and others specific to the site may be important for the performance of an ET cover; however, one or more of them may be most important for a particular site. Therefore, site characterization and RB/PB site evaluation are needed to identify the factors that control performance requirements and, thus, are important for the design of a specific ET landfill cover.

TABLE 8.2
Basic Requirements for Success of Conventional and ET Landfill Covers

Conventional Cover	**ET Landfill Cover**
Controls infiltration resulting from precipitation	Controls infiltration resulting from precipitation
Isolates waste and prevent movement	Isolates waste and prevent movement
Good design/construction	Good design/construction
Gas collection usually needed	*Gas collection if needed*
Effective barrier layer	*Adequate precipitation storage*
High soil density	*Low soil density*
Drainage layer	*Robust plant cover*
Barrier layer often assumed to be impermeable	*Requires site-specific design*

8.2.2 ALLOWABLE LEAKAGE THROUGH COVERS

A performance standard or guide is needed for criterion (a), that is, control infiltration of precipitation into the waste, to assist in defining requirements for a landfill site. A reference point for allowable leakage through the cover would be helpful during planning and design.

Recent research suggests that infiltration of precipitation into landfill waste may be beneficial. Hicks et al. (2002) found that increasing surface infiltration into landfill waste by recirculation of waste liquid or by pumping groundwater could *"reduce the time required for biological stabilization of the landfill waste."* The innovative bioreactor landfill requires the addition of extra water to the top of the waste to increase the rate of waste decay (Reinhart and Townsend 1998; ITRC 2006).

The measured leakage rates for conventional landfill covers presented in Chapter 3 provide a basis for estimating the allowable leakage through landfill waste. The measurements of leakage through conventional landfill covers included sites with wide climatic variation (see Table 3.1). Because conventional covers are widely accepted as adequate, these measurements provide guidance for a general allowable infiltration requirement for landfill covers. The measurements summarized in Table 3.1 represent expected performance of new barrier-type covers under good conditions because the experimental sites were carefully built, and only a few years old.

Table 8.3 summarizes annual leakage at sites with more than 300 mm per year precipitation. The conventional compacted-clay barrier covers leaked, on average, 10% of the precipitation falling on the cover. The composite-barrier cover controlled leakage better than the other covers; but it leaked, on average, 2% of the precipitation falling on the cover. The maximum annual average leakage through compacted soil, compacted clay, and composite covers was 20, 25, and 7%, respectively.

It is widely accepted that barrier covers are satisfactory. One may conclude that the currently used barrier covers perform satisfactorily in spite of significant movement of precipitation into the waste.

TABLE 8.3
Annual Percentage of Precipitation Leaking through Conventional Covers at Sites with More Than 300 mm per Year Precipitation (see also Chapter 3, Table 3.1)

		Annual Leakage	
Cover Type	**Sites Number**	**Range (%)**	**Mean (%)**
Compacted-soil barrier	3	1–20	10
Compacted-clay barrier	5	Trace–25	10
Composite barrier	9	< 0.5–7	2

8.2.3 A LEAKAGE CRITERION

The leakage criterion for landfill covers proposed in the following text is based on the measured leakage rates for conventional-barrier landfill covers shown in Table 3.1, and summarized in Table 8.3. The performance measurements demonstrated that conventional covers leak and that some might leak a surprising amount. In spite of the measured leakage quoted here, the author found no evidence suggesting that conventional-barrier landfill covers fail to protect the public health and the environment. This suggests that some leakage is acceptable. Common sense suggests that there is a limit beyond which leakage is too much; however, the author found no guidance on how much that might be.

The following leakage criterion is proposed for municipal waste:

- The average allowable annual deep percolation rate through municipal waste should not exceed 3% of average annual precipitation.
- Where waste decay or other factors require more water, the allowable leakage may be greater.

The proposed criterion is 1% more than the average leakage through composite-barrier covers, but less than half the maximum value. It is less than one-third the average measured for compacted-soil and compacted-clay barrier covers (Table 8.3). The criterion is conservative, yet allows latitude in design and performance.

Average annual precipitation in the United States varies from less than 250 mm to greater than 1500 mm per year (ASCE 1996). Table 8.4 contains typical allowable deep percolation amounts using the proposed criterion.

8.3 COVER TYPE

After establishment of the site characteristics and performance criteria, the next step is to select an appropriate cover type for review. The cover choices should include

TABLE 8.4
Proposed Criterion for Allowable, Average Annual Deep Percolation into Municipal Waste

Annual Precipitation (mm)	Average Annual Deep Percolation	
	(%)	(mm)
200	3	6
500	3	15
1000	3	30
1500	3	45

both conventional and alternative covers, and their characteristics should be compared to site requirements. If a conventional-barrier cover best meets site requirements, the design process reverts to conventional methods.

If an ET cover appears appropriate for the site, the first review for an ET cover should be a regional evaluation using the methods explained in Chapter 7. After selecting an ET landfill cover for a site based on a regional analysis, the next step is preliminary design to ensure that an ET cover will meet the requirements of the site and that adequate soil resources are available.

8.4 PRELIMINARY DESIGN

A preliminary design is needed to justify expenditure of funds for a complete ET landfill cover; it should be inexpensive. Adequate preliminary design should be possible with data gathered during site characterization. The preliminary design should evaluate alternate ET cover designs and expected future performance of the cover to determine whether it will meet the requirements for the site.

8.4.1 Design Model

The model used should be flexible, easy to run, and produce summary data that is pertinent to ET cover design. It should not require calibration or adjustment of model parameters. It should estimate water balance for each day of a 100 year period. The model should stochastically generate future daily weather having statistical variability similar to measured precipitation records at the site. In addition, cumulative and extreme events should be statistically similar to measured events. It should estimate missing soil chemical and physical parameters, and run with readily available soil properties from standard soil surveys. The environmental policy integrated climate (EPIC) model is suitable for both preliminary design and final design of an ET landfill cover (see Chapter 9).

8.4.2 Cover Soil Properties

Soil properties sufficiently accurate and complete for preliminary design are easily available with little or no cost for most sites. The Natural Resources Conservation

Service (NRCS) of the U.S. Department of Agriculture (USDA) has already mapped and measured soil properties for most counties in the United States (USDA, NRCS 2006). They usually defined the soil profiles downward to the top of parent material. Soil scientists and engineers from within and outside the agency reviewed each description for accuracy. They describe typical properties for each soil series, so the soil at a particular site may differ slightly from the USDA description.

The data contained in the standard USDA, NRCS survey are adequate for detailed farm planning and for use in preliminary design of ET landfill covers. The EPIC model (Sharpley and Williams 1990) and the "Hydraulic Properties Calculator" (Saxton 2005; Saxton and Rawls 2005) estimate soil properties not found in USDA soil survey data; they are adequate for preliminary design.

8.4.3 PLANT COVER

Selection of one native grass species should provide an adequate preliminary design. At sites where tree or shrub cover may be the final vegetation, grass data should provide an adequate preliminary design. Both trees and grass get the energy for evaporating water from the sun, both evaporate water to cool the plant, and both utilize stomata as the gas exchange mechanism. Actual ET should be similar between trees and grass cover with full canopies. Chapter 5 contains suggestions regarding sources for data describing plants.

8.4.4 PRELIMINARY COVER THICKNESS

The purpose of estimating minimum cover thickness at this stage of planning and design is to verify that the ET cover will satisfy site requirements when using available resources and to provide a reasonable estimate of soil volumes needed. After this initial estimate of cover thickness, choose a cover type, collect data for final design, and begin the final design, including a new estimate of cover thickness.

8.4.4.1 Sensitivity Analysis and Calibration

Some design recommendations propose use of "sensitivity analysis" to estimate cover thickness (ITRC 2003). Sensitivity analysis is the systematic change in one or more model parameters to determine the resulting change in a parameter of interest. Model developers use sensitivity analysis to guide model revision by showing which of several parameters within the model caused greatest effect on the desired answer; the results of sensitivity analysis should be tested against field measurements. Sensitivity analysis is part of model calibration and testing. The estimation of cover thickness is not "sensitivity analysis." Model calibration or sensitivity analysis during design is inappropriate for several reasons, including the following:

- Adequate measured data is seldom, if ever, available to test the results for the site.
- Because of model complexity, modification of some parameters within a model to fit calibration data may produce unintended consequences and significant errors in model estimates for a particular site.

8.4.4.2 Thickness Estimate

Simple single-equation estimates of cover thickness based on long-term averages are unlikely to capture the effect of limits on water use by plants and on the water balance. Interactions between soil, plants, and weather produce highly variable water use from day to day. The limitations on growth reduce plant water use below the potential for the site on most, but not all days. Water may be used at the optimum rate from one soil layer, but reduced or zero from other layers on any given day. Plant water use may be limited because dry soil, soil temperature, or other factors limit water extraction. A simple equation based on averages is inadequate for estimating cover thickness.

Using an adequate model, perform several model runs with a range of soil thickness to estimate the required soil thickness. The computer model should simulate, as closely as possible, daily plant water use from the ET cover soil, and all terms of the water balance for each day of a minimum 100-year period. The model should be capable of making reasonable estimates with incomplete data, because at this stage of design complete data are seldom available. A comprehensive model meets the requirements. After a suitable model is set up for the first run, it is normally fast and easy to rerun the model to evaluate alternative designs for a particular site. The range of soil thickness should include extremes to verify that an optimum depth was included within the range. Choose the thinnest cover that meets the remediation objectives for the site.

A preliminary estimate of ET landfill cover thickness for a site in Oklahoma City illustrates the process. Table 8.5 shows soil properties found in soil surveys and those estimated by the EPIC model. The plant cover for this preliminary estimate was a monoculture of switchgrass, a plant native to Oklahoma. The model used plant parameters stored within the EPIC database.

TABLE 8.5
Soil Properties Available in Soil Survey Data and Those Calculated by the EPIC Model for Preliminary Estimates of Cover Thickness for an ET Cover at Oklahoma City

Soil Survey		Calculated by EPIC
Sand/silt content (%)	14/43	Clay content
Soil density (Mg/m^3)	1.4	Soil porosity
pH	6.8	Layer thickness
Organic carbon (%)	0.8	Saturated hydraulic conductivity
$CaCO_3$ content (%)	0.4	Aluminum saturation
CEC, CMOL/kg	22	Labile phosphorus
Wilting point (v/v)	0.12	Phosphorus absorption ratio
Field capacity (v/v)	0.37	Nitrate content
Albedo	0.13	SCS curve number for each day
Hydrologic soil group	D	Root zone soil water content

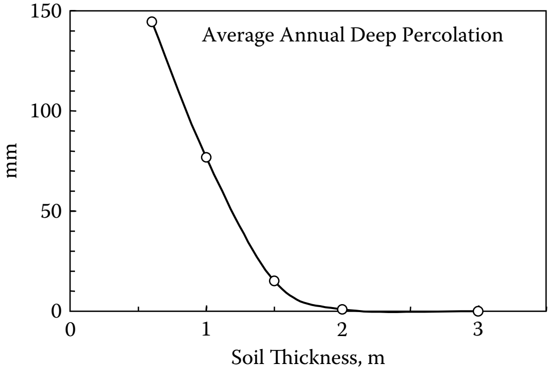

FIGURE 8.1 Effect of cover thickness on the estimated average annual deep percolation at Oklahoma City.

Figure 8.1 shows average annual deep percolation estimates computed from daily estimates by the EPIC model during each day of a 100-year period at Oklahoma City for five different cover thicknesses. The average annual precipitation at the site is about 810 mm. If the 3% guideline (Section 8.2.2) meets site requirements for average annual deep percolation, then a cover producing less than 24 mm of deep percolation is adequate. A cover that is 1.5 m thick is more than needed (Table 8.6), if the available soil has properties similar to those used.

However, before making a final decision regarding cover soil thickness, examine the extreme events expected at the site. Table 8.6 contains data that are useful in examining extreme events. A cover that is 1.5-m thick produced about 224 mm of deep percolation during one year of a 100-year design period; however, the leakage was greater than 100 mm in only 3 years, and zero during 74 years. The 1.5-m-thick cover performed well. A 2-m-thick cover performed very well; it had 99 years of zero deep percolation. A 3-m-thick cover produced no deep percolation; it is much thicker than needed.

TABLE 8.6
Preliminary Estimates of Average Annual Deep Percolation through a Silty Clay ET Cover at Oklahoma City (100 Year Estimate)

Cover Thickness (m)	1.5	2.0	3.0
Average annual percolation (mm)	14.9	0.9	0.0
Greatest annual amount (mm)	224	89	0
Number of years zero or less	74	99	100
Number of years greater than 100 mm	3	0	0

8.5 SITE-SPECIFIC DESIGN

Chapter 4 describes confirmation of the ET landfill cover concept at 13 locations; however, one must apply the concept at other sites where no measurements exist. Successful ET covers utilize soils and plants combined in a system that will control precipitation under the influence of weather at the site and meet all other cover requirements for a particular landfill. Successful use of the ET cover concept at a particular site requires that one understands the factors that control performance of an ET cover. This section presents examples of weather, soil, and plant variability, as well as their integration for application at a particular site.

8.5.1 WEATHER

Daily weather may be the most variable parameter affecting ET cover performance estimates for a particular site. Weather variability from day to day and the magnitude of extreme events have profound influence on performance of landfill covers.

Existing weather records are measurements of past events; it is unlikely that future weather will repeat site historical records. The new cover should meet requirements for the site with unknown future weather. Current engineering design practice assumes that the statistical properties of future climate will be similar to those of accurate existing records. Therefore, stochastically generated daily weather parameters are adequate for design if the generated statistical properties match those from measured records. The preliminary design should provide performance estimates for each day of a 100-year period to provide information about long-term performance of an ET landfill cover. Stochastic estimates of future daily weather generated by a tested model provide a realistic basis for design.

8.5.2 SOILS

Soil properties may vary horizontally on a scale of meters or hundreds of meters. In addition, soil profiles at any spot usually contain multiple layers, each having different properties from the other layers.

The soils of eastern Oklahoma present an example of the differences that may exist between soils near a landfill site. The region has high rainfall, but plants requiring abundant water and deep fertile soils grow poorly on some upland soils. Some upland soils have cemented or acid layers in the profile; they may limit or restrict root growth. Plants growing on upland soils often cannot extend an adequate number of roots into all soil layers to remove the stored soil water; they may suffer drought stress. Some of these soils in their native condition may appear to be poor soil material for an ET landfill cover.

River-terrace soils of eastern Oklahoma present a significant contrast to upland soils. Many are deep, fertile, and have near-neutral pH. The thick river-terrace soils have desirable properties because the source of the sediments that formed them was the fertile, neutral-to-calcareous soils of western Oklahoma, Kansas, and Texas. River-terrace soils have few limitations to plant growth. Plants suited to the climate thrive on river-terrace soils, and they remove water from deep in the soil profile. River-terrace soils may be suitable for use in ET landfill covers with little or no modification.

There are at least three ways to use the available soil resources at or near a site: (1) by using borrow soils that naturally meet requirements, (2) by selection of appropriate layers from local soils, and (3) by modification or mixing locally available soil material.

Upland soils of eastern Oklahoma commonly contain layers of soil that would be suitable for use in an ET landfill cover. Thorough mixing of soil layers may produce soil material that is suitable for ET landfill covers. One must exclude some soil layers, for example, acid or sandy material, from the mixture to ensure suitable cover soil.

Subsoil that meets other requirements may be satisfactory soil material (Chichester and Hauser 1991). Mix suitable subsoil with fertile topsoil, if available; amend the mixture with nutrients and lime, if needed. Properly amended mixtures containing subsoil should be suitable for ET cover soil at many sites.

8.5.3 PLANTS

The definition for the ET landfill cover states that the plants on the cover should be a mixture that is native to the site. Native plants became “native” because they eliminated the competition; as a result, they are well adapted to the climate, soil, plant diseases, and insects found at the site. Plants native to a site are typically a mixture or a community of plants. Success with the ET landfill cover requires that the plant cover grow profusely every year to remove stored soil water quickly. A mixture of native grasses satisfies that requirement. In addition, grasses provide superior soil erosion control.

It is desirable that the plant cover on an ET landfill cover provide green growing vegetation for the longest possible growing season. A mixture of native plants is an excellent way to ensure that plants will be growing when water is available in the soil. Because of the extreme competition among plants during development of the modern “native” plant community, the native mixture includes plants able to grow when the resources for plant growth are available. The resources include soil water, energy, nutrients, and adequate air and soil temperature.

Almost all native plants have the potential to establish a robust root system deep in the soil; indeed, most of them can root deeper than soil and climate allow. The ability of plants growing on the cover to consume the soil water stored in the bottom of the cover depends on their ability to produce a robust root system deep in the soil.

The native grass communities of Oklahoma offer an example of widely differing plants. In eastern Oklahoma, where water supply is abundant, native plants on deep fertile soil include tall prairie grasses and forbs; the mixture produces dense plant mass more than 2 m tall, with roots growing an equal distance into good soil. In the Oklahoma panhandle, where the climate is semiarid to arid, native plants on deep fertile soil include short grasses and associated forbs; the mixture produces a relatively dense growth of plants up to 0.6 m tall, with roots capable of penetrating more than 2 m deep in fertile soil. The difference between native plants found in eastern and western Oklahoma is primarily the result of the water supply available to the plants.

8.5.4 INTEGRATION AND INTERACTION

Chapters 5 and 6 describe individual parts of the technology that controls ET landfill cover performance. However, application of that technology in design introduces complexity because important factors interact with others to limit and control the function of the cover. An adequate design and evaluation of an ET landfill cover for any site employs integration of site-specific properties of plants, soil, and climate into the hydrologic estimates. Plant variables that control cover performance include biomass-to-energy ratio, optimal and minimum temperature for growth, maximum potential leaf-area index, leaf-area development curve, maximum stomatal conductance, critical soil aeration, maximum root depth, nutrient supply, and aluminum toxicity. Daily plant growth and water use respond to soil water content, air temperature, soil temperature, frost, soil salt, disease, and insects. Basic soil variables that control performance include particle size distribution, gravel and rock content, soil density, water-holding properties, pH, CEC, nutrients, heat transfer, and oxygen transfer rate. Weather variables that control performance include solar radiation, precipitation, air temperature dew point, and wind. Weather is often highly variable from day to day.

There are numerous interactions between variables. Accurate estimates require a robust model that uses site-specific factors and their interactions for local plants, soil, and weather; it should correctly use those that limit plant growth and water use. Because of the potential for weather variability from day to day, the model should estimate a complete hydrologic water balance for each day.

A suitable design includes estimates of future hydrologic water balance for each day of a long time period (100 years is often appropriate). With the aid of a good model and site-specific soil, plant, and weather data, one can make a good estimate of the performance of an ET landfill cover at a site.

8.6 FINAL DESIGN

After the preliminary design shows that the ET cover is appropriate for the site, additional measurements of soil properties, assessment of potential plant materials, and collection of the best possible weather data will be needed. Final design is similar to preliminary design, but uses the best site-specific measured information. It should be complete.

Before final design starts, the borrow source for the soil cover should be identified and the properties of the soil measured. Natural soils contain layers; therefore, the designer should select layers that are suitable for mixing and use in the cover. Collect and analyze several samples of each proposed soil mixture separately to provide a measure of the expected variability from the average. Where the properties of the borrow soil vary, the design should be based on soils that provide the least plant available water capacity.

