Waste Management Principles and Practice

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Sustainable Practices for Landfill Design and Operation

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Preface

This book was developed for waste and materials management practitioners all over the world, including researchers, practicing engineers and scientists, municipality staff and management, landfill operators, and regulatory agencies. The body of work presented here results from the development of bioreactor landfill design guidelines for the US Environmental Protection Agency's Office of Research and Development, along with the combined knowledge and experience of the authors pertaining to sustainable practices for design and operation of sanitary landfills. We presume the reader has a basic understanding of landfills, although the initial chapters attempt to set the stage by providing introductory commentary and a discussion of fundamental landfill concepts (both traditional and sustainable).

Following the introductory Chaps. 1–3, we provide a series of case studies that highlight the state of the practice of sustainable landfilling throughout the world. We sequenced the book so that readers could obtain a practical view of historic and current practices at operating facilities and how approaches to sustainable landfilling can differ from one location to another. Subsequent chapters are broken up to present discrete, focused discussion on the various infrastructure components, design practices, operational considerations, and monitoring elements that promote the more sustainable use of landfills as a component of integrated solid waste management systems.

This book was not written from a position of advocacy. Although the idea of accelerating decomposition in landfills has been around for decades, we felt that the opportunity to present the current state of science, including benefits and concerns, as well as current limitations and uncertainties, was appropriate, particularly in light of the significant amount of research and full-scale operational experience in the last 20 years. Furthermore, this text was not intended to be a rigorous design manual sufficient to completely design landfill-integrating sustainable technologies. Rather, the book was developed to serve as a tool for designers, regulators, and other parties interested in sustainable landfill practices and to be used in conjunction with fundamental design methodologies, location-specific regulations, new and emerging research results, and good engineering judgment. Dozens of graphs, figures, and tables provided throughout the text provide the designer an excellent foundation to begin their analysis and apply the principles from this book to their site or facility. In like fashion, operational experiences are provided throughout, tying in the important underlying fundamental concepts (e.g., accelerated gas production after liquids addition) to critical operational considerations (e.g., how to effectively collect the additional gas that is produced).

This book was designed to be assimilated by the reader in two ways. First, for the novice on the topic of sustainable landfills, a back-to-front reading through the chapters in sequence will provide an excellent background on sustainable landfilling practices since the chapters are presented in a progressive order; planning considerations are followed by detailed design and operational considerations, which are in turn followed by end-of-facility-life considerations. Second, for the more advanced reader, individual chapters may be examined with enough context so that the reader can apply the information presented in the book to their particular problem without heavy reliance on previous or subsequent chapters.

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A special acknowledgement must be given to the numerous collaborators, researchers, and funding agencies that allowed for such significant development of our understanding of sustainable landfilling and the benefits and challenges that sustainable landfilling can provide. Much of the work presented in this book comes as a result of funding from the Hinkley Center for Solid and Hazardous Waste Management, the Florida Department of Environmental Protection, the New River Solid Waste Association, the Alachua County Public Works Department, and the Polk County Waste & Recycling Division.

Finally, the authors also wish to acknowledge each of their families for tolerating the many long nights and early mornings spent developing this book.

Contents

Abbreviations, Acronyms, and Initialisms

ACSWL	Alachua County Southwest Landfill
BMP	Biochemical methane potential
BOD	Biochemical oxygen demand
BTU	British thermal units
C&D	Construction and demolition
CDM	Clean development mechanism
CFR	Code of Federal Regulations (USA)
CHP	Combined heat and power
COD	Chemical oxygen demand
CPT	Cone penetration test
CPVC	Chlorinated polyvinyl chloride
CSWMC	Central Solid Waste Management Center
DI	Deionized (water)
DO	Dissolved oxygen
DOE	Department of Energy (USA)
DPT	Direct push technology
DSWA	Delaware Solid Waste Authority
EIA	Energy Information Administration (USA)
EGC	Exposed geomembrane cap
ERT	Electrical resistivity tomography
ET	Evapotranspiration
EU	European Union
FEMA	Federal Emergency Management Agency (USA)
FID	Flame ionization detector
FOS	Factor of safety
FTIR	Fourier transform infrared (spectroscopy)
GCCS	Gas collection and control system
GHG	Greenhouse gas
GCL	Geosynthetic clay liner
GPS	Global positioning system
HDPE	High-density polyethylene

HELP	Hydraulic evaluation of landfill performance
HIL	Horizontal injection lines
HIT	Horizontal injection trenches
HOL	Head on the liner
IPCC	Intergovernmental Panel on Climate Change
ITRC	Interstate Technology and Regulatory Council
LCA	Life cycle analysis
LCI	Life cycle inventory
LCRS	Leachate Collection and Removal System
LFG	Landfill gas
LLDPE	Linear low-density polyethylene
LMOP	Landfill Methane Outreach Program
LRF	Leachate recirculation feature
MBT	Mechanical biological treatment
MC	Gravimetric moisture content
MSW	Municipal solid waste
MSW-DST	Municipal Solid Waste Decision Support Tool
MTG	Moisture, temperature, and gas
NESHAP	National Emissions Standards for Hazardous Air Pollutants (USA)
NMOC	Non-methane organic compounds
NRRL	New River Regional Landfill
NRSWA	New River Solid Waste Association
O&M	Operation and Maintenance
Open-Path FTIR	Open-path Fourier transform infrared microscopy
ORP	Oxidation–reduction potential
PCC	Post-closure care
PCNCLF	Polk County North Central Landfill
PGTT	Partitioning gas tracer test
PID	Photoionization detector
POTW	Publicly owned treatment works
PVC	Polyvinyl chloride
PW	Present worth
RCRA	Resource Conservation and Recovery Act (USA)
RD&D	Research development and demonstration
RFM	Rainfall modification
RO	Reverse osmosis
SCADA	Supervisory control and data acquisition
SPT	Standard penetration test
SSI	Subsurface inflow
TKN	Total Kjeldahl nitrogen
TDR	Time-domain reflectometry
TDS	Total dissolved solids
TEPC	Total earth pressure cells
TOC	Total organic carbon

TOUGH	Transport of unsaturated groundwater and heat-landfill gas migration
UCL	Upper confidence level
USACE	United States Army Corps of