8.6.1 LAYERED SOIL COVERS

It is common to assume that ET cover soils should be uniform mixtures. However, it may be an advantage to place the soil in layers with differing properties to satisfy requirements at some sites. For example, a site with high rainfall may need a small amount of deep percolation. Inclusion of a high clay soil between the depths of 0.2 and 0.5 m with a layer of sandy loam on the surface may substantially increase surface runoff and satisfy site needs. Soils with high clay content near the surface produce more surface runoff than uniform soils, and a sandy loam soil on the surface will ensure robust grass growth. There may be other reasons for using layered soils.

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9 Models for Design and Evaluation

Items of interest in design include estimates of evapotranspiration (ET), surface runoff, and deep percolation. In addition, the evaluation should estimate probability for success, thus requiring daily estimates of performance over many years or decades.

Interacting processes govern ET landfill cover performance; the interaction introduces complexity into the modeling challenge. A model that incorporates all of the important elements of engineering design, including the interactions between weather, plants, and soil, best serves engineering design and evaluation of ET covers. The model used for design or evaluation of an ET landfill cover should produce estimates that allow the user to evaluate the cumulative effect of each day's water balance activity and thus identify critical events.

9.1 A MODEL PHILOSOPHY

All numerical models calculate an approximation to a specific real-world topic of interest. When used for their intended purpose, they are often useful. However, it is inappropriate to use a model created for one purpose to estimate a solution to a problem not within the scope of the original purpose of the model. For example, an economics model is not suitable for design of a landfill cover. In the same way, it may not be appropriate to use a model developed for design of conventional-barrier landfill covers to estimate performance of an ET landfill cover. The engineer should select a design model that is appropriate for the problem.

9.2 REQUIREMENTS FOR ET LANDFILL COVER MODELS

The requirements for model estimates of ET cover performance are different from those for conventional landfill covers. Conventional cover design focuses on barrier-layer design and performance. The focus in an ET cover design is on water balance within the cover as controlled by weather, plant growth, soil properties, and related ingredients.

The ET landfill cover relies on using the soil as a water reservoir, and grass or other plants to empty the reservoir rapidly and completely after a precipitation event. Therefore, the model should accurately estimate daily values of actual evapotranspiration, surface runoff, and deep percolation (ET, Q, and PRK).

9.2.1 WATER BALANCE

The model must solve the water balance within the cover soil. The hydrologic water balance is the accounting of all water entering and leaving an ET landfill cover: a mass balance. The complete mass balance (Chapter 6, Equation 6.1) may be simplified for design as

incoming water = outgoing water, or

$$P = ET + Q + PRK + \Delta SW \tag{9.1}$$

where

P = Precipitation (includes irrigation, if applied)
ET = Evapotranspiration (the actual amount)
Q = Surface runoff
PRK = Deep percolation (below cover or root zone)
ΔSW = Change in soil water (SW) storage

Two terms in Equation 6.1 are not included in Equation 9.1. Within the cover soil, there is little or no lateral flow, and it is assumed zero. Although the error term is not zero, it should be small if one uses a good model, and it is usually impossible to estimate its size. The error term is unknown and dropped from the design equation.

9.2.2 ACTUAL ET

Because the amount of water that may percolate through the cover and into the waste is a major design issue for landfill remediation, estimates of deep percolation (PRK) are important. However, both PRK and Q are much smaller than ET, as illustrated in Figure 9.1. Daily estimates of water balance are central to ET cover design; it is noteworthy that during most days, ET is 100% of the outgoing water from an ET cover. Evapotranspiration controls the amount of water available for deep percolation. The accuracy with which a model predicts ET may define its usefulness in ET

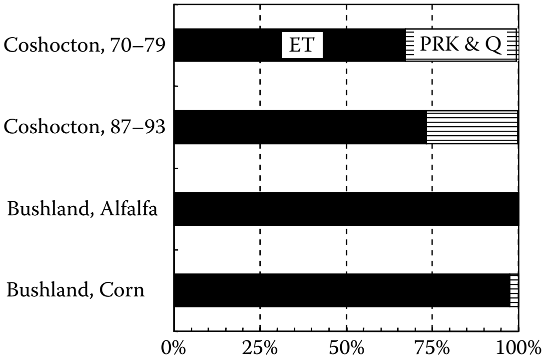

FIGURE 9.1 Annual outgoing water balance for irrigated crops at Bushland, Texas, and for rain-fed meadow at Coshocton, Ohio. (Drawn from data in Hauser et al. 2005. *Environ. Sci. Technol.* 39(18), 7226–7233.)

landfill cover design even though PRK is the focus of cover performance. Because ET is the largest part of the outgoing water balance, its accurate estimation is a high priority for models.

Plant growth, soil water content, root growth and distribution, and related parameters control the amount of actual ET. The way in which a design model estimates these parameters has profound effects on the accuracy of ET estimates. For example:

- There are several methods of estimating potential evapotranspiration (PET). Because ET is calculated from PET, errors in PET estimates affect all other model calculations. Using the wrong method for a site may introduce large errors in estimates of actual ET.
- The density of soil may control the presence, absence, or number of roots found in a particular soil layer. The density of plant roots in a soil layer determines how much water plants can remove from the layer and its rate of removal. A model that does not consider the effect of soil density on root growth may not accurately estimate actual ET.
- Much of the root mass of perennial plants dies during drought or during dormant periods every year. During a growing season, dryness of a particular soil layer may significantly reduce the living root mass in that layer; however, new roots grow when the soil is rewet. The entire root system of annual plants dies each year. Therefore, it is important for the model to estimate the changes and the growth of new roots.

9.2.3 MODELS AND CALIBRATION

Some computer-based models are accurate only after "calibration" for the problem in question. In order to make the model output match calibration data, one or more parameters within the model are changed. A complex model suitable for ET cover design may contain parameters that the user may change. Changes in a few internal parameters may create unexpected or unknown changes in other parts of the model. The calibrated model may match the calibration data but become less accurate for general use.

A model used to estimate performance of an ET cover should not require calibration for two reasons. First, measurements suitable for use in model calibration are seldom, if ever, available for a particular landfill site. Second, a requirement for calibration raises the question, "Does this model truly mimic the real world of a landfill cover?"

9.2.4 DESIGN MODEL REQUIREMENTS

As noted earlier, the focus in an ET cover design is soil, plant growth, and water balance. Scientists use models to estimate the same variables but from a different perspective. Their models often require calibration and trial-and-error testing for every problem; they usually estimate the water balance for a few months or a crop-growing season. Scientists typically use more time to perfect their models for each problem or site than a design engineer can afford.

The factors that affect the hydrologic design of ET covers encompass several scientific disciplines, and all of them should be included in a comprehensive computer model. The model should effectively incorporate soil, plant, and climate variables; include their interactions; and estimate their effects on hydrology and water balance. It should be capable of estimating long-term performance for 100 years or more, and the water balance for each day of the evaluation period. The model should correctly estimate the impact of many ingredients on the water balance, including plant biomass production, effect of soil density, temperature, plant growth stage, and available plant nutrients. Estimates of long-term performance should include an estimate of long-term loss of primary plant nutrients from the ecosystem.

An engineering design model for ET landfill covers should be robust and simulate the entire hydrologic cycle. Model requirements include the following:

1. The model should be tested against field measurements of P, ET, Q, and PRK, and proved to produce small error.
2. It should be tested and proved in different climates.
3. No calibration should be needed; ready to use.
4. Input data should be easily available.
5. It should provide reliable answers with less than optimum input data.
6. The model should estimate missing input data.
7. It should stochastically generate precipitation (rain and snow), air temperature, wind, solar radiation, and humidity from known local parameters.
8. The model should realistically simulate all parts of the water balance equation.
9. It should simulate daily values of all parameters for decades or centuries.
10. It should contain files of basic data inside the model for numerous site-specific climates, plants, and soils.
11. The model should realistically simulate effect of plant growth and biomass production on water balance.
12. Output data should be complete, user-selectable, flexible, and easy to import into other design software.

9.3 POTENTIAL MODEL ACCURACY

Designers, owners, and regulators should understand the limits of accuracy that are reasonable to expect from design, construction, and implementation of remediation measures on landfills. Therefore, knowledge of possible limits to model accuracy is helpful when choosing a model for design.

Field measurements and observations typically provide the basis for model development and testing. Because the accuracy of field measurement is limited, it is unlikely that the models developed from the data will be perfect. In order to improve the quality of the model, the developer should use field measurements from several sources during development and testing, thus reducing the potential error of the model during general use. An understanding of the potential accuracy of field research measurements provides useful insight into possible model accuracy.

Hauser et al. (2005) evaluated measurements by three high-quality lysimeter facilities that measured all parts of the hydrologic water balance. The records included 17 years of measurements from Coshocton, Ohio, and two lysimeter records of 2 years each from Bushland, Texas. These experimental sites are among the best in the world, and the precision of the lysimeters was better than that of a single class-A rain gage measurement. The lysimeter at Coshocton is sufficiently sensitive to provide accurate measurements of daily ET, and those at Bushland are capable of measuring hourly values of ET. The precision of the Coshocton and Bushland lysimeters was 0.25 and 0.045 mm/day, respectively. The data were independent measurements of all parts of the water balance; as a result, one can readily estimate measurement errors. The annual water balance errors from these high-quality lysimeter facilities, with widely differing climate, ranged between 5 and 15% of precipitation, measured by a standard rain gage at each site. Model developers usually use measured data from several sites during development and testing. Models developed from measurements at several locations are expected to be more accurate for general use than those developed at a single site. As a result, one should expect annual total water balance estimates by good models to be in error by about 5%, with possible errors up to 10% of annual precipitation.

9.4 MODELING SOIL WATER MOVEMENT

In order to estimate deep percolation below a soil profile, it is first necessary to estimate water movement within the soil profile. There are two leading methods to estimate water flow within the soil. Some numerical programs compute water flow within the soil using the "Richards' equation." These models are sometimes called *theoretical* or *scientific* models because they use the Richards' equation. Other models employ "water storage routing" to simulate water movement within the cover.

9.4.1 RICHARDS' EQUATION

The "theoretical" models utilize numeric approximations to a complex set of equations based on Richards' equation (Richards 1931). Warrick (1990) discusses both the development and status of this equation. No one has mathematically solved the equation, but assumptions allow a numeric solution. Warrick (1990) presents four different forms of Richards' equation. Numeric methods employ numerous calculations using complex equations; therefore, computer simulation is required for their solutions.

Important assumptions are used to allow numeric solutions for the Richards' equation; they may compromise the theoretical basis of the equation. They include the following:

1. Darcy's law is incorporated into the solution.
2. The density of water is constant.
3. A unique relationship exists for each soil between water content (theta) and water pressure (head) for unsaturated soil.
4. A unique relationship exists for each soil between water content (theta) and unsaturated hydraulic conductivity (K_{unsat}).

Darcy's law was developed for saturated sand filters. ET cover soils are unsaturated soil; thus, the assumption that Darcy's law applies may be questionable. The density of water in unsaturated soil is beyond the scope of this book.

When applied to the ET landfill cover problem, the definition of the relationship between theta and head or between theta and K_{unsat} is particularly troublesome. The relationships are logarithmic, and small changes in water content may cause large changes in the value of head or K_{unsat}. Small changes in particle size distribution, particle arrangement, organic content, or soil density can significantly alter these relationships. In addition, the soil within an ET cover or natural field is not homogeneous. It is difficult to define these logarithmic functions with sufficient accuracy for use in model estimates of ET cover performance. To add to the difficulty, the relation between these parameters is different for the wetting and drying soil situations.

There are other assumptions, but these are important and serve for discussion purposes. In spite of the possible discrepancies introduced by the assumptions, the numerical solutions to Richards' equation have produced good results when applied to scientific studies of unsaturated flow that are limited in time and space. Richards' equation is superior to other methods in many applications; however, it may or may not be superior for engineering design of ET covers.

9.4.2 Water Storage Routing

Some models use water storage routing to simulate water movement through the soil. This section describes water storage routing by the Environmental Policy Integrated Climate (EPIC) model; other models use similar methods.

Within the model, flow out of a soil layer occurs when the soil water content exceeds field capacity. Water drains downward from the layer until the storage returns to field capacity. The saturated hydraulic conductivity controls flow rate through the layer. The routing process applies layer by layer from the surface downward through the deepest layer.

Because the hydraulic conductivity of some layers may be lower than that for layers above them, the routing scheme can create the impossible situation where the water content of the layer exceeds the pore volume. For that situation, a back pass upward moves water into upper layers until none holds more water than the volume of the pore space.

EPIC may move water upward from a layer if that layer's storage exceeds field capacity, but movement is dependent on the water tension in that layer and the layer immediately above. When the water content of all layers is less than or equal to the field capacity, the water storage routing method does not allow water to move upward through the profile. The water storage routing method assumes a simplistic model of water flow within the soil. In spite of its limitations, this method performs well in the EPIC and other models.

9.5 PREVIOUS MODEL EVALUATIONS

There are several reports of model evaluations for vegetative landfill covers. One report compared 18 models with one another and evaluated them against incomplete field measurements. They stated, "*Drainage could be estimated to within about*

±64% by most codes" (Scanlon et al. 2002). Others evaluated one or more models (Roesler et al. 2002; Khire et al. 1999; Khire et al. 2000; Choo and Yanful 2000; Anderson et al. 1993).

These investigations had common characteristics. All compared model estimates against predictions by other models or incomplete field measurements of short duration. Even though actual ET is the largest and most important part of the site water balance, none measured it; instead, they either calculated potential ET from weather measurements or estimated actual ET by difference from the other measurements. None of the investigators assessed the accuracy of the measurements that they used to test model accuracy.

Neither the models nor the tests met the requirements for designing ET landfill covers contained in Section 9.2.4. Although these comparisons may be useful to model developers or others, none provided recommendations that are useful to the landfill cover design engineer.

9.6 EVALUATION OF THREE MODELS

This section compares estimates by three models with excellent quality field measurements made by three lysimeters at two locations. The models are (1) the Hydrologic Evaluation of Landfill Performance (HELP) model, version 3.07 (Schroeder et al. 1994a,b), (2) the Environmental Policy Integrated Climate (EPIC) model, version 8120 (Mitchell et al. 1998; Sharpley and Williams 1990; Williams et al. 1990; Williams 1995), and (3) the HYDRUS-1D version 3.0 (Simunek et al. 2005). The HELP and EPIC models are engineering models; HYDRUS-1D was developed as a scientific model, but it has been used to solve engineering problems. These models are uniquely different from one another and represent three classes of models. The developer and others extensively tested each of them; they were widely acclaimed for their intended use.

The purpose was to evaluate fully developed and tested models for use in engineering design of ET landfill covers. The models estimated the major input and output terms of the water balance (P, ET, Q, and PRK). The model estimates were compared to independent field measurements of all terms in the water balance. The accuracy of the field measurements was known.

9.6.1 HELP MODEL

The HELP model was developed during the early deployment of barrier landfill covers. It is an engineering model designed for analysis and design of barrier-type landfill covers. It is widely used and accepted for that purpose. The primary purpose of the HELP model is to provide water balance estimates with which to examine the expected performance of barrier design alternatives and the resulting effect on landfill contents.

The HELP model uses climate, soil, and design data to estimate daily landfill hydrologic performance as expressed by surface storage, snowmelt, runoff, infiltration, ET, soil moisture storage, leachate recirculation, and leakage through barrier layers. It is capable of modeling landfill systems for up to 100 years. The HELP model was extensively tested during development; however, it failed to meet expectations for the evaluation of vegetative covers (Benson and Pliska 1996; Khire et al. 1997).

9.6.2 EPIC MODEL

The EPIC model is an engineering model designed to estimate all parts of the daily water balance, soil erosion, plant production, and soil's physical and nutrient status. The development of EPIC began in 1981; from the beginning, it was built for use on ungaged watersheds. EPIC estimates the hydrologic water balance, including all terms in Equation 9.1. It uses a daily time step to simulate climate and hydrologic parameters for a wide range of soils, climates, and plants. EPIC uses readily available input data and can simulate hydrologic response for hundreds of years.

The EPIC model was tested for water balance estimates in dry and wet climates, including sites with significant accumulation of snow in winter. Gassman et al. (2004) cite 200 research papers reporting testing and use of the EPIC model worldwide. Testing of the EPIC model against measured field data demonstrated that it estimated PRK with satisfactory accuracy (Chung et al. 1999; Chung et al. 2001; Hauser et al. 2005). In addition, Meisinger et al. (1991) offered convincing evidence that EPIC estimates PRK accurately (see Figure 9.2).

EPIC has no easy provisions to model barrier layers, although it would be possible to specify soil layers with very low hydraulic conductivity. It can estimate lateral flow; however, it would be difficult to describe layer properties for solid waste and the barrier-layer -drainage system under the waste.

9.6.3 HYDRUS-1D MODEL

HYDRUS-1D is primarily a scientific model, although it has been used to solve engineering problems. The model numerically solves Richards' equation for variably saturated water flow and convection-dispersion type equations for heat and solute transport. HYDRUS-1D is available in three versions: one-, two-, and three-dimensional water, heat, and solute flow. HYDRUS-1D is the one-dimensional model and

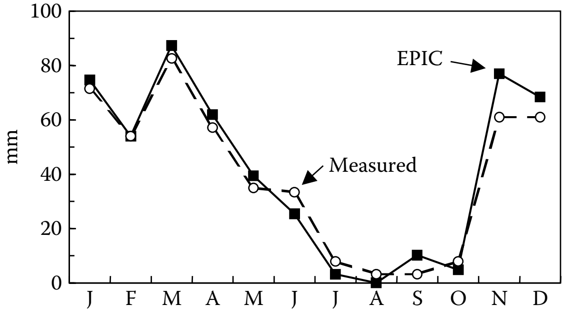

FIGURE 9.2 Lysimeter measured, monthly percolation during 3 years at Coshocton, Ohio, compared with estimates by the EPIC model. (Drawn from data in Meisinger et al. 1991. *Proceedings, Cover Crops for Clean Water.* Soil Conservation Society, Ankeny, Iowa, pp. 57–68.)

is most suitable for ET landfill cover design. It is described in the manual and in the online Web page, *PC-Progress Discussion Forums* (Simunek et al. 2005).

HYDRUS-1D estimates actual ET; however, the user must separately calculate and enter daily values of precipitation, potential soil evaporation, and potential plant transpiration. The user obtains actual ET from the model output by adding the model estimates for "actual root uptake" and "actual surface evaporation." It estimates infiltration with a model-supplied infiltration equation, and surface runoff as the difference between precipitation and infiltration. HYDRUS-1D is sensitive to time-step definition, and may require iterative runs to find an acceptable time-step definition for a particular problem.

9.6.4 MODEL DIFFERENCES

There are significant differences between the models. The EPIC model contains a complete plant growth model, as well as hydrological estimates. The others provide less complete plant growth simulation.

The estimate of ET dominates hydrologic modeling accuracy, because it is the largest part of the water balance and it controls the size of the other terms estimated by the model. The mass of plant roots in a soil layer limits the amount of water that plants can remove from the layer during each day; therefore, root mass and rate of root growth are important for accurate ET estimates. The stage of plant growth, soil density, and temperature control root mass and growth rate processes. Table 9.1 shows the differences between model characteristics that are important to root growth estimates.

The HELP model treats frozen soils as impermeable; however, the EPIC model treats them as having reduced permeability. The HYDRUS-1D model allows snow accumulation, but the manual does not indicate how it handles infiltration into frozen soil. These differences may significantly affect water balance estimates.

Both EPIC and HELP are engineering models that estimate all hydrologic terms important to ET landfill cover design. They have different origins, but both evaluate the hydrologic cycle and satisfy basic requirements for engineering design. The HELP model was designed to evaluate barrier covers; EPIC was designed to simulate the water balance in a soil profile in response to weather, plant growth, and soil

TABLE 9.1
Characteristics of the EPIC, HELP, and HYDRUS-1D Models That Are Important for Root Growth Estimates

Characteristic	EPIC	HELP	HYDRUS-1D
Actual root growth[a]	Yes	No	Y/N[b]
Soil density vs. root growth	Yes	No	No
Soil temperature vs. root growth	Yes	No	No

[a] Root growth in response to season, soil conditions, and plant parameters.

[b] Estimates root growth one time, and no further change.

properties. The HYDRUS-1D model began as a scientific model for soil physics investigations; it does not share the same focus as the other two.

9.7 MODEL TEST DATA

The models were tested against accurate field measurements made by the Agricultural Research Service (ARS) of the U.S. Department of Agriculture (USDA) at two locations. At Coshocton, Ohio, the ARS measured the hydrologic response of meadow with a lysimeter for a total of 17 years. At Bushland, Texas, ARS measured the hydrologic response of alfalfa and corn with two lysimeters for 2 years.

At both locations, the investigators measured all parts of the water balance directly (P, ET, Q, and PRK). The lysimeters measure ET and P by weighing the mass of the lysimeter each hour of the day or more often. Percolation from the soil and surface runoff were continuously measured. The measurements of Q and PRK were independent of each other and the ET and P measurements. These model tests used daily measurements of each parameter of the water balance. Hauser et al. (2005) described the data.

9.7.1 COSHOCTON DATA

ARS, USDA personnel made the Ohio measurements at the North Appalachian Experimental Watershed (NAEW). The site is located about 16 km (10 mi) northeast of Coshocton, Ohio, at 40.4° N latitude and 81.5° W longitude. The vegetation was meadow and similar to plant cover that might be established on an ET landfill cover in that region.

The dimensions of the soil block contained in the lysimeter are 4.3 m (14 ft) long, 1.9 m (6.2 ft) wide, and 2.4 m (8 ft) deep, with the long dimension up- and downhill. The lysimeter soil block is an undisturbed natural soil profile from the site; it includes bedrock in the bottom layers, thus ensuring natural percolation processes. The land slope is about 23%, and the lysimeter precision was 0.25 mm/day. The lysimeter is similar to that shown in Chapter 6, Figure 6.3.

Precipitation, air temperature, humidity, wind, and solar radiation measurements were available from a nearby weather station, and precipitation was measured at the site. Percolation outflow was about 31% of precipitation (Harrold and Dreibelbis 1958,1967; Malone et al. 1999).

9.7.2 BUSHLAND DATA

Personnel at the Conservation and Production Research Laboratory, ARS, USDA, made the Texas measurements. The lysimeters were located near Bushland, Texas, on the Texas High Plains in a semiarid climate at 35.2° N latitude and 102.0° W longitude (about 24 km west of Amarillo). The two weighing and recording monolithic lysimeters contained undisturbed columns of Pullman clay loam soil with surface area of 9 m^2. The soil depth was 2.3 m. Irrigated corn grew in one lysimeter during 1989 and 1990, and irrigated alfalfa grew in the other lysimeter during 1996 and 1997.

Precipitation, air temperature, humidity, wind, and solar radiation measurements were available from a weather station operated at the site over irrigated grass and from another station at laboratory headquarters located over mowed native grass (Marek et al. 1988; Howell et al. 1989). In spite of heavy irrigation, percolation outflows were small or zero from these lysimeters.

9.8 COMPARISON OF THREE MODELS

The models used available data, duplicating their use in an engineering design. The models were not calibrated, even though measured results were available. They differed in their input data needs and their handling of plant, plant–soil interaction, and ET estimates.

The estimates by the models and the measured values used to test them were daily values. The daily variability in weather created significant variations in ET, Q, and PRK in both the measurements and model estimates. Monthly and annual sums are less variable and are more easily statistically evaluated and compared to measurements. The comparisons between measured values and the model estimates are based on annual or monthly sums of ET, Q, and PRK.

9.8.1 DATA EVALUATION

Many preferred statistical measures for evaluating hydrological data are based on the assumption that the data came from a normally distributed population. Hauser et al. (2005) evaluated the input data for Coshocton and Bushland and found that the annual totals and the maximum month totals for each year for ET and PRK were normally distributed; but the Q measurements were not normally distributed. Therefore, annual and monthly averages of the model estimates for ET and PRK, and the median values for model estimates of Q are compared with similar data from the measurements. It is also useful to examine the total value and associated error of each term in the water balance over the duration of the measurements.

The reference value used to estimate the "percentage error" term influences the interpretation of results. For example, the error of the PRK estimate by HELP for corn at Bushland is −16.5 mm/year. The percentage error based on the measured PRK value is −75%, but it is only −2.0% if based on precipitation. The intuitive assumption is that percentage error should be based on measured parameter values. There are valid reasons for also examining error estimates based on total precipitation, including the following:

- The relative size of the water balance terms is important. Even though the error of PRK, for example, may be only a few millimeters, the percentage error may be large when calculated from a small measured amount.
- Small parts of the hydrologic water balance, such as PRK, are measured directly and independently in lysimeter measurements. However, model estimates of PRK are not independent; they contain increased error caused by errors made by the model in estimating the larger terms.
- It is important to define the error in a way that is consistent with the intended use of the model estimates. A major concern in landfill cover design is the fraction of annual precipitation that may infiltrate through the cover and into the waste.

Error estimates presented here used both measured parameter values and precipitation as reference values. Table 9.2 contains average annual estimates of ET, Q, and PRK by the EPIC, HELP, and HYDRUS-1D models, as well as the comparable measured values; error estimates are based on measured values. Table 9.3 contains totals for the period of record shown (10, 7, 2, and 2 years), and error estimates are based on precipitation.

9.8.2 ET ESTIMATES

All of the models estimated ET with errors less than 4% for alfalfa at Bushland (see Tables 9.2 and 9.3). Both EPIC and HELP models accurately estimated ET for corn at Bushland. The Coshocton measurements provide important tests because of their length; neither the HELP nor HYDRUS-1D models estimated ET with adequate accuracy for the Coshocton data. Only the EPIC model consistently estimated average annual ET with small errors for all of the field measurements, as shown in Tables 9.2 and 9.3.

9.8.3 Q ESTIMATES

Surface runoff (Q) is more difficult to estimate than ET because the methods available to estimate Q are less accurate than those available for ET. Because the measured amount is small, relatively small errors in runoff amount result in large percentage errors when compared against the measured amount.

It is natural to think that the difference between rainfall rate and infiltration rate should produce superior estimates of Q. However, it is not that simple. Instantaneous rainfall rates are generally unavailable; therefore, the design engineer must use total daily rainfall in model estimates. The infiltration rate decreases exponentially with time during a storm for any soil; in addition, the curve relating infiltration rate and time varies with the beginning soil water content and unknown factors. The infiltration rate may be controlled by soil properties, or it may be controlled by the soil crust. Soil crusts typically have different properties compared to the soils from which they are created. Available methods do not adequately explain the soil crust issue. As a result, the "curve number method" is widely used, perhaps because it is easier to understand, and provides estimates equal to or better than those of other methods. The EPIC and HELP models used the curve number method in these tests. EPIC has the alternative of using an infiltration method. HYDRUS-1D uses only an infiltration equation method. The models produced poor estimates of Q, except for Bushland, where the lysimeters allowed no runoff; it was easy to set each of the three models to produce zero surface runoff (Table 9.2). The error in total Q estimates by each of the models was small when measured against precipitation, because Q is so much smaller than P (Table 9.3).

9.8.4 PRK ESTIMATES

The EPIC model consistently produced the smallest errors in PRK estimates (Table 9.2). EPIC errors were all less than 4% of measured precipitation (Table 9.3).

TABLE 9.2

Annual Average of ET and PRK, and Median of Annual Values of Q for Coshocton and Bushland Measurements and Model Estimates

Measured					Model Estimates					
P	ET	Q	PRK		ET		Q		PRK	
Mean (mm/yr)	Mean (mm/yr)	*Median* (mm/yr)	Mean (mm/yr)	Model	Mean (mm/yr)	Error[a] (%)	*Median* (mm/yr)	Error (%)	Mean (mm/yr)	Error (%)
				Coshocton, Meadow, 1970–1979						
1107	767	4.4	368	EPIC	753	−2	3.4	−23	318	−14
				HELP	547	−29	71	+1500	492	+34
				HYDRUS	1000	+30	<0.1	−98	106	−71
				Coshocton, Meadow, 1987–1993						
1024	764	1.2	276	EPIC	732	−4	0.0	−100	259	−6
				HELP	570	−25	7	+500	429	+55
				HYDRUS	984	+29	<0.1	−92	31	−89
				Bushland, Alfalfa, 1996 and 1997						
1476	1514	0	0	EPIC	1460	−4	0	0	0	0
				HELP	1478	−2	0	0	71	>+100
				HYDRUS	1532	+1	0	0	2	>+100
				Bushland, Corn (Growing Season)[b], 1989 and 1990						
832	809	0	22	EPIC	867	+7	0	0	31	+41
				HELP	869	+7	0	0	5.5	−75
				HYDRUS	506	−37	0	0	0.4	−98

[a] Percentage error based on measured parameter value.

[b] Bushland corn: average of May 1 to December 31 only for 1989 and 1990.

TABLE 9.3
Total P, ET, Q, and PRK Measured at Coshocton and Bushland for the Periods Shown, and the Model Estimates

Measured					Model Estimates					
P	ET	Q	PRK		ET		Q		PRK	
(mm)	(mm)	(mm)	(mm)	Model	(mm)	(%)	(mm)	(%)	(mm)	(%)
				Coshocton, Meadow, 1970–1979						
11,067	7,670	63	3,678	EPIC	7,532	−1	312	2	3,177	−4
				HELP	5,472	−20	669	6	4,917	11
				HYDRUS	9,997	−21	0.2	−1	1,064	−24
				Coshocton, Meadow, 1987–1993						
7,170	5,351	14	1,930	EPIC	5,125	−3	185	2	1,815	−2
				HELP	3,987	−19	159	2	3,005	15
				HYDRUS	6,890	22	0.8	<−1	214	−24
				Bushland, Alfalfa, 1996 and 1997						
2,953	3,028	0	0	EPIC	2,920	−4	0	0	0	0
				HELP	2,957	−2	0	0	142	5
				HYDRUS	3,065	1	0	0	2	<1
				Bushland, Corn (Growing Season)^2, 1989 and 1990						
1,664	1,616	0	44	EPIC	1,734	7	0	0	62	1
				HELP	1,738	7	0	0	11	−2
				HYDRUS	1,013	−36	0	0	0.8	−3

[a] Percentage error based on total precipitation.

[b] Bushland corn—totals for May 1 to December 31 only during 1989 and 1990.

The HELP model produced errors in PRK estimates between 34 and 100% when evaluated against measured values (Table 9.2). The HYDRUS-1D model produced errors in PRK estimates between 71 and 100% when evaluated against measured values (Table 9.2). All models produced smaller errors in PRK estimates when they were compared with P (Table 9.3).

9.8.5 MONTHLY ESTIMATES

A model should mimic the measured natural pattern as well as the annual or total amount of ET, Q, and PRK. Figures 9.3 and 9.4 present the average monthly ET and PRK estimates by each model along with the measured values during the 10 year period 1970–1979 at Coshocton.

In North America, ET for the month of June is generally higher than for any other month, but the measured ET was low in the Coshocton record, as seen in Figure 9.3. June is often the month for the first hay harvest from meadow, which is most likely the cause of the reduced average ET measured during this month. The EPIC model closely approximated the measured amounts in all months except June. The HELP model underestimated ET during May through September, the critical

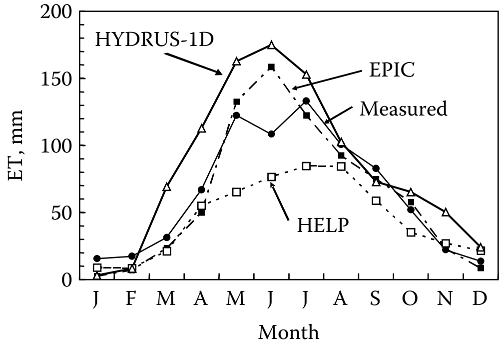

FIGURE 9.3 Monthly ET at Coshocton during 1970–1979.

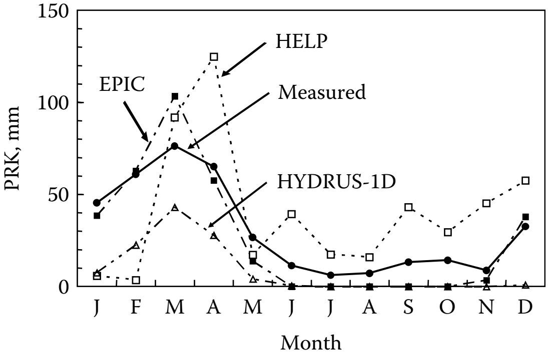

FIGURE 9.4 Average monthly deep percolation at Coshocton during 1970–1979.

growing season months, when maximum energy is available to evaporate water. The HYDRUS-1D model estimated too much ET for March through July, and again for November. The EPIC model estimated ET with little error during the whole year; the others did not.

Figure 9.4 presents the average monthly PRK estimate by each model with the measured value for each month during the 10 year period 1970–1979 at Coshocton. The EPIC model estimates generally paralleled the measured amounts, whereas the other models produced significant departures from the pattern. Figure 9.2 presents a comparison of the measured PRK from a different Coshocton lysimeter along with estimates by the EPIC model (Meisinger et al. 1991).

9.9 MODEL CHOICE

This discussion refers to model choice for the design of ET landfill covers. The HELP model was developed and tested for design of barrier covers; it is a good model for that purpose, but not for ET cover design. The HYDRUS-1D model was developed and tested for use in scientific investigations of water, solute, and heat flow in soils; it is a good model for that purpose, but has proved not useful for ET cover design.

9.9.1 HELP MODEL

New users should find the HELP model relatively easy to learn. The output data are suitable for engineering design use. Even though this model is superior for barrier-type landfill cover design, it has characteristics that limit its usefulness when used for ET cover design:

- Soils descriptions are incomplete.
- It describes the root system by a single parameter, "evaporative depth."
- It does not account for the effects of soil density or temperature on soil water use.
- It contains insufficient plant parameters that are important to ET estimates.

9.9.2 HYDRUS-1D MODEL

New users may encounter difficulty in learning to use this model; however, extensive help is available at the model Web site. The output data may not be easy to use for some engineering design purposes. It has characteristics that limit its usefulness when used for ET cover design. For example:

- Soil descriptions do not include plant nutrient information.
- It assumes that the plant root system is static for all time.
- It contains insufficient plant parameters that are important to ET estimates.

A significant strength of the HYDRUS-1D model is its use of Richards' equation to estimate water flow in unsaturated soils.

9.9.3 EPIC Model

The EPIC model is suitable for ET landfill cover design and produces water balances with accuracy similar to that of high-quality hydrologic measurements. EPIC is a flexible model and can create multiple runs and different landfill cover designs with little additional effort after it is set up for the site. The model output data is highly satisfactory for engineering design; it allows the user to select the amount (daily, monthly, annual, or other) and content of the output numbers.

The EPIC model is flexible because there are multiple independent input data files. Each of them may be used in different estimates for a given site. Therefore, the flexibility of EPIC requires organization by the user; assistance is available from the source. Appendix C contains additional discussion of model use and sample forms to assist the EPIC 8120 user.

9.9.4 Model Conclusion

Several models estimate water balance or water movement within the soil. This evaluation represents a snapshot in time; each of these models may be redeveloped or improved, and other models may appear that should be considered. Of the three models tested, the EPIC model appears to be best suited for ET landfill cover design and evaluation.

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10 Design Components

This chapter covers several design components that are pertinent to evapotranspiration (ET) landfill cover design.

10.1 WEATHER

Basic weather records may contain daily or hourly measurements of total precipitation, and maximum and minimum air temperatures. Records that are more complete include daily or hourly measurements of precipitation, air temperature, dew point, wind run, and total solar radiation. Daily values of weather parameters are adequate for ET landfill cover design.

10.1.1 PRECIPITATION

The most basic, and perhaps the most important, input data used in design or evaluation of an ET landfill cover is the precipitation record for the site. Precipitation input data is more important to ET cover design than to conventional cover design because water balance estimates indicate probable success or failure for the ET cover. An error in precipitation estimate is less important to conventional-barrier cover design because the barrier is assumed impermeable and the drainage layer above the barrier is designed to remove all water that percolates through the cover soil. However, the accuracy of the precipitation data used limits the accuracy of ET cover performance estimates.

The only choice available to the designer is to use the longest and most accurate precipitation record available. Because it is difficult to assess the accuracy of precipitation data for a given site, the common practice is to accept records of the U.S. Weather Bureau, U.S. Department of Agriculture (USDA) or state agricultural experiment stations, and similar trustworthy sources. An understanding of possible accuracy of precipitation data provides insight into possible accuracy of performance estimates (see Chapter 6).

10.1.2 SOLAR RADIATION

Solar radiation measurements are generally available for a shorter time than other measurements because instruments sufficiently accurate and robust for routine measurements were unavailable until recently. Solar radiation at the top of the earth's atmosphere is relatively constant from year to year. It varies seasonally as the earth rotates around the sun and the earth's axis tilts relative to the sun. Clouds, thickness of the atmosphere as affected by land surface altitude, pollution, and other factors reduce the radiation falling on the earth's surface at a specific site. However, solar radiation at a particular site on days with little or no cloud cover is relatively predictable from year to year. As a result, the variability of solar radiation at a site is less than for other weather parameters. Therefore, a relatively short record of solar radiation provides an adequate basis for stochastic estimates of future solar radiation. This situation is fortunate for the design engineer because, in any case, the engineer must use available data.

10.1.3 LENGTH OF WEATHER RECORD

An adequate measurement of the climate at a site utilizes the longest available weather record; it should contain measurements for at least 30 years. Annual precipitation records from Coshocton, Ohio, illustrate the importance of long climatic records. The 35 year average annual precipitation is 940 mm (37 in.); one 5-year period averaged 88% of the overall average, and another averaged 115%. A short record is unlikely to provide accurate estimates of average values or daily statistical variability of the measurements.

10.1.4 WEATHER RECORD UNCERTAINTY

Daily weather measurements are a sample of the long-term climate. Existing weather records do not contain all of the extreme events that are possible for a site; but extreme events are important to estimates of possible future performance of an ET landfill cover.

Weather records of at least 50 years duration usually estimate the mean values relatively well, but may not include extreme events that are important to ET cover design. Figure 10.1 illustrates the effect of the length of weather records on the size of extreme precipitation events. The annual precipitation amounts found in a 100 year precipitation record are compared with a 50 year subset of the record for a site in southeastern Oklahoma. Although the mean values are similar, the maximum annual rainfall in the 50 year record (1880 mm) is about 15% less than the maximum for the 100 year record.

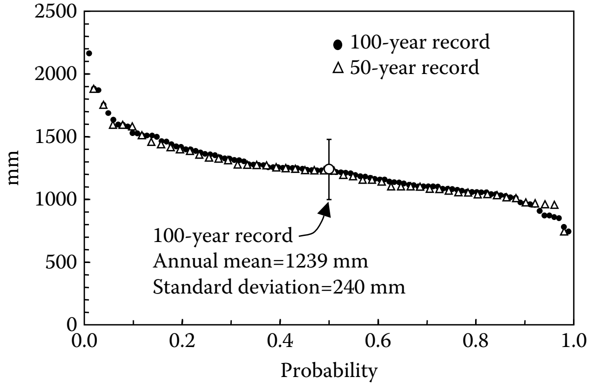

FIGURE 10.1 Extreme events found in 50 and 100 year annual precipitation amounts for southeastern Oklahoma.

There is uncertainty in all of the other parameters measured and recorded in weather records. The design of an ET landfill cover should include estimates of the effect of future extreme events and variability because the cover should function for decades or centuries longer than existing weather records.

10.1.5 FUTURE WEATHER

We expect the cover to control precipitation under the influence of future weather; therefore, both preliminary and final design should be based on reliable estimates of future weather. Sequences of recorded weather events are unlikely to repeat, and future extreme events may be greater than recorded measurements. Because future weather is unknown, a suitable alternative is the use of a statistically based estimate of future weather and its variability.

The statistical properties of available weather records may be used to make a reasonable estimate of future weather variability. Annual precipitation records for Stapleton Airport, Denver, Colorado, provide an example; measured precipitation data for 45 years are available for that site. The Environmental Policy Integrated Climate (EPIC) model utilized weather statistics for the site and stochastic processes to generate precipitation and other weather parameters for a period of 100 years. Figure 10.2 shows the measured annual precipitation amounts for 45 years and each of the 100 years of annual precipitation stochastically generated by the EPIC model. The generated precipitation follows the measured amounts closely, except for extreme events. The mean of the generated data is less than 1% different from the mean of the measurements.

Extreme events are important to ET landfill cover design. The generated maximum value of annual precipitation for Stapleton Airport is 18% larger than the measured maximum value (Figure 10.2). The use of generated weather data extending over 100 years or more provide a basis for a conservative yet realistic estimate of future ET landfill cover performance because it generates future extreme events from statistical parameters derived from measurements at the site or appropriate nearby sites.

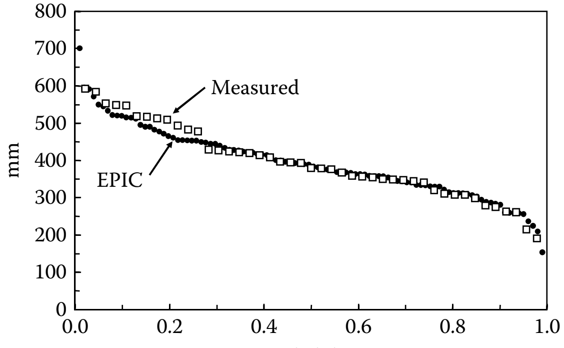

FIGURE 10.2 Measured annual precipitation compared to stochastic estimates by the EPIC model for Stapleton Airport, Denver, Colorado.

10.2 SOIL

The accuracy of soil properties used in design and construction can determine success or failure for an ET landfill cover. Soils vary from site to site; indeed, they may vary significantly within a borrow pit. The book series by the Soil Science Society of America, referenced in Appendix A, provides useful and practical descriptions of soil properties that are important to ET landfill cover design and evaluation.

10.2.1 Natural Soils

Most soils contain layers; they may be thick or thin, and the number of layers varies greatly. Generally, the layers are parallel to the surface because the weathering and other forces that create soils originate at the surface. Soil may form on relatively recent wind or water deposits, and/or ancient geologic materials. It is the biologically active layer found above parent material, and its thickness may vary from a few centimeters to several meters. Figure 10.3 is a photograph of a soil profile. The elevated soil organic matter created the dark color of the upper layer, suggesting that this soil formed in a moist, cool climate. The properties of soil layers may differ significantly over vertical distances of a few millimeters; yet some soils contain uniform soil layers that are meters thick.

FIGURE 10.3 Typical soil profile. (Photo courtesy of USDA, Agricultural Research Service.)

10.2.2 SOIL DESCRIPTIONS

Soil properties should be described by measures important to plant growth because the ET cover relies on plants to remove water from the cover soil. The USDA developed widely used and accepted descriptions of soil properties; the focus of their work is plant growth. Other soil descriptive systems exist; those focused on plant growth are similar to the USDA system. Some soil descriptive systems focus on the use of soil as a construction material and not on plant growth; although useful for construction, they have limited use in plant growth endeavors. The USDA soil descriptive system is pertinent to ET cover design.

One of the most important soil descriptors is particle size distribution. The USDA defines soil as material less than 2 mm in size (#10 ASTM sieve) and soil particle sizes for soil separates as follows (SSSA 1997; Gee and Or 2002):

- Clay: <0.002 mm
- Silt: 0.05–0.002 mm
- Sand: 2.0–0.05 mm

They also define material larger than 2 mm as gravel, coarse sand, or rocks. These large particles add little or nothing to the productive properties of the soil, and they reduce its water-holding capacity in proportion to the volume that they occupy. When coarse materials are included in the ET cover soil, the water-holding and other soil properties need adjustment.

The surface area of soil particles exerts major control over soil properties that are important to plant growth, including water-holding properties, ion exchange, microbial attachment, heat transfer, soil aggregation, and contaminant adsorption. The specific surface area of soil materials is the surface area per unit of soil mass, expressed as square meters per kilogram. The total surface area includes the area on the surface of clay lattice layers within clay minerals. The specific surface area is large for clay particles and organic matter but diminishingly small for sand particles. Pennell (2002) summarized measurements of total specific surface measured by the EG/EGME method (Table 10.1). The specific surface area of soil is important; soil with large specific surface area holds and recycles large amounts of plant nutrients and tends to have large plant-available water-holding capacity.

In the absence of specific surface measurements on a particular soil, an important parameter is the amount and kind of clay contained in the soil mass. The kind and amount of clay contained in soil indicates plant nutrient storage capacity and strongly influences soil water-holding properties.

10.2.3 SOIL DESIGN DATA

Usually, ET cover soil will be a mixture of natural soil layers and may include subsoil. The following discussion provides a framework for evaluating soils.

The first steps in a preliminary design include an inventory of soils found near the site and available for use in the cover. The designer needs an estimate of soil

TABLE 10.1
Total Specific Surface Area of Selected Materials by the EG/EGME Method and the Ratio with Silica

Soil Sample	Organic C Content g/kg	Total Specific Surface Area m²/kg	Total Specific Surface Area Ratio
Silica	0.1	8,700	1
Aquifer material	0.1	10,500	1
Boston silt	26.6	46,000	5
Kaolinite clay	0.1	21,300	2
Montmorillonite clay	0.2	733,000	84
Webster soil	33.2	168,400	19
Houghton muck	445.7	162,900	19

Source: Pennell, K. D. (2002). Specific surface area. In *Methods of Soil Analysis: Physical Methods,* Part 4, Dane, J. H. and Topp, G. C. (Eds.). Soil Science Society of America, Madison, WI, pp. 295–315.

properties, volume available, distance from the site, and cost for acquisition and hauling to the site. The preliminary design produces an estimate of the performance of a cover utilizing available soil and determines whether it is appropriate to continue with the design of an ET cover for the site. After preliminary design demonstrates that an ET cover is appropriate for the site, the next step is a complete, site-specific soil evaluation.

Descriptions that are suitable for initial analysis of soils found near the site are usually available within official soil surveys of the U.S. Department of Agriculture, Natural Resource Conservation Service (USDA/NRCS). USDA soil surveys are available for most counties in the United States; they are available without cost from county or state offices and on the NRCS soil Web site (NCSS 2006; USDA, NRCS 2006). The Land Grant Universities are also a source of soil data for their respective states. The USDA/NRCS soil surveys include aerial photos of each county with individual soil units delineated and marked for reference to the data contained in their tables. The user should collect information about soils that are available within a reasonable haul distance of the landfill site.

10.2.3.1 Preliminary Soil Data

The following discussion illustrates the use of soil data during preliminary design. Table 10.2 contains field data, summary, and estimates for cover soil. The survey data came from a preliminary soil survey for a site on the western edge of the central Great Plains. The field data contain the raw data. The summary in Table 10.2 contains the user summary of the raw data, and the estimates for cover soil contain soil data prepared for use in a preliminary cover design.

The preliminary field samples contained only clay content and soil sieve results covering the silt and sand particle ranges (Table 10.2). The material held on the

TABLE 10.2
Soil Data from Preliminary Field Samples from West-Central Great Plains

Field Data

Depth (cm)	0–8	8–38	38–150
USDA Class	Loam	Loam	Loam
Clay, %	15–27	18–35	18–27
% pass #200 sieve[a]	50–70	55–70	50–65
% pass #10 sieve[b]	95–100	95–100	95–100
% pass #4 sieve	95–100	100	100
Bulk density, Mg/m^3	1.25–1.35	1.3–1.4	1.3–1.4
K, cm/h	1.5–5	1.5–5	1.5–5
AWC[c], cm/cm	0.15–0.18	0.16–0.19	0.15–0.17
pH	6.6–7.8	7.4–7.8	7.4–8.4
Soil organic matter, %	2–4	1–3	0.5–1
CEC[d], meq/100 g	9–16	11–25	10–16
$CaCO_3$, %	—	—	3–5
Salinity, mmhos/cm	—	0–2	0–2

Summary

Depth (cm)	0–8	8–38	38–150
Gravel/rock[e], %	2.5	2.5	2.5
Sand, %	40	38	43
Silt, %	39	36	35
Clay, %	21	26	22
Bulk density, Mg/m^3	1.3	1.4	1.4
AWC[c], cm/cm	0.16	0.17	0.16
pH	7.0	7.6	7.6
Soil organic matter, %	3	2	0.8
CEC[d], meq/100 g	12	18	13

Estimates for Cover Soil

Gravel/rock[e], %	2.5	Wilting point, cm/cm	0.16
Sand (2.0–.05 mm)%	42	Field capacity, cm/cm	0.32
Silt (.05–.002 mm)%	35	CEC[b], meq/100 g	14
Clay (<.002 mm)%	23	pH	7.6
Bulk density, Mg/m^3	1.4	Soil organic matter, %	1.1

[a] Soil passing #200 sieve includes clay, silt, and part of very fine sand.

[b] Soil passing the #10 sieve (2 mm opening) includes clay, silt, and sand; coarse sand, gravel, and rock held on this sieve are not included in the soil.

[c] AWC = available water holding capacity, cm/cm.

[d] CEC = cation exchange capacity, meq/100 g.

[e] Gravel/rock = coarse sand, gravel, and rocks >2 mm in size, not soil material.

ASTM #10 sieve (0–5%) defines the gravel/rock content of the soil material. Soil passing the ASTM #200 sieve provides an approximation to the total clay and silt in the soil. The difference between soil passing the #200 sieve and the clay percentage approximates the soil's silt content. Because sand, silt, and clay should be 100% of the soil, the sand content was estimated by difference. The data presented demonstrate a substantial range of properties; the range of properties was taken into account when estimating soil properties for the summary section of Table 10.2.

The data in the estimates for cover soil are depth-weighted averages of the numbers in the summary (Table 10.2). The field data did not contain field capacity and wilting point measurements; the EPIC model estimated them. An independent evaluation by the hydraulic properties calculator produced slightly smaller water-holding capacity values (Saxton 2005; Saxton and Rawls 2005).

10.2.3.2 Final Soil Data

After making the decision to proceed with ET cover design and construction, the user should sample and evaluate the soil in the proposed borrow source. Sample sufficient sites and soil layers to describe the soil variability and evaluate possible soil mixtures.

10.3 PLANT PROPERTIES

Several plant properties control the function of an ET landfill cover. Important plant properties include biomass–energy ratio (conversion of solar energy to biomass), optimal and minimum temperature for growth, maximum potential leaf area index, leaf area development curve, maximum stomatal conductance, critical soil aeration, and maximum root depth.

During both preliminary and final design, one should use accurate plant descriptions. Fortunately, plant properties within a species and variety remain constant, for practical purposes. The EPIC model contains a ready reference of plant properties for many grasses, cultivated and native plants, and for some trees. The plants described grow in hot, cold, wet, and dry climates within the United States.

10.4 INTERACTION OF PLANTS, SOIL, AND CLIMATE

Interactions between plants, soil, and climate are important to evaluation of ET landfill covers and should be included in models used for design. Examples of interactions include:

- Bright sunlight, high air temperature, low dew point, and wind may combine to cause plants to use large amounts of water at the potential ET rate when the soil is wet. If the soil is partially dried, the plants may extract much less than the potential ET amount from the soil, causing them to wilt and produce less biomass.
- Bright sunlight combined with low air temperature and high dew point may result in little water demand and no plant wilting even when the soil is relatively dry.

- Low soil pH may cause excessive aluminum to become available in the soil solution and reduce plant growth or kill the plant.
- High soil density or dry soil may limit root growth, which in turn limits water extraction from the soil.
- Low air temperature may reduce evaporation potential, biomass production, and root growth rate, and thus influence water use.
- Clouds, high dew point, and rain may significantly reduce daily plant water use.

10.5 CRITICAL DESIGN EVENT

Where minimum percolation is an important goal for the cover, critical events expected during the life of the cover are important considerations during design and evaluation. The critical design event is that event or series of events which results in the greatest soil water storage requirement during the expected life of the cover. Critical events may result from a single-day storm, a multiple-day storm, or other causes.

In a normal design, some deep percolation is expected, and a careful evaluation of the critical events is a valuable addition to ET cover assessment. In extreme cases, the requirements for the cover may allow no deep percolation; in that event, the critical design event defines whether the cover is adequate.

The two examples that follow resulted from designs at Cheyenne, Wyoming, and at an eastern suburb of Denver, Colorado. Both sites are on the dry western edge of the semiarid Great Plains, and have good quality soils with high water-holding capacity available for the cover. An ET cover adequate to control infiltration was too thin to isolate the waste. Therefore, the requirement that the ET cover isolate the waste and prevent its movement determined the cover thickness; they were thicker than needed to control infiltration.

At Cheyenne, an adequate ET cover soil was 0.6 m thick, and composed of soil with high water-holding capacity. The plant cover included several native cool-season grasses; they grow rapidly and use much water during the spring. Figure 10.4

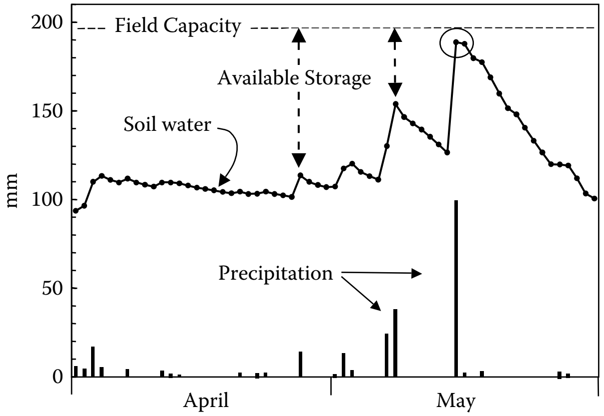

FIGURE 10.4 Estimated daily values of precipitation, water content of the cover soil, and critical event for Cheyenne, Wyoming.

presents estimates of daily rainfall and soil water content during 2 months from the wettest year of a 100 year simulation; this period includes the greatest daily storage of soil water during the 100-year period. In this example, the critical event was the result of several days with rainfall followed by a large single-day rainfall event. The native grasses maintained the soil water content near the wilting point during April, until 2 days of rainfall wetted the profile in early May. Between May 8 and 15, the soil water content decreased rapidly, and by June 1 it dropped to near the wilting point, because during May evaporative demand is high and the native cool-season grasses grow rapidly. The soil water content resulting from this most critical event from a 100-year estimate was less than the field capacity for the soil and predicted no deep percolation.

At the Denver site, an adequate ET cover soil was 0.5 m thick, and it had high water-holding capacity. The plant cover was cool-season grasses, which grow rapidly and use much water during the springtime and early summer. Figure 10.5 presents the estimates of daily rainfall and soil water content for year 9 of a 25-year design period; it includes the extreme event. The average precipitation during the 25-year period was 399 mm, and the largest annual value was 976 mm in year 6. However, the critical event occurred during year 9, a year with annual rainfall only 72% of the highest annual value. The critical event occurred during mid-October, a month with relatively low rainfall; however, the plant cover was beginning a new growth cycle, and evaporative demand was relatively low. The soil water content was below the wilting point before the large rain in June, and remained near the wilting point throughout the remainder of the month. Much larger daily rain events and greater total monthly rainfall fell in June than in October. June began with dry soil; plant growth was robust, and evaporative demand was relatively high. These factors combined to keep the soil water content below or near the soil's wilting point during June. The critical event did not fill the water storage capacity in the soil cover; therefore, the cover selected was adequate for the site. The requirement that the cover isolates the waste and controls its movement by wind and water governed the selection of cover thickness.

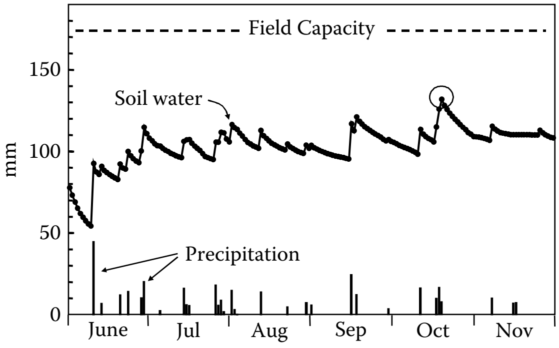

FIGURE 10.5 Estimated daily values of precipitation, water content of the cover soil, and critical event for an eastern suburb of Denver.

10.6 LAYERED ET COVER SOILS

The simplest ET cover contains a single soil layer with uniform properties. However, where precipitation is high, air temperatures are low, soil resources have low water-holding capacity, or for other reasons, a uniform soil may allow excessive deep percolation through a landfill cover. It is possible to increase the fraction of precipitation that leaves the site as surface runoff, thus reducing the required size of the soil water reservoir.

Most natural soils contain layers with differing properties. Limiting layers with low hydraulic conductivity dominate and control surface runoff, a major part of the water balance. Soil descriptions are the basis for the USDA Soil Conservation Service (SCS) curve number method; they are shown in Table 10.3 (ASCE 1996). The properties of the least permeable soil layer near the surface control the assignment of a curve number (CN) to a natural soil. Soil surveyors assign CNs by evaluating measured soil infiltration rates, soil texture, and structure. The USDA, NRCS assigned SCS curve numbers to most named soil series within the continental United States. For purposes of ET cover design, the texture and measured values of saturated hydraulic conductivity may be used to establish CN for ET cover design.

For example, if the soil available at the site is permeable and falls in or between soil groups B and C, the addition of a layer of clay soil from soil group D near the surface will increase surface runoff (Table 10.3). The clay layer should have a low infiltration rate to limit the amount of water entering the soil profile. It is important that roots grow profusely within and through each layer, including the clay, and have potential to extend to the full depth of the cover soil. Therefore, the clay layer should not reduce root growth and should allow adequate oxygen exchange between the surface and lower soil layers. Placing the clay with soil density equal to or less than 1.4 Mg/m^3 should assure that the cover soil satisfies site needs.

TABLE 10.3
Final (or Minimum) Infiltration Rates after Prolonged Wetting That Govern the Soil Classification for Selecting SCS Curve Numbers

Soil Group	Final Infiltration Rate (cm/h)	Expected Runoff	Typical Soil Texture
A	0.8–1.1	Near zero	Sand
B	0.4–0.8	Small	Silt loam or loam
C	0.1–0.4	Large	Layered sandy clay loam
D	0–0.1	Very large	Clay or hardpan layers

Source: ASCE. (1996). *Hydrology Handbook,* 2nd edition. Manual 28 (Chapter 3, pp. 98–100). American Society of Civil Engineers, Reston, VA.

10.7 SOIL EROSION

Technology developed to control soil erosion on clean tilled agricultural land or a bare construction site is sometimes mistakenly applied to landfill covers. A cover of grass or other native vegetation growing on an optimized ET landfill soil cover reduces soil erosion to near zero amounts.

Soil erosion by both wind and water action are widely recognized as serious threats to humanity (USDA 1938; Bennett et al. 1951; Follett and Stewart 1985). Continuous clean tillage to produce crops without measures in place to control soil erosion is the primary cause of the threat posed by erosion. Other activities such as road and building construction may cause serious erosion.

Indeed, several civilizations fell during the past 7000 years because the citizens did not conserve their soil resources over centuries of use (Lowdermilk 1953). Figure 10.6 illustrates the potential effect of soil erosion by water, and Figure 10.7 illustrates the potential effect of wind erosion; both situations resulted from poor land management and clean tillage for crop production in the United States.

Modern farm production practices keep plant residue on the soil surface and utilize other practices to control soil erosion; as a result, soil erosion on farms has been substantially reduced. Geologic erosion that occurs under natural systems of grassland or forest on stable slopes or flat land is generally equal to or less than the rate of new soil formation and thus not a threat to humanity. Figure 10.8 illustrates a natural grassland system similar to an ET landfill cover; it should produce near zero amounts of soil erosion.

Soil erosion rate may be high for a short time during plant establishment and therefore deserves attention for an ET landfill cover. Experience demonstrates that some erosion during grass establishment is not serious because of the short time involved. Good management during plant establishment can minimize erosion risk. Accordingly, the following discussion covers soil erosion concepts that are important

FIGURE 10.6 Water erosion caused by clean tillage for crop production in the humid southeastern United States. (Photo courtesy of USDA, Natural Resources Conservation Service.)

FIGURE 10.7 Wind erosion caused by clean tillage for crop production in the Great Plains of the United States. (Photo courtesy of USDA, Natural Resources Conservation Service.)

FIGURE 10.8 A natural grassland system—soil erosion is near zero. (Photo courtesy of USDA, Natural Resources Conservation Service.)

to an understanding of the principles of soil erosion control, and to ET landfill cover design, construction, and maintenance.

10.7.1 WATER EROSION

Water erosion is the detachment of soil particles from the soil mass by raindrops and flowing water, and their transport by rainfall runoff. Soil movement is often intermittent, with detachment, transport, and deposition recurring repeatedly as the soil moves through a watershed system. On bare soil, both raindrop impact and shear from flowing runoff are major forces causing soil detachment. Factors that affect soil erosion by water include rainfall energy, soil erodibility, slope length, slope steepness, plant cover, and erosion control practices (Smith and Wischmeier 1962).

Several trillion raindrops annually bombard each hectare of land in the humid United States at impact velocities up to 9 m/s. The erosive power of rainfall results from the energy dissipated upon raindrop impact. Vegetation absorbs raindrop energy and reduces the velocity of surface runoff; therefore, surfaces covered by robust grass cover suffer little or no erosion.

Surface runoff causes soil erosion on bare land surfaces where runoff concentrates, and the critical tractive force of the flowing water exceeds the limit for the existing soil conditions. On bare soils, the rills that result from soil erosion are much more apparent than the sheet erosion between the rills, although the total erosion by each on a watershed basis may be similar.

10.7.2 WIND EROSION

Wind erosion is the detachment, movement, and abrasion of soil by wind. It begins when the pressure of the wind against the surface soil grains overcomes the force of gravity on the grains. Wind moves soil grains along the surface of the ground in a series of jumps known as *saltation*. The concentration of saltating soil grains in the air increases downwind until it reaches the maximum that the wind can sustain. The saltating grains collide with objects in their path and cause disintegration of any material that is soft enough to erode. Wind erosion occurs only when soil grains capable of being moved in saltation by the velocity of the wind are present in the soil, and only dry soil particles are moved by the wind (Chepil 1958; Chepil and Woodruff 1963). Fryrear and Randel (1972) state, “The wind velocity must exceed 4.5 m/s (10 miles per hour) before most bare erodible soil surfaces will start to erode.”

Woodruff and Siddoway (1965) developed a wind erosion equation that summarizes the important variables affecting wind erosion. They found that wind erosion amount is a function of soil erodibility index, surface roughness, climatic factor, field length in the direction of the wind, and the quantity of vegetative cover.

10.7.3 EROSION AT ARID SITES

At some arid sites, wind and water erosion are long-term erosion threats because there is insufficient rainfall to produce a sufficiently dense vegetative cover to protect the soil on a landfill cover. Gravel added to the top soil layer may adequately control both wind and water erosion. Erosion exposes a stone pavement between plants that mimics stable desert pavement and that can effectively control soil erosion (Waugh et al. 1994). The addition of stones to the upper soil layer causes infiltration from small showers to move a few centimeters deeper into the soil profile than for soil with no stones; this action may significantly improve growing conditions for the grass cover under dry conditions.

10.7.4 SOIL EROSION COMPARISONS

Given the importance of the soil erosion issue, it is important to understand the degree of risk posed by erosion of ET landfill covers. This section contains erosion and soil productivity estimates by the EPIC model; the estimates were for two sites and two cover conditions.

Modern erosion control technology was developed for production agriculture in response to the concerns expressed previously. Common cultivated crops are annuals, and the soil is often tilled for weed control and soil loosening between harvest and planting of the next crop. The fallow period may last for 1–15 months depending on the local weather and the crops grown. The soil surface may be bare for several months. Soil erosion potential is high when the soil is bare and during the establishment phase of the new crop.

Erosion estimates were calculated for Idabel and Goodwell, Oklahoma; they are located in southeastern Oklahoma and in the Oklahoma panhandle, respectively. The climate at Idabel is wet, and the erosive potential of the rainfall is high, but the wind erosion hazard is low. The climate at Goodwell is semiarid, the erosive potential of the rainfall is moderate to low, but the wind erosion hazard is high (Wischmeier and Smith 1978; Woodruff and Siddoway 1965).

The soil used in the simulation was a mixture of a fertile soil profile with good water-holding and plant nutrient capacity, and has moderate-to-low water and wind erosion potential. The estimates by EPIC included a 5 year initialization run to set soil water content, plant parameters, plant biomass, plant residue, and other calculated variables used as the beginning point for the 100 year estimates described herein.

The plant covers tested were perennial grass cover, native to each site, and winter wheat. Winter wheat is a common crop at both sites. At Idabel, the grass cover was switchgrass, and at Goodwell, it was a mixture of short range grasses. Tillage during fallow after wheat harvest included offset disk harrow for primary tillage after harvest. As a reference point for evaluating the results, Figures 10.9, 10.10, and 10.11 show soil loss that is tolerable for sustained crop production for both thin and thick soils (Wischmeier and Smith 1978).

Figure 10.9 compares estimates for water, wind, and total erosion for winter wheat with different land slopes at Goodwell; the slope length was 152 m. Water erosion rate was low, as expected. Wind erosion dominates the total erosion estimate.

Water erosion increases rapidly with increasing land slope. Figure 10.10 shows the estimates of total erosion from both winter wheat and grass at Idabel and Goodwell. Because almost all of the erosion at Idabel resulted from water erosion, there is a substantial increase in the erosion amount from winter wheat with increasing land slope. All land slopes greater than 2% exceeded the tolerable soil loss under winter wheat culture. There was no significant soil erosion at either site under native grass at any land slope.

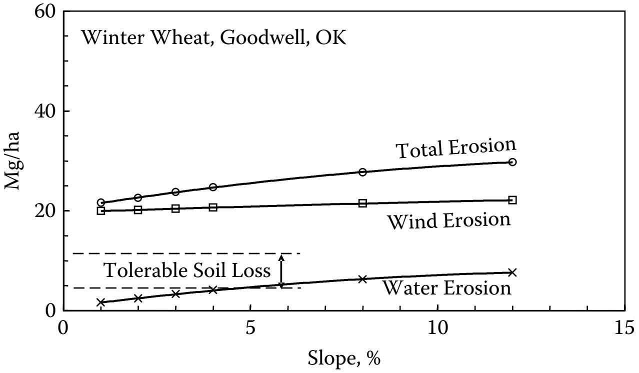

FIGURE 10.9 Water, wind, and total soil erosion vs. land slope for winter wheat at Goodwell, Oklahoma.

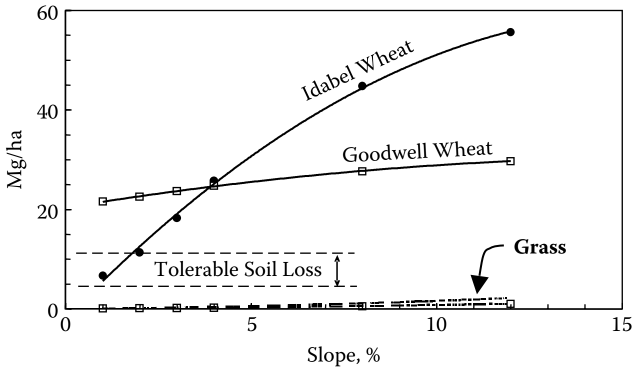

FIGURE 10.10 Total soil erosion for winter wheat and grass vs. land slope at Idabel and Goodwell, Oklahoma.

For cultivated and tilled land, slope length has a significant effect on potential soil erosion by water; the field width in the direction of the wind affects wind erosion. Figure 10.11 shows the relation between estimated soil erosion and slope length for both Idabel and Goodwell; the land slope for all of these estimates was 4%. However, total erosion under grass is near zero at all the slope lengths evaluated; thus, no further erosion control is needed for a grass cover.

10.7.5 EROSION CONTROL STRUCTURES

Erosion control structures such as diversion terraces or waterways lined with grass or riprap protect the soil at sites where crops are cultivated, or land disturbance renders the soil erodible on a continuing basis. Erosion control structures concentrate surface runoff water—concentrated surface runoff water is much more erosive than runoff spread evenly over the land surface. As a result, poorly maintained structures may

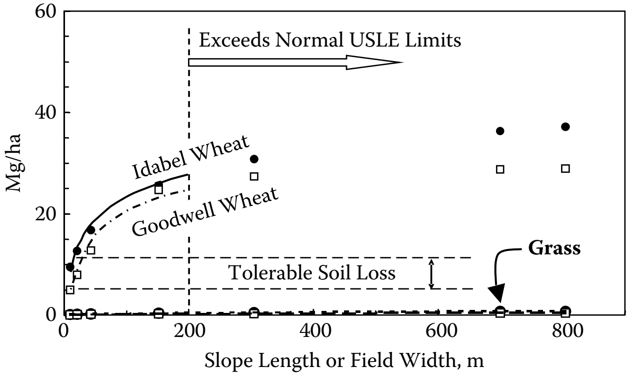

FIGURE 10.11 Total soil erosion for winter wheat or grass vs. slope length or field width at Idabel and Goodwell, Oklahoma.

cause significant erosion on a grass-covered site because of the release of concentrated surface runoff water. All erosion control structures need frequent maintenance.

Terraces or waterways on an ET cover may cause serious erosion because structures are prone to fail, even under grass. For example, rodents frequently build burrows on grass-covered terraces because the ridge is the driest site in the area; the burrows weaken the structure and may cause failure. Structures on a grass-covered landfill surface significantly increase the need for frequent and expensive maintenance.

Shaping the land to avoid concentration of water on the surface of a native grass landfill cover will control soil erosion from long slopes. A grass cover without structures can easily protect an ET landfill cover from erosion.

Examination of erosion or its absence in the natural world is instructive. Landscapes with land slopes up to 12% or greater and slope length greater than 800 m (0.5 mi) seldom suffer soil erosion if they remain under native grass. Landfills located in some arid regions may present an exception and may need shorter and flatter slopes. Observation of natural landscapes near a landfill site is instructive regarding maximum slope and slope length.

Gully erosion is not a significant threat to an ET cover. For example, grass cover successfully controls erosion in farm field waterways carrying water at greater depth and higher velocity than that expected on landfill covers.

Native grass provides excellent control of both wind and water erosion for soils with slopes and slope length common to ET landfill covers. Soil erosion is a threat to ET landfill covers during the plant establishment period only; proper management during that period can effectively control soil erosion. During the life of a landfill cover, soil erosion by wind or water is not a significant threat to properly constructed and managed ET landfill covers; there is no need for mechanical erosion control structures.

10.8 LANDFILL SETTLEMENT

Wastes deposited in landfills naturally settle for decades or longer. The waste is normally compacted during placement in modern landfills; however, additional settlement is likely before the final cover is placed on the landfill. Because the waste is heterogeneous, uneven settlement is common. A load (e.g., a cover) placed on top of the waste increases the settlement rate. The design of any landfill cover should take into account future settlement because it may result in cracks or holes in the cover and in local land-surface grade reversals.

There are two settlement phases, primary and secondary. Secondary settlement begins after primary settlement and continues for the life of the landfill. Primary settlement may be complete in about 4 months; thus, the cover is usually installed near the beginning of secondary settlement.

Sharma and Anirban (2007) reviewed five methods for estimating future waste settlement. They present the following equation to describe secondary settlement of waste under self-weight:

$$S = CH \log \frac{T_2}{T_1}$$

where

S = settlement
C = coefficient of settlement under self-weight
H = waste thickness at the end of primary settlement
T_1 = time for primary settlement (use 4 months)
T_2 = time of interest

Their equation for settlement under external load is similar in form but uses a unique value for C, which is contained in their table of recommended values for the coefficient.

To illustrate the range of settlement that is possible, Figure 10.12 presents settlement values calculated with coefficients suggested by Sharma and Anirban (2007). The figure includes estimates for (1) a typical conventional landfill with roller compaction and a cover in place (C = 0.03), and (2) waste undergoing active decomposition with self-weight (C = 0.22), which may approximate conditions in a bioreactor landfill. The settlement is expressed as a percentage of the beginning

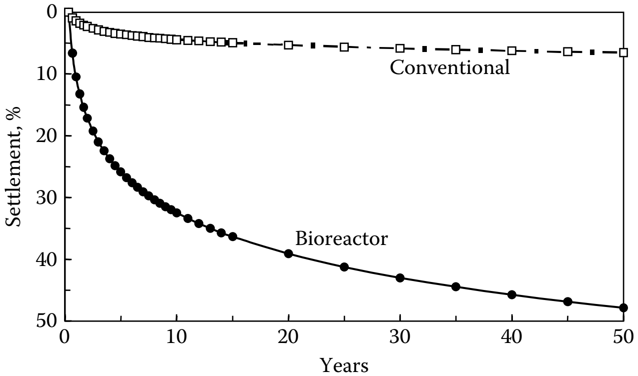

FIGURE 10.12 Landfill settlement as percentage of beginning thickness for a bioreactor and a conventional landfill.

waste thickness, and the estimates are extrapolated beyond the 15 year period of measurement reported by Sharma and Anirban (2007).

The ET landfill cover is less prone to damage by settlement than other cover types, and when repairs are needed, they are easier and less costly to accomplish. However, cover settlement is an important consideration when establishing the slope of the finished cover.

10.9 LANDFILL COVER SLOPE

Uneven settlement of waste could cause ponds to develop on the landfill surface if the beginning slope is too flat. Therefore, the minimum slope on a finished landfill cover should be at least 2%.

Steep land slopes are incompatible with ET landfill covers. Although grass grows on steep slopes, grass plants seldom grow robustly there. Robust growth of the cover vegetation is a requirement for an effective ET cover. Litter accumulates between plants under bunch grasses and effectively controls soil erosion on moderate land slopes, even with several inches of water flowing on the surface. Erosion control is dependent on robust growth of grass plants; however, robust plant growth cannot be assured on steep slopes.

If a bare spot develops on a moderate slope, grass can easily cover the ground again by natural processes, but on steep slopes, recovery will be slower and not assured. Where snow is an important part of the annual precipitation at semiarid sites, uniform distribution over the surface of the landfill is important to assure adequate water supply to all parts of the cover. With steep side slopes, wind is more likely to remove snow from some areas and deposit it in deep drifts in others. When deep snowdrifts melt, they may produce excessive localized deep percolation and may damage the grass cover. Snow is more difficult to control on steep slopes.

The purpose of steep slopes on conventional landfill covers is to provide additional storage volume for waste. With ET covers, the gain in volume may not be worth the price in reduced performance of the cover and the potential for increased maintenance cost.

Bulldozers and other construction machinery can safely work on land slopes less than 8%. An ET cover with land slopes less than 8% presents little or no threat to slope stability. Land slopes of 2–8% should be satisfactory for ET landfill covers.

10.10 SAFETY FACTOR FOR MINIMUM PERCOLATION

Landfill covers that are required to minimize percolation of precipitation into the waste need a cover thickness safety factor. Similar to other remediation measures, the ET cover design needs safety factors because both design and construction introduce uncertainty regarding performance. Control of water flow into the waste requires the following safety factor considerations for the ET cover:

- The degree of precipitation control required to meet site demands.
- The size of the soil water reservoir in the cover soil should be adequate to contain extreme or design storm events consistent with site needs.

10.10.1 Soil Thickness Basis

One basis for providing a safety factor is to increase the soil thickness (i.e., build the soil cover thicker than indicated as adequate by design). However, this intuitive approach may not produce the desired result. Although the total water-holding capacity is similar for each soil layer of a uniform soil, the distribution of roots and the rate and amount of water extraction are not.

As discussed in Chapter 5, several factors control root growth, including soil water content and soil temperature. As a result, the distribution of roots in the soil profile changes in response to the limiting factors present and may differ between years in a particular soil cover. Figure 10.13 shows the possible root distribution in a cover soil at three times during a year and the potential maximum root mass for any soil layer during that year. Even though good soil tilth maximizes root mass in each layer, the potential root mass is less near the bottom of the soil profile than at the top.

Figure 10.13 shows possible soil water content at the end of the growing season where an arbitrary thickness of soil was added as a "safety factor." The soil added as a safety factor layer had properties similar to the remainder of the soil. However, the plant root distribution established in the new cover will include many roots in the surface layer and fewer in the bottom layer. Even though the safety factor soil layer is on top, its impact on water balance and percolation is measured at the bottom of the profile. With the situation illustrated, the cover could fail during the following year.

Because of the distribution of plant roots in the soil, the addition of a defined thickness of soil is unlikely to achieve the desired safety factor. Plants remove less water and extract it more slowly from deep soil layers than from near-surface layers. Figure 10.14 shows a conceptualized relationship between soil thickness and seasonal soil water removal by ET where soil thickness was increased from A to B. The actual change in plant-available and usable water storage capacity is not a straight line relationship between soil thickness and storage, particularly for thick ET landfill covers.

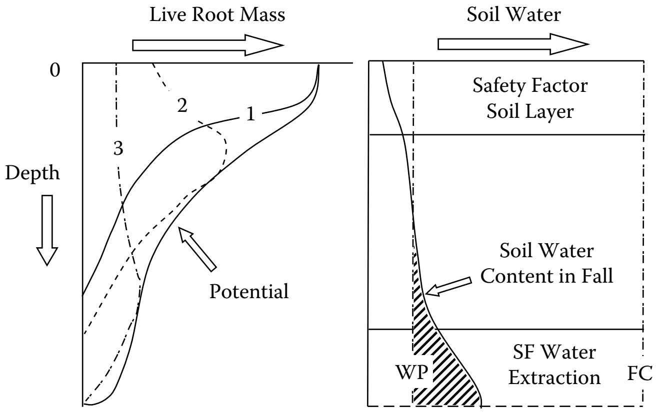

FIGURE 10.13 Possible distribution of live roots during the growing season, and the soil water content in fall, with a soil layer added as a safety factor.

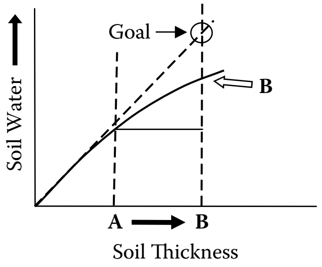

FIGURE 10.14 Soil water removed by ET as changed by increased soil thickness.

10.10.2 HYDROLOGIC BASIS

A better way to provide a safety factor is to utilize hydrologic factors with a proven design model to estimate performance. For example, the model evaluation could include one or more of the following:

- Increased daily precipitation (i.e., 110% of average precipitation).
- Design for a cover with uniform soil properties, but install a 15 cm thick layer of clay soil on top of the cover to increase surface runoff.
- Design for either warm- or cool- season plants, but establish both; this extends the growing season and thus increases total ET.

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11 Construction

This chapter presents construction methods and components that are unique to evapotranspiration (ET) landfill cover construction. The Interstate Technology and Regulatory Council (ITRC 2003) presented cover-construction guidance for alternative landfill covers; some of that work is pertinent to ET landfill cover construction.

11.1 SOIL

It is relatively easy to modify soils during cover construction; some modifications are unintended, and some of them may degrade the quality of the soil. It is also easy to add major plant nutrients—nitrogen, phosphorus, and potassium—to the soil placed in the ET cover, and to adjust low soil pH. Soil density may be controlled within an optimum range during construction. However, modification of properties such as high pH, excess sodium, or very high total soil salt may be impractical. Soil modification to improve its quality costs relatively little when compared to the total construction cost, but it has the potential to improve performance, lengthen life of the cover, and to reduce long-term maintenance costs.

Chapter 5 contains a discussion of soil properties that are important to ET landfill covers. The engineer should identify and specify soil properties before construction begins and closely monitor soil quality during construction, because some soil properties are difficult and expensive to modify after construction is complete. Table 11.1 lists important soil properties, and Table 11.2 lists test methods for soil properties that are important to ET landfill cover soils.

11.1.1 SOIL PH

An effective means of correcting acid soils is to mix lime into each lift during placement. Standard methods are available to determine the lime requirement (Sims 1996). If the proposed borrow area supports robust plant growth, the pH of the soil is probably adequate; however, it should be tested for pH level. Where soil pH is too high for native plants, it is necessary to seek an alternate soil source because reducing soil pH is normally impractical.

11.1.2 SOIL HUMUS CONTENT

Humus (often called *soil organic matter*) is an important component of soils (SSSA 1997). It is composed of stable organic compounds in soil exclusive of undecayed organic matter. Humus is resistant to decay, provides significant cation-exchange capacity in addition to that of clay minerals, and improves soil structure. Large

TABLE 11.1
Soil Properties That Are Important for Design and Construction of ET Landfill Covers

Basic Properties	Other Properties
Particle size distribution	Salinity (including Ca^{++} and Mg^{++})
Sand and rock content[a]	Sodium content
pH	Sodium absorption ratio
Electrical conductance	Major nutrient supply[b]
Cation-exchange capacity	Humus content
Field capacity	Volume of each soil type
Wilting point	Toxic substances
Bulk density of soil in the cover	

[a] Particles larger than 2 mm.

[b] Nitrogen, phosphorus, and potassium (in leached soils, include sulfur and aluminum; in basic soils, include available iron and zinc).

amounts of humus in soil are desirable, but not required, for good plant growth. Plants grow well in fertile soils that contain little humus (e.g., soils of the southern Great Plains and the irrigated deserts of the 11 western states).

Compost, manure, and grass clippings are organic materials, but they are not humus. The addition of organic material to soil usually improves soil water-holding capacity, tilth, and fertility. However, the effects of organic material on soil properties may be temporary and may not be worth the expense in a landfill cover because most of the added organic material decays and disappears in a few months or years. After the applied organic material decays, soil properties revert to those of the original soil material.

11.1.3 HARMFUL CONSTITUENTS IN SOIL

Landfill cover soils should be free of harmful amounts of synthetic chemicals, oil, and natural salts. The salts of calcium, magnesium, and sodium occur naturally and can create high salinity in the soil solution.

11.1.3.1 Soil Salt

Excess amounts of calcium, magnesium, and sodium create saline soils. Soils containing high percentages of sodium in the soil salts are special cases. Soil salts may raise the osmotic potential of the soil solution high enough to prevent plants from using all of the soil water. High concentrations of soil salts may kill plants or prevent seed germination and plant establishment.

The electrical conductivity (EC) of an extract of a saturated soil paste defines soil salts; the units are deciSiemen per meter (dS/m). Calcium, magnesium, and sodium salts are often the primary contributors to high salinity levels. Modern soil scientists prefer to measure EC of the soil solution in place in the field; however, a measurement of the EC of the borrow soil is appropriate for use in design and planning for an ET landfill cover soil.

TABLE 11.2
Test Methods for Soil Properties That Are Important to ET Landfill Cover Soils

Physical Properties	Measurement Methods
Clay, silt, sand, and coarse fragment content	SSSA-4 2002, Section 2.4
Soil organic matter	SSSA-3 1996, Section 34
Soil bulk density	SSSA-4 2002, Section 2.1
Soil pH	SSSA-3 1996, Section 16
Cation-exchange capacity (CEC)	SSSA-3 1996, Section 40
Electrical conductivity	SSSA-3 1996, Section 14
Soil nitrogen (inorganic)	SSSA-3 1996, Section 38
Soil nitrogen (organic)	SSSA-3 1996, Section 39
Phosphorus	SSSA-3 1996, Section 32
Potassium	SSSA-3 1996, Section 19
Sulfur	SSSA-3 1996, Section 33
Micronutrients	SSSA-3 1996, Various sections
Total soil salt content	SSSA-3 1996, Section 14
Total soil sodium	SSSA-3 1996, Section 19
Sodium adsorption ratio	SSSA-3 1996, Section 40
Soil classification and taxonomy	USDA 1994, and SSSA 1997
Water content	SSSA-4 2002, Section 3.1
Hydraulic conductivity	SSSA-4 2002, Section 3.4
Unsaturated hydraulic conductivity	SSSA-4 2002, Section 3.4
Water retention and soil water content	SSSA-4 2002, Section 3.3

Sources: SSSA. (1997). *Glossary of Soil Science Terms*. Soil Science Society of America (SSSA), 677 S. Segoe Rd., Madison, WI.

Individual plant species have differing tolerance to soil salt. Soils having EC values greater than 2.5 dS/m should be carefully evaluated, and those having EC greater than 5 dS/m may be unsuitable for use in an ET cover soil. Rhoades and Loveday (1990) provide an overview of soil salts and also provide significant guidance for the design engineer.

11.1.3.2 Sodium

In addition to its contribution to soil salinity, sodium can cause deflocculation (i.e., dispersion) of clay particles, thereby causing poor soil tilth. Soils with either high or low salinity may have serious sodium problems. Soils with high sodium adsorption ratios have poor structure and tilth, and they are not suitable for use in an ET landfill cover. Plants grow poorly, if at all, in sodic soils. The total electrolyte content of soil controls the effect of sodium on soil behavior. Where precipitation is the source of water, the electrolyte content of soil water may be low, and relatively small amounts of sodium may cause poor soil structure. Do not use soils with sodium adsorption ratios greater than 6 in ET landfill covers (Rhoades and Loveday

1990). Excessive soil sodium content prevents the robust plant growth needed on an ET cover.

11.1.4 Soil Physical Properties

Natural soils contain layers whose material properties vary substantially. Mixing soil layers with diverse properties may produce good soil material for an ET landfill cover. If the ET landfill cover soil contains mixtures of two or more layers, it is important to know or estimate the properties of the mixture.

Mix soils with differing properties before placing them in the cover. Wheel loaders or machines similar to trenching machines that cut a uniform volume of soil from each layer in each rotation of the wheel produce adequate mixing. Alternate mixing methods should achieve an equal amount of mixing.

Soil structure is the combination or arrangement of primary soil particles into secondary units or peds. The soil in the borrow pit has a naturally developed structure. Good soil structure is important to good soil tilth, root growth, and plant development, and it may take decades or centuries to create a new structure in a finely ground soil. It is not desirable to homogenize or grind the soil during mixing. Maintain a significant amount of the original soil structure; the amount for any particular soil will vary with its properties. Sandy soils may disintegrate into mostly primary particles. Clay soils contain stronger peds and structural elements, and much of the original soil structure may remain in clay soils after placement in an ET cover.

11.2 SOIL DENSITY AND STRENGTH

Creation of good soil tilth during cover construction is important because correction of soil tilth problems after construction ends is costly and may be unsuccessful. Soil density and strength usually control soil tilth, and they are important soil physical properties; therefore, they should be controlled during construction. Correct construction adds little to construction cost; however, it requires knowledge of methods for achieving and maintaining good soil tilth. Soil compaction creates high soil density, and these terms are used interchangeably here.

The ITRC (2003) recommends the use of soil density goals suggested by Goldsmith et al. (2001). They presented recommendations for desirable soil densities that are compatible with plant growth and mechanical stability of soils in levees. They suggested that (1) the plants should control water erosion of the embankment, (2) the fill should be structurally stable with steep side slopes, and (3) the embankment should limit seepage. In this setting, optimum plant root growth is not needed. Restricted root growth can anchor the plant and produce enough vegetative cover to control erosion. Plants with a relatively shallow root mass and only a few roots that penetrate deeply into the soil are adequate. Goldsmith et al. (2001) recognized that optimum root growth is not possible with the soil densities that they recommend. Their recommendations for density and root growth are similar to the earlier works of Sharpley and Williams (1990) and Jones (1983), who described the zone of restricted root growth shown in Chapter 5, Figure 5.8. Although their recommendations appear sound for plants growing on levees, they do not apply to the ET landfill cover, because root growth should be optimized on ET covers.

Soil density for the finished ET landfill cover should be less than 1.5 Mg/m^3. Lower density is desirable and promotes best plant growth and water extraction. The soil should be compacted to a minimum density to ensure stability and to offer resistance to compaction forces on the soil. A minimum density of 1.1 Mg/m^3 is appropriate; however, the soils available may influence the value chosen. A soil density between 1.1 and 1.45 Mg/m^3 should produce stable soils with optimum conditions for plant growth.

11.2.1 CAUSES OF SOIL COMPACTION

"*Soil compacts when it is too weak to bear the stresses imposed on it—which could mean that the soil is weak, or that the load causing the stresses is excessive, or both*" (Raper and Kirby 2006). Soil may be weak when it is loose, wet, or both. During landfill cover construction, excessive loads are likely to result from heavy wheeled machines such as earthmovers. High soil density may also result from traffic by lightweight vehicles with small tire prints, such as pickup trucks, especially when operating on loose or wet soil.

11.2.2 SOIL WATER CONTENT

Soil water content has a large effect on soil strength. The *plastic limit* is "the minimum water content at which a small sample of soil material can be deformed without rupture" (SSSA 1997). It is an important measure of a soil's ability to support heavy or vibrating loads.

Dry soils can support substantial loads, but wet soils are weak. At the plastic limit, most soils can support the weight of some vehicles (Raper and Kirby 2006). McBride (2002) described standard laboratory methods for estimating the plastic limit. Very wet soils technically do not compact because all the pores are full of water; however, traffic or tillage of wet soils smears the soil, destroys soil pore continuity, and creates conditions for plant root growth worse than that produced by simple compaction alone. The water content of soil placed in an ET landfill cover should be substantially less than the plastic limit because construction machinery is heavy.

11.2.3 FIELD ESTIMATE OF PLASTIC LIMIT

During construction of an ET landfill cover, daily or even hourly decisions must be made about the suitability of soil used in the cover. Wet soils compact easily and dry soils resist compaction. Because it is better to avoid soil compaction than to correct it, there is need for a rapid method for estimating the water content of soil in the field. "*The plastic limit is a readily measured index of soil condition, defined as the moisture content dividing a plastic state from a rigid state, and corresponding to a liquidity index of zero*" (Raper and Kirby 2006). Soil scientists and agronomists developed a field method to estimate the plastic limit; it is suitable for use during ET cover soil construction. A quick field test to judge whether soil is wetter than, at, or drier than the plastic limit for agricultural operations follows:

- Work a small ball of soil (half the size of a golf ball) in the hand, and then roll a part of it into a thread or worm it between two hands.
- If the soil cannot be rolled but smears easily, then it is much wetter than the plastic limit. Compaction will result from traffic by all vehicles and tillage tools.
- If a long, thin thread (about 5-cm by 3- to 5-mm diameter) is rolled easily, the soil is wetter than the plastic limit. Compaction will result from traffic by most vehicles.
- If the soil cannot be rolled into a thread but crumbles or breaks into hard crumbs, it is drier than the plastic limit. Severe compaction is unlikely.
- If the soil can just be rolled without crumbling but is "on the edge" of crumbling, it is near the plastic limit. Heavy vehicles, particularly wheeled vehicles, will compact the soil. Lightweight vehicles or those with low ground pressure (e.g., small tracked vehicles or those with low-pressure tires) may not.

These guidelines are rough, but they are useful field guides during construction. The laboratory test is similar, but performed under controlled conditions. The machines used to place soil in an ET landfill cover are heavier than agricultural machines and they work in loose soil, so the soil should be drier than the plastic limit when placed in an ET cover.

11.2.4 VEHICLE OR MACHINE WEIGHT

Large, heavy vehicles compact the soil deeper in the profile and to a higher density than do lightweight vehicles. Farm tractors, harvesting machines, and other agricultural machinery are big enough to cause excessive soil compaction on wet field soils. Industrial earthmoving machines are used in landfill cover construction; they are heavier than agricultural machines, and therefore they are highly likely to cause excess soil compaction and leave the soil with high soil density that is unacceptable for good plant growth. Axle loads of 10 Mg and greater are likely to cause significant soil compaction in farm fields and reduce plant growth (Raper and Kirby 2006). They recommend maximum axle loads of 6 Mg for farm machines. Raper and Kirby (2006) provide recommendations for farm fields having an existing soil structure that is better able to support loads than loose fill soil on an ET cover during construction. Therefore, axle loads for machines working on new ET covers in loose fill soil should be less than 6 Mg.

11.2.5 WHEELS AND TRACKS

Soil compaction is most severe under wheels and tires. Tracked vehicles spread the load over a larger area and reduce soil compaction. Dual tires spread the load over a greater area than single ones, but they may cause either more or less soil compaction than the latter, depending on inflation pressure of the tires. Radial tires produce less compaction than bias-ply tires because their footprint is larger. Inflation pressure controls the soil–tire contact area and it is important for all tires; the correct pressure reduces compaction (Raper and Kirby 2006).

11.2.6 MEASUREMENT OF SOIL DENSITY AND THE CONE INDEX

There are two practical ways to estimate the response of plant roots to soil strength; they are to measure (1) soil bulk density or (2) the cone penetrometer index. Soil density is a basic soil property; it is related to soil strength and root growth as explained in Chapter 5, Section 5.1. The cone penetrometer index is a more direct measure of the probable influence of soil conditions on root growth; however, it may or may not be appropriate for use on ET landfill cover soils.

Soil bulk density is a standard measure of soil properties that is convenient to use during construction of ET landfill covers. The units for soil density are Mg/m^3 or the numerically equivalent g/cm^3. Soil density is easy to measure in the field by commonly used gamma ray meters and other methods. Such field measurements apply directly to estimates of future root and plant growth.

The term *Proctor Density* is widely used in the construction of roads, buildings, dams, etc.; however, it has no direct application to root growth. It is indirectly related to soil density through a laboratory measurement on a representative sample or samples of soil. Percent of Proctor Density is widely used during construction to describe the adequacy of soils used as structural material. However, it is not a direct measurement of soil density or the potential for growing plants on a particular soil.

Grossman and Reinsch (2002) present standard methods for measuring soil bulk density by the soil core, sand-cone, or gamma ray radiation methods. A field measurement of soil density reported in Mg/m^3 indicates the probable success for root growth in the particular soil measured without further manipulation of numbers.

Cone index is the force required to insert a standard 30° (steel) cone into the soil (ASAE standards 2004a,b). Lowery and Morrison (2002) present the background and theory for soil cone penetrometers.

Cone index measurement integrates soil density, particle size distribution, soil water content, and soil chemistry, as these parameters control root growth in soil. It does not predict root growth at a drier soil water condition. Soils having cone index values less than 1.5 Mpa generally do not limit root growth (Raper and Kirby 2006). The cone index value may have limited usefulness for ET landfill cover soils because its value changes with changing soil water content. However, the cone penetrometer identifies thin layers with high soil strength better than soil density measurements; this feature is important to ET landfill cover construction.

11.2.7 FIELD OPERATIONS AND REMEDIATION

Loosen the soil where compaction has already occurred on an ET cover soil. Subsoiling (chiseling) can loosen high-density soils if applied correctly. The soil water content should be less than the plastic limit to the full depth of tillage during subsoiling (Raper and Kirby 2006). Wheel traffic over soil loosened by subsoiling may compact the soil to its original density; therefore, it is much better to avoid excessive soil compaction than to attempt to remediate soils with high density. Subsoiling can improve compacted soils; however, after soils are compacted, it may be impossible to return the soil to its best state of soil tilth by subsoiling.

The best, if they are present, construction procedure is to measure the soil density of each lift and correct high-density soils before covering the lift. Before placing the next lift, chisel and then disk, or otherwise thoroughly till a compacted layer to the bottom of the lift or the bottom of the compacted soil if greater than the lift thickness. Then uniformly compact the loosened layer to the specified soil density.

11.3 SOIL PLACEMENT

Loose soil is easily compacted; as a result, new construction methods may be needed to place it at the desired density in an ET landfill cover. Excess soil compaction is a primary threat to the correct functioning of the cover. It is clear that heavy wheeled machines are inappropriate for use on an ET landfill cover. If the unlikely situation of loose soil occurs, it is easily compacted by additional passes of available construction machinery over the lift.

Bulldozer blades are normally dull; the "cutting" edge is commonly 2 to 6 mm wide and rounded by abrasion. The rounded edge exerts downward pressure on the soil, and it vibrates. As a result, the layer of soil immediately under the blade is compacted by the blade. In addition to this compaction, the soil is compacted by the tracks of the tractor.

Fulton and Wells (2005) show that high soil density is a primary cause of poor plant growth on reconstructed minesoils in Kentucky. Mining companies cannot produce adequately low soil densities using conventional mining machinery. Fulton and Wells (2005) measured soil density for conventional placement by mining machinery (bulldozers) and found that it averaged 1.6 Mg/m^3; however, the soil in the surface layer (15 cm) had a density of 1.7 Mg/m^3. They stated that bulldozers commonly compact surface soils to a higher density than soil at the bottom of the soil lift. It is important to note that they studied compaction in a wet climate and did not state the water content of soil during placement. They recommend soil densities below 1.5 Mg/m^3 and state that for optimum root growth, the soil density should be less than 1.3 Mg/m^3.

Hauser and Chichester (1989) placed two dry soils in 30-cm-thick lifts with a medium-size, tracked bulldozer; after placement, the soil had a uniform density of 1.4 Mg/m^3. In addition to compaction by the dozer blade, they ran the tractor tracks over the entire surface. Generally, dry soils compacted by the tracks of a bulldozer should produce satisfactory ET landfill covers.

11.3.1 MACHINERY AND HAUL ROADS

Conditions may be less than optimum for soil placement on ET landfill covers. When soil is loose, it is easily compacted too much. Heavy machines or moist soil may require use of track-mounted machines with extrawide tracks. Thick lifts of soil may help to control soil density. If the first pass of the track-laying machine leaves the soil too loose, it is easily compacted to higher density by additional passes.

If the bulldozer "push distance" becomes too long, a network of haul roads provides an alternative to deliver cover soil to the placement equipment. Compaction under haul roads could extend to a depth greater than 1 m. Chisel and disk or otherwise loosen the high-density soil under haul roads to the bottom of the finished cover before the haul-road site is included within the ET cover soil.

Fulton and Wells (2005) reported results from a new soil placement machine called the *Soil Regenerator.* The machine consists of a large auger mounted on a bulldozer blade that is pushed by a tracklaying tractor. The machine picks up a windrow of soil and moves it laterally to the cover soil. The resulting cover may be up to 1.2 m thick. Their tests show that the density of soil in place was less than 1.0 Mg/m^3. Their machine proved capable of placing soil at low density.

11.3.2 REMEDIATION OF COMPACTION

Chiseling followed by disking to the full depth of the compacted soil is a good method to remediate compacted soil. Chiseling is most effective if carried out when the soil is dry. Moldboard plowing, if it extends to the full depth of compaction, is a particularly effective practice for loosening compact soil. Plowed soil may be so loose that it requires some compaction to increase its density and load-bearing capacity. A minimum soil density of 1.0 Mg/m^3 is adequate for many soils.

Air voids left in the soil by deep chiseling should cause no harm to the cover unless they are very large. The offset disk harrow or a similar tillage tool effectively reduces large clods and soil voids created by chiseling.

11.3.3 TEST COVERS

A test cover provides an opportunity to verify the proposed construction methods and machines. A test cover may be particularly useful at humid sites, where soil is relatively wet during the construction period, and may prove that proposed methods are suited to the local soil. After the construction methods are verified, the soil from the test pad may be placed in the final cover or it may be retained as a test site at which to evaluate changes in the borrow soil during construction.

Soil density measurements evaluate construction methods. Where the borrow soil is relatively wet, the cone penetrometer may provide useful additional data. The use of both methods to verify the construction procedure may increase confidence in the suitability of the methods used.

11.4 INTERIM SOIL EROSION CONTROL

The establishment of the final vegetative cover should begin immediately after the construction of cover soil is complete. Delay may allow unwanted soil erosion.

ET landfill covers need a robust, healthy stand of grass or other dense vegetation to control soil erosion. After establishment, native vegetation provides highly effective erosion control; but during grass establishment, the soil may be vulnerable to soil erosion.

Because bare soil is vulnerable to soil erosion, establish temporary plant cover soon after construction. A single severe storm falling on bare soil could remove enough soil to require rebuilding the surface (Figure 11.1). Many native plants are difficult to establish and they may grow slowly for up to 2 years; they need protection from competing weeds and effective soil erosion control during that time. Fortunately, temporary plant cover or crop stubble can adequately control soil erosion for 2 years or longer (Figure 11.2).

FIGURE 11.1 Soil erosion resulting from a single rain on a bare seedbed. (Photo courtesy of USDA Natural Resources Conservation Service.)

FIGURE 11.2 Drill seeding in standing crop residue. (Photo courtesy of USDA Natural Resources Conservation Service.)

If the cover construction is completed during a nongrowing season, assess the probability of soil erosion or deep percolation. Temporary erosion control may be needed. Straw is an excellent temporary cover; however, even low-velocity winds can remove it. Anchor straw mulch by crimping it into the soil, using chemical binders or some other means. Other locally available temporary covers (e.g., wood chips, etc.) may be acceptable.

If the cover construction is complete, during or just before an active growing season, establish temporary vegetative cover immediately and irrigate if needed. An adequate, temporary vegetative cover will control erosion, leave the cover soil in a relatively dry condition, and control harmful soil crusts that may prevent grass establishment.

11.5 GRASS ESTABLISHMENT

Native grasses and forbs are difficult to establish in all climates, but especially so in semiarid and arid climates. Seeding efforts to establish native grasses often fail. For example, a 3 year study of native grass seeding in the humid areas of the Southern Great Plains showed that 50% of farm and ranch seeding efforts failed (Great Plains Council 1966).

The seeds of most native grasses and forbs are small; therefore, the maximum seeding depth is shallow. Even in humid climates, the top 12 mm (1/2 in.) of bare soil may dry below the plant wilting point in less than 1 day after a rain or irrigation. The planting depth for most small seeds is between 3 and 6 mm (1/8 and 1/4 in.). Small seeds planted deep, where the soil remains moist longer, produce few, if any, plants because they have small food reserves. Small seeds exhaust their meager food reserves before the seedling can produce leaves above ground. In addition, the best available seed supply usually contains some immature seeds of poor quality; they produce seedlings with low vigor that cannot survive deep planting.

11.5.1 SPECIES

In natural grassland ecosystems, most of the plant species will be grasses, but forbs also form an important part of the plant community. Grasses are more widely planted than are the associated forbs because grass seeds are easier to harvest than are forbs; thus, they are more readily available. If seed supplies of locally adapted, desirable forb species are available, they should be included in the mixture. However, forbs may appear naturally in a planting of multiple grass species. At some locations, both warm- and cool-season grasses are native; in such cases, plant both, but they may need separate seeding dates.

11.5.2 FERTILIZER

Fertilizer produces a beneficial effect on cover establishment; however, do not apply nitrogen fertilizer before establishing seeded permanent plants (Howard et al. 1977). Nitrogen fertilizer applied before seeding the permanent species encourages excessive growth of weeds during the grass establishment period. Phosphorus and potassium applied before or during seeding may be less damaging than nitrogen. Excessive weed growth seriously damages plant seedlings by competing for sunlight and soil water. Apply nitrogen fertilizer, after the seeded species are established.

11.5.3 SEEDING MACHINES

Many grass seeds have fluffy seed coats that are difficult to remove; however, seed producers have developed methods to improve many of these seeds. Many desirable plant species have small seeds. Seeding machinery should be tight enough to hold the seed and capable of planting uniform rates of fluffy seeds over the entire land surface.

Some cool-season grasses and forbs may be planted up to 19 mm (3/4 in.) deep in the standing stubble; but most warm-season grasses and forbs should be planted not more than 6 mm (1/4 in.) deep. Depth of seed placement is very important; furrow openers using double disks with depth control bands or wheels on each furrow opener best achieve the correct depth. Close the furrow with dual-angled press wheels or an equivalent device to consolidate the soil around the seed. The seeder should have adequate weight and down-pressure control to force the furrow openers into firm soil and to ensure that each opener acts independently to accommodate uneven ground surfaces. The seeding machine should travel at less than 4 km/h (2.5 mi/h) to ensure correct planting and seed covering; higher speeds may result in uneven planting or dropping of seeds on the soil surface.

11.5.4 SEEDING METHODS

Currently used methods for establishing native grasses and forbs include the following:

- Hydroseeding
- Solid sod application and sprigging
- Broadcast seeding on the surface
- Drill seeding in bare soil
- Drill seeding in standing crop residue

11.5.4.1 Hydroseeding

Hydroseeding was developed for steep slopes such as embankments along roadways where conventional seeding machines cannot operate. It employs mixtures of seeds and fibers suspended in water. The seed and fiber mix is pumped through nozzles at high pressure to permit application up to 30 m away from the mobile seeding unit. The fibers used are commonly wood or straw; binders glue the fibers together to reduce movement by wind or rain after placement. Hydroseeding may deposit the seed within the fiber mulch, thus separating the seed from the soil and preventing plant establishment. High winds may roll up the hydroseeded mats. Hydroseeding is expensive, and in the western Great Plains, resulted in a 10% success rate on reclaimed minelands (Dr. Gerald Schuman, personal communication, August 18, 1995).

11.5.4.2 Solid Sod Application and Sprigging

Solid sodding and sprigging successfully establish monocultures of sod-forming grasses; however, both are expensive and need frequent irrigation during the establishment period. Other methods are more appropriate for establishment of grass on landfill covers where several species, including bunch grasses, are preferred rather than a sod-grass monoculture.

11.5.4.3 Broadcast Seeding

Broadcasting seeds on the soil surface—either with or without mulch cover—produces many seeding failures. Ants, mice, birds, and other creatures remove or destroy large numbers of seeds. The germinating seeds dry rapidly in both humid and arid conditions, producing high seedling mortality rates.

11.5.4.4 Drill Seeding in Bare Soil

Seeds may be planted by drilling into furrows on bare soil. Erosion control during plant establishment is a major problem, although mulch application after seeding reduces erosion if enough mulch is applied. Rain on the bare soil may produce a strong soil crust and other long-lasting unfavorable soil physical properties that limit plant growth. Irrigation improves the success rate; however, this seeding method is only moderately successful in arid and semiarid locations. It is more successful at humid locations.

11.5.4.5 Drill Seeding Mulch Cover

A mulch of mature plant parts on the ground surface greatly improves the probability for seeding success. Straw provides a good mulch cover. Even light winds move loose straw; anchor it by crimping the straw into the soil with straight disks or with materials that glue the fibers together. Standing crop residue is excellent low-cost mulch; it substantially improves the probability for seeding success. Drill seeding in standing crop residue is both successful and economical (see Figure 11.2).

11.6 DRILL SEEDING IN STANDING CROP RESIDUE

11.6.1 Benefits

Planting an annual grain crop such as barley, wheat, or oats quickly produces a thick cover of standing stubble. The crop residue forms high-quality, durable mulch. These annual grasses are easily established, and they produce a thick standing cover of stubble. It is desirable to prevent the formation of viable grain in the plant heads to avoid a second crop of grain. When the grain in the heads is forming, but still immature, and the stalks are mature, mow the crop at a height of about 0.2 m (8 in.) to produce standing stubble or kill the crop with chemicals. The standing stubble will control both wind and water erosion. Seed the desired perennial grasses and forbs directly into the undisturbed standing stubble. The stubble cover reduces evaporation of soil water from the seed zone, protects seedlings from temperature extremes, and significantly reduces weed competition.

Both field research and production experience demonstrated that this method of seeding is reliable and low in cost. With the addition of irrigation water during the plant establishment phase, this method has a high probability for success.

11.6.2 Mulch Crop

Seed the mulch crop during the appropriate season. Examples of options for the sites in Southern Great Plains with differing completion dates, include (1) in spring or summer, seed Sudan grass; (2) in fall, seed winter wheat, rye, barley, or oats; (3) in winter, seed spring barley, or oats. In the central and Northern Great Plains, spring barley or wheat produces a durable and effective cover (Pinchak et al. 1985; Schuman et al. 1980). The plants should be mowed 0.2 m (8 in.) high when immature seeds are in the milk stage (grain is filled with milky or soft material) of grain development to prevent reseeding the area with the crop. Seed the permanent vegetation into the standing stubble during the next appropriate planting season. Preserve the standing stubble by minimizing machine operations on the land. The standing stubble accomplishes the following:

1. Controls both wind and water erosion for up to 2 years
2. Shelters the seedlings from wind and the beating action of intense rainfall
3. Reduces the rate of soil drying
4. Maintains more uniform temperatures around seeds and seedlings than bare soil
5. Increases infiltration of precipitation or irrigation over that for bare soil
6. Costs one-fourth to one-twentieth as much as straw mulch applied to bare soil
7. Suppresses undesirable weed growth
8. Improves soil physical properties to the 0.4-m depth (Schuman et al. 1980)

11.7 IRRIGATION

The cost of irrigation during cover establishment is a small fraction of the total cost for landfill completion; it greatly improves the probability for success with any seeding method and at any location. Irrigation produces success in arid and semiarid regions where failure is likely with rainfall alone. It is beneficial at humid sites.

Sprinkler irrigation is the most practical method for irrigating a landfill cover. Sprinkler irrigation (1) can control the depth of soil wetted, thus protecting the waste from drainage; (2) is adaptable to any cover shape or land slope; and (3) does not require permanent structures on or near the cover. Water that is suitable for use on irrigated crops is best for irrigating an ET cover. Irrigation requirements for field crops assume the use of water for many decades with consequent salt buildup in the soil; this restriction does not apply to establishment of vegetation on an ET landfill cover. Because ET covers need irrigation for a short time, water of lesser quality may be used. Treated sewage effluent and other water with moderate salt content may be suitable for irrigating seedlings on ET covers.

11.8 NEW GRASS ESTABLISHMENT METHODS

Pregermination of grass seeds before planting was effective in experimental plantings (Hauser 1986). It is effective and used commercially for vegetables; however, grassland seeding with pregerminated seeds would require new equipment and training of personnel.

Water applied in the seed furrow is an inexpensive technique; it doubled the number of seedlings established as compared to no water application in the seed furrow [Figures 11.3 and 11.4; (Hauser 1989)]. The equipment needed is inexpensive and readily available, and the user can attach it to any planter. In experimental plantings, water applied in the seed furrow improved stand establishment in either moist or dry conditions.

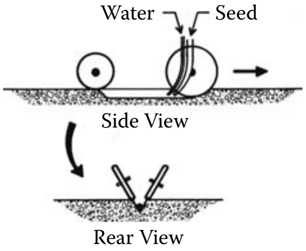

FIGURE 11.3 Double-disk furrow opener with water application in seed row. (Hauser 1989, *J. Soil and Water Conservation* 44(2): 153–156. With permission.)

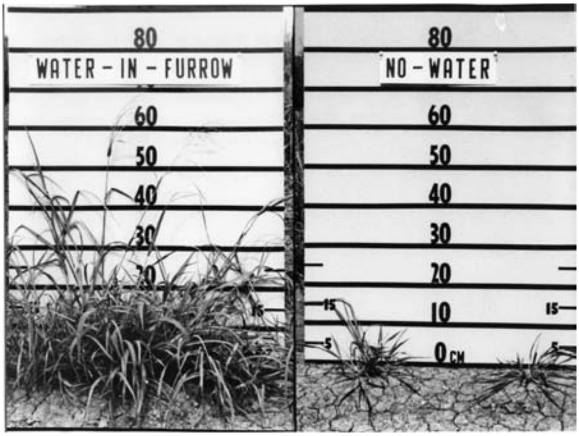

FIGURE 11.4 Grass growth 78 days after seeding. (Hauser 1989, *J. Soil and Water Conservation* 44(2): 153–156. With permission.)

11.9 CONSTRUCTION COMPLETION

The owner, appropriate governmental regulatory bodies, and other interested parties will require certification that the cover meets the requirements for the site. Certification includes (1) construction QC reports, (2) construction records, and (3) certification that the records and reports are true and accurate. The guidance document published by the ITRC provides specific requirements of the U.S. Environmental Protection Agency (EPA) regarding certification (ITRC 2003).

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12 Maintenance and Monitoring

After construction is complete, maintenance and monitoring are required to assure that the landfill cover protects human health and the environment for decades or centuries. In many ways, maintenance of an evapotranspiration (ET) cover is no different from that needed for a conventional landfill cover or other long-term remediation effort.

The four basic topics important for landfill maintenance are (1) cover integrity, (2) leachate management, (3) groundwater monitoring, and (4) landfill gas monitoring and management. Of the four, the cornerstone of ET cover maintenance is cover integrity. Maintaining the integrity of the cover assures that it can function as designed. Good cover integrity minimizes the possibility for groundwater quality deterioration, unexpected leachate concerns, and other potential problems.

McBean et al. (1995), Koerner and Daniel (1997), ITRC (2003), and United States federal and state regulations discuss maintenance and monitoring of conventional landfills and their covers. This chapter focuses on concepts that are important to cover integrity for the ET landfill cover.

12.1 DEEP PERCOLATION MONITORING

In this book, deep percolation (PRK) is the amount of precipitation passing per unit of time through the landfill cover into the waste in a landfill (see Chapter 6). There is no requirement to measure PRK through conventional-barrier landfill covers. Barrier covers that satisfy the design requirements contained in United States Environmental Protection Agency (U.S. EPA) rules and regulations and are designed with the aid of the Hydrologic Evaluation of Landfill Performance (HELP) model are accepted as adequate. No further proof of performance is required after the cover is built and accepted. This policy has resulted in apparent satisfactory performance by a large number of conventional-barrier landfill covers currently installed on landfills.

Measurements included in research at 24 conventional-barrier landfill covers are available (Table 3.1, Chapter 3). The covers conformed to specifications found in EPA rules and regulations for barrier landfill covers. Performance measurements for the barrier test covers show that where annual precipitation exceeded 300 mm per year, 16 of 18 covers leaked (Table 3.1). Surprisingly, four of six barrier covers located at arid sites with less than 300 mm per year of precipitation also leaked. These measurements demonstrate that conventional-barrier landfill covers leak and suggest that the current practice accepts, without PRK monitoring, landfill covers that are probably leaking.

Chapter 4 and Hauser et al. (2001) summarize the ample proof that the ET landfill cover concept is sound and capable of controlling PRK. Chapter 9 demonstrates that the Environmental Policy Integrated Climate (EPIC) model is adequate and sufficiently accurate for use in the design of ET landfill covers. Measurements of PRK through barrier covers have not been required, and there is no apparent reason to measure PRK through an ET landfill cover.

12.2 COVER INTEGRITY

The ET cover must remain intact in order to perform as expected. During inspections observe, measure if appropriate, and record the following cover conditions:

- Appearance and condition of the vegetation
- Vegetation stress or death due to landfill gas
- Eroded soil deposited at the toe of steep slopes
- Sheet or other soil erosion
- Rills or cracks in the cover
- Changes in surface slope and settlement of the waste
- Intrusion by humans or animals
- Holes of any kind that allow surface runoff to enter the landfill directly
- Trails beaten out on the cover
- Damage by vehicles or maintenance machines

12.3 GROUNDWATER MONITORING

The primary goal of groundwater monitoring around landfills is to detect release of harmful materials from the waste. Design and implementation of a good groundwater monitoring system should be based on a thorough understanding of the hydrogeologic properties of the site and the cover.

Following extreme events, there is potential for water to move into the landfill waste and extra monitoring may be justified. For example, following a 3 day precipitation event with return frequency of 50 years, extra groundwater monitoring may be appropriate. Determine monitoring requirements and the duration of increased monitoring from previous site history, hydrogeology of the site, thickness and properties of the waste, and the kind and condition of the landfill liner. Groundwater monitoring of landfill performance is similar for landfills with any cover in place.

12.4 VEGETATION MANAGEMENT

The vegetative cover is particularly important on an ET landfill cover. Typical native prairie grass needs little or no attention. Normally, there will be no grazing animals on an ET cover, and it will seldom be allowed to burn for obvious reasons; however, these are important parts of native grass prairies. Therefore, two links are missing from the native ecosystem. It is unlikely, but possible, to encounter problems on an ET landfill cover not seen in typical native grass prairies. Periodically inspect the cover for burned areas, overall plant vigor, disease or pests, change in plant cover, and weed infestation.

Investigate the cause of low plant vigor, and apply corrective action if needed. Low plant vigor resulting from drought is generally not a cause for concern. A native grass cover will contain normal plant disease and pests, but they seldom attack all species at the same time and are unlikely to kill the plant cover.

After completion of the cover, periodic inspections should verify that the planned plant species are growing on the cover. Changes in plant species growing on the cover may be acceptable if the new plants are part of the native vegetation found in nearby stable ecosystems. In any case, the plants growing on the cover should be capable of producing large amounts of biomass and consuming the maximum amount of water available at the site.

12.5 BURNING

Occasional burning might be employed to control weeds, brush, or tree invasions. However, one must first determine that there are no flammable gasses coming from the landfill, which might carry the fire into the waste. In addition, any pipes or other structures on the landfill must be protected from damage. The burning should be planned to keep the heat from the fire low enough to prevent damage to the plant crowns.

Burning is a possible way to manage the vegetation; however, it will require substantial effort to assure that goals are met and the landfill is not damaged. Frequent burning or burning at the wrong time of year will weaken the plant cover.

12.6 GRAZING

Grazing may be suggested as an alternative land use or for maintenance of ET landfill covers. In order to maintain a correctly functioning ET cover, the following limits should apply to grazing:

- Grazing animals should not remove more than 50% of the annual biomass.
- The standing plant height should be greater than 40% of the maximum.
- Maintain a living leaf area index greater than four at all times.
- When soil water content in the top 0.3 m of cover soil is greater than the plasticity index, there should be no grazing. Hooves of grazing animals compact wet soil.

These requirements make grazing impractical. Conventional grazing is much too severe for use on a landfill cover. In addition, the vegetation may contain contaminants that should not enter the food chain. Generally, grazing an ET landfill cover is incompatible with objectives for the cover.

12.7 WEED CONTROL

Wild free-roaming animals and fire maintained healthy weed-free stands of native grasses before interference by humans. The goal for a landfill cover is a similar healthy grass community. However, wild free-roaming animals and perhaps fire are not viable options for the management of ET landfill covers. Therefore, action may be required occasionally to maintain a good grass cover.

Shrubs and trees naturally invade grasslands. Periodic mowing to a height of 15 to 20 cm should control shrubs and trees. Mow the cover in the fall or at the end of the growing season when grass seeds have matured. All biomass including the seeds should remain evenly spread over the cover to control soil erosion and recycle plant nutrients. Mowing may prevent deep snowdrifts during winter and encourage even distribution of snow over the cover. Base the mowing interval on site needs; 2- to 5-year intervals will be adequate at many sites.

Plants commonly called weeds may produce large amounts of biomass and some are a desirable part of a native grass cover. On the other hand, some weeds have short growing seasons, kill the desirable forbs and grasses, or use less water than native grasses. Some weeds will appear periodically. Judgment based on knowledge of local native plant communities is needed to determine if troublesome weeds have invaded the cover and the need for action, if any.

Do not use herbicides to control broadleaf weeds, because they may kill desirable forbs. Use mowing during a critical time of the weed's life cycle, instead. The best defense against weeds is a healthy vigorous cover of native grasses. They naturally control the vegetation cover at the site. Normally, there will be no need for weed control after the grass is well established.

12.8 SOIL FERTILITY AND CHEMISTRY

There should be few changes in soil chemistry that need monitoring and maintenance. Excessive fire or unusually high rainfall may deplete the store of nutrients, particularly in the surface soil layers; apply fertilizer to correct deficiencies.

Soil pH may change, if so, adjust low soil pH upward into the neutral range; the desired pH value should match the requirements of plants native to the area. Investigate soil pH values above 8.0 immediately; chemicals may have been dumped on the landfill.

Plant appearance is an indicator of need for added nutrients. If the plants are light in color, have yellow leaves, or have other symptoms of nutrient deficiency, test the soil and apply needed fertilizer. Plant nutrients should recycle after a healthy stand of grass is established and the initial fertilizer is applied. If plant material is removed or burned, fertilizer may be required. Extra fertilizer may be needed during the first few years, before the nutrient recycling process is fully established.

Repeated application of some nitrogen fertilizers may significantly reduce the pH of the surface soil. Test the pH of the surface soil. It is relatively easy to correct low pH of surface soil by the application of agricultural lime.

12.9 SOIL DENSITY CONTROL

Healthy, robust plant growth on ET landfill cover depends on the maintenance of good soil tilth, as explained in Chapters 5 and 10. When construction is complete, the maintenance of good tilth and low soil density remains a high priority for as long as the cover remains on the landfill.

Natural processes are unlikely to correct the effects of soil compaction. Mechanical correction is expensive and may only improve the soil rather than fully correcting the effects of compaction. As a result, prevention of compaction is important during each year of cover life. The following actions should limit or prevent soil compaction:

- Never allow tractors, machines, or other vehicles on the cover when the soil is wet.
- Require that wheeled tractors have no extra ballast on the tractor or in the wheels.
- Use the lightest weight tractor available.
- Use lightweight, tracked tractors on the landfill cover.
- Never allow cars or trucks to drive on the landfill.
- Use wheeled tractors and machines mounted on low ground pressure tires.
- Measure the cone index and soil density to assess the effects of possible compaction.

At the end of the growing season, the soil is usually dry, the optimum soil condition for mowing. If heavy rains occur before scheduled mowing or other machine operations, then consider postponing the operation until the following year or at least until the soil has dried. The soil should be well below the plastic limit to a depth of 0.3 m or more, depending on weight of the tractor or machine.

A disadvantage of using tractors with steel tracks is the plant damage that they can cause when turning the tractor. However, it may be better to suffer some plant damage in order to prevent soil compaction.

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13 Miscellany and Summary

This chapter contains topics that did not fit in other chapters, sources for technical data, and a closing summary statement.

13.1 DESIGN AND PRESCRIPTIVE RULES

Rules and regulations prescribe important parts of conventional-barrier cover design. Such restrictive rules and their application allow limited freedom for the design engineer to create new and better landfill covers.

Fortunately, the regulations also allow alternate designs; however, this important feature of regulations lay dormant and unused for many years. At present, some regulators and engineers actively promote and examine alternative designs. Thus, the situation is improving.

13.2 ALLOWABLE LEAKAGE

When the evapotranspiration (ET) landfill cover was first introduced to regulatory bodies, they rejected the concept because it does not follow the prescriptive rules and regulations and also because of the widely held perception that conventional covers are "impermeable." The myth of "impermeability" was part of the accepted notion that conventional-barrier covers are adequate and provide a suitable "presumptive remedy" for landfill remediation.

The performance measurements for conventional-barrier landfill covers cited in Chapter 3 were the result of relatively short field tests. None of the published measurements exceeded two decades in duration; most measurement periods were less than 5 years in length. In some instances, the percolation rate through the cover was increasing at the end of the short test. The duration of these tests is short when compared to an expected need for a cover that extends to multiple decades or centuries. In addition, future events are likely to increase the leakage through barrier covers; for example, waste settlement creates major stresses on the cover.

Conventional-barrier landfill covers oppose natural forces; this is a major reason to expect them to leak more, not less, in the future. In spite of the strong evidence that they leak, correctly built barrier covers have protected human health and the environment; therefore, it is logical to conclude that some leakage through a landfill cover is not harmful.

Each landfill has site-specific needs. The allowable deep percolation through the cover at the site is perhaps the most important site requirement. Average allowable leakage estimates for ET covers are developed and contained in Chapter 8, Section 8.2; they provide guidance when setting the site-specific allowable deep percolation amount.

A criterion is proposed for landfills that need a minimum deep percolation through the cover:

- The average allowable annual deep percolation rate through municipal waste should not exceed 3% of average annual precipitation.
- Where waste decay or other factors require more water, the allowable leakage may be greater.

The proposed criterion is based on field measurements at numerous field sites. It is conservative, yet allows latitude in design and performance. Where deep percolation should be greater (e.g., on a bioreactor landfill), the ET cover is easily designed to meet the needs of the site. The ET landfill cover can easily meet site requirements.

13.3 TECHNICAL RESOURCES

The ET landfill cover utilizes different technical resources than those needed for design and installation of conventional covers. Because ET cover technology emphasizes soil, plants, climate, hydrology, and their numerous interactions, the required engineering and science background includes several disciplines. Useful information sources available to the design engineer are

- American Society of Agricultural and Biological Engineers
- Soil Science Society of America
- Agronomy Society
- Crop Science Society of America
- U.S. Department of Agriculture

Agricultural engineers have used this science in their work for decades. The standard tests needed to implement ET covers are contained primarily in publications of these societies; Appendix A contains a list of selected publications and addresses.

13.4 RESEARCH NEEDS

Because the quest for knowledge should be unending, the author expects new developments in the future. Concepts that appear worthy of research investigation include

- *A new concept for waste disposal that does not use landfills.* Landfills pass to future generations a large and unknown maintenance cost with little hope for cost recovery. They consume vast amounts of capital, produce little that is useful to humans, and consume capital that should be used to create new jobs and industries producing useful products.
- *Continued development of landfills as rapid waste digesters.* Important work is underway on this topic now. The potential benefit is large.
- *Mechanisms for and the true magnitude of preferential flow.* Research shows evidence of preferential flow. However, available evidence from

long-term field measurements indicates that preferential flow is not a significant threat for ET landfill covers. The evidence is conflicting.

- *Improved methods for soil mixing and placement.* The movement and correct placement of soil on landfills for ET covers are difficult.
- *Methods to create or preserve soil structure.* Poor soil structure dooms an ET cover to failure.

13.5 SUMMARY

Chapter 3 describes alternative vegetative covers that do not meet the requirements for a landfill cover or for an ET cover. Section 3.5.5 (Chapter 3) describes common elements of failure for such vegetative covers. It is important to understand the difference between ET landfill covers and alternative covers that do not satisfy relevant requirements; the primary difference is soil density.

This book contains the philosophy for landfill covers; proof of the ET landfill cover concept; the technical basis for the ET cover, its design, construction, and monitoring; and a basis for defining the allowable leakage through an ET landfill cover. The proof of the ET cover concept includes measurements representing decades and centuries of water movement.

In addition, this book presents a unified engineering approach that describes the ET cover, how it meets requirements, its technical basis, modeling, and design. Although it focuses on landfill covers, the principles are similar for application of the ET cover to other wastes.

The ET landfill cover meets requirements for remediation of waste sites; it reduces remediation cost below that for conventional covers and provides a self-renewing cover suitable for centuries of use.

APPENDIX A— Reference Bibliography

Appendix A contains a selected reference bibliography to assist the reader in finding additional information.

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AGRICULTURAL ENGINEERING

ASABE, American Society of Agricultural and Biological Engineers, 2950 Niles Road, St. Joseph, MI 49085—Journals, Transactions, Books, Published Meeting Papers, Proceedings and Standards and Practices. http://www.asabe.org (accessed March 3, 2008).

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1. ASAE S268.4—Design, Layout, Construction, and Maintenance of Terrace Systems.
2. ASAE S442—Water and Sediment Control Basins.
3. ASAE S422—Mapping Symbols and Nomenclature for Erosion and Sediment Control Plans for Land Disturbing Activities.
4. ASAE S526.2—Soil and Water Terminology.
5. ASAE EP407.1—Agricultural Drainage Outlets–Open Channels.
6. ASAE S313.3.—Soil Cone Penetrometer.
7. ASAE EP542.—Procedures for Obtaining and Reporting Data with the Soil Cone Penetrometer.

APPENDIX B—Acronyms

A	Cross-sectional area
AFCEE	Air Force Center for Environmental Excellence
ASA	American Society of Agronomy, 677 South Segoe Road, Madison, WI 53711, USA
ASABE	American Society of Agricultural and Biological Engineers, 2950 Niles Road, St. Joseph, MI 49085-9659 (269) 429–0300
ASTM	American Society for Testing and Materials
AWC	Plant-available water-capacity—the difference between field capacity and wilting point
CEC	Cation Exchange Capacity
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CFR	Code of Federal Regulations
EPA	Environmental Protection Agency
EPIC	Erosion Policy Impact Climate model
ET	Evapotranspiration, the sum of evaporation from soil and plant transpiration, the actual amount
GM	Geomembrane
H	Hydraulic head
ΔH	Difference in hydraulic head or gradient
HELP	Hydrologic Evaluation of Landfill Performance computer model
I	Irrigation amount
ITRC	The Interstate Technology and Regulatory Council
K	Hydraulic conductivity, used for both saturated and unsaturated hydraulic conductivity
L	Lateral flow within the soil
MSW	Municipal Solid Waste
NRCS	Natural Resource Conservation Service (an agency of the U.S. Department of Agriculture), performs soil surveys, responsible for soil erosion control, irrigation, and flood control on agricultural lands
OSWER	Office of Solid Waste and Emergency Response
P	Precipitation
PET	Potential evapotranspiration
PRK	Deep percolation of water below the rooting depth or through the bottom of a landfill cover
Q	Surface runoff rate
q	Flux density or flux (flow per unit area), water movement within soil
RB/PB	Risk-based/performance-based
RCRA	Resource Conservation and Recovery Act
SCS	Soil Conservation Service; an agency of the U.S. Department of Agriculture, now renamed as Natural Resource Conservation Service (NRCS)
SSSA	Soil Science Society of America, 677 South Segoe Road, Madison, WI 53711, USA
ΔSW	Change in soil water storage, usually expressed volumetrically
t	Time
USDA	United States Department of Agriculture
U.S. EPA	United States Environmental Protection Agency
V	Flow volume per unit of time, or velocity

APPENDIX C—EPIC 8120

C.1 DESCRIPTION

The model named EPIC has evolved during continuous research that began in the early 1980s. The first model name was Erosion Productivity Impact Calculator (EPIC); the second was Environmental Policy Integrated Climate (EPIC), and the most recent name was Erosion Policy Impact Climate (EPIC) model (Gassman et al. 2004). The model was built for ungaged watersheds where calibration data were not available.

All versions of EPIC evaluate the effects of wind and water erosion on plant growth and food production. It was used to predict the relationship between wind and water erosion on soil productivity and food production throughout all of the United States. Because of the focus on productivity of plants in response to soil erosion, EPIC was required to make superior water balance estimates. Plant production changes slowly in response to erosion; therefore, EPIC can simulate all process over hundreds of years. It is a comprehensive model and continuously simulates all processes, using a daily time step and readily available inputs.

All versions of EPIC estimate PET, ET, Q, soil–water storage, and PRK—these complete the hydrologic water balance for an ET landfill cover. It accurately estimates plant growth and biomass production, ET, Q, PRK, the effect of changing carbon dioxide in the atmosphere, nutrient cycling, nutrient loss, and erosion by wind and water.

EPIC is generally applicable and computationally efficient. It includes seven physically based components for simulating hydrologic processes, Table C.1. Analysis of ET landfill covers does not use all EPIC model components; the user may omit them from model output files. A major advantage of EPIC is its proven capability to simulate climate in a realistic way over periods longer than measured weather records by using the stochastic climate generator.

The U.S. Department of Agriculture, Agricultural Research Service, and the Texas Agricultural Experiment Station with numerous cooperators developed the EPIC model (Mitchell et al. 1998; Sharpley and Williams 1990; Williams et al. 1990; Gassman et al. 2004). More than 200 engineers and scientists participated in the early development of EPIC, and numerous publications describe testing and use of it. It was tested for water balance estimates in dry and wet climates, including sites with significant accumulation of snow in winter. EPIC is in use by the Natural Resource and Conservation Service and by the Agricultural Research Service of the USDA; Iowa State, Texas A&M, Washington State, and other universities; the INRA of Toulouse, France; and in Australia, Syria, Jordan, Canada, Germany, Taiwan, and other countries.

TABLE C.1
Seven Major Components of the EPIC Model

Physical Component	Model Component
Weather	Daily values for rainfall, snow, snowmelt, air temperature, solar radiation, wind, and relative humidity. It stochastically generates realistic weather data or uses measured data.
Hydrology	Potential ET, actual ET, soil water content, surface runoff volume, peak runoff rate, deep percolation, snowmelt, lateral subsurface flow, and water table dynamics
Erosion–sedimentation	Water and wind erosion—evaluates management practices
Nutrient cycling	Nitrogen and phosphorus
Soil temperature	Influence on water use, plant growth, and root distribution
Plant growth	Potential growth, actual growth, growth cycle, water use, nutrient uptake, biomass, winter dormancy, root growth (constrained by stresses), temperature stress, nutrient stress, and water stress
Tillage	Simulates the effect on water balance, hydrology, erosion, and plant growth caused by tillage or by untilled grassland and forest, and the influence of living and dead plant material or bare soil

C.2 USING EPIC

The flexibility of EPIC requires organization by the user; assistance is available from the sources shown in Section C.3. Table C.2 contains a checklist that is useful when setting up EPIC for a particular site.

C.3 AVAILABILITY

EPIC is nonproprietary; it is available from the Texas Agricultural Experiment Station [Dr. J. R. Williams, Blackland Research Center, 720 E. Blackland Road, Temple, TX 76502 (e-mail: Williams@brc.tamus.edu) or Avery Meinardus, at (e-mail: epic@brc.tamus.edu) or on the Web at http://www.brc.tamus.edu/epic/ (accessed March 3, 2008) or at (254) 774–6000.]

TABLE C.2
Checklist Before Running EPIC 8120

Model for: ____

Data file names: (specific to this run)

Master file		Weather	
Operations		Crop data	
Soil		Print cntrl.	

File/Function	**Contents**	**Display with**	**File Name**	**OK**
Master data file	**Main data**	***util epic***	**User.dat**	
Soil data file	Density, part. size, etc.	*util soil*	User.**sol**	
Operations data	Plant, till, irrig., pest	*util opsc*	User.**ops**	
Weather data file, if used	Daily weather data	*wordpad or text editor*	User.**wth**	
List/Control files	Control files contain lists of files	*User Change*		——
SOIL8120	**List**: avail. soil files	*util soillist*	*Control file* **soil8120.dat**	
opsc8120	**List**: operation files	*util opsclist*	*Control file* **opsc8120.dat**	
EPICFILE	**List**: data files used	*util file*	*Control file* **epicfile.dat**	
EPICRUN	**List**: files to run	*util run*	*Control file* **epicrun.dat**	
Crop data	Crop properties	*util crop*	**crop8120.dat or: Usercrp2.dat**	
Tillage data	Tillage description	*util till*	**till8120.dat**	
Pesticide data	Properties of pest	*util pest*	**pest8120.dat**	
Fertilizer data	Properties of fertilizer	*util fert*	**fert8120.dat**	
TR55 data	**Do not change**	*util tr55*	**TR558120.dat**	
PARM data	**Do not change**	*util parm*	**parm8120.dat**	
Multirun data	Control data for multiruns/single runs	*util mlrn*	**mlrn8120.dat**	
Print/output control	Variables that appear in output files	*util prnt*	**prnt8120.dat or:**	

To run EPIC, type “epic8120”, then enter (or return key)

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Index

ENVIRONMENTAL ENGINEERING

Evapotranspiration Covers for Landfills and Waste Sites

New, natural, self-renewing, and low-cost, evapotranspiration (ET) covers for landfills provide a solution to landfill waste that is clean, green, and economical. ***Evapotranspiration Covers for Landfills and Waste Sites*** examines the conceptual theory and the practical proof, then explains the technology, design, and application. The author discusses why several vegetative covers have failed and provides simple, inexpensive solutions. He examines the design and construction of ET covers and other methods, highlighting their differences and successful alternative construction methods. The book also covers how the technology meets the requirements for covers on landfills, mining waste, and other sites.

Features

- Discusses design steps and contains an in-depth application of fundamental technology for selected design components
- Offers guidance regarding where ET covers may be appropriately used
- Explores how soil density affects root growth and water balance and discusses methods to control soil density
- Provides an analysis of the performance of conventional covers
- Presents construction requirements, maintenance, and monitoring issues unique to ET covers

This is the first resource to explore the technology required to apply the ET cover concept to landfill waste, spill sites, mineland restoration, and similar waste sites. After thoroughly describing the concept, technology, design, construction, and maintenance of ET covers, the book explains how this cost-effective, practical, easily maintained, and self-renewing biological system should maintain its effectiveness for centuries.

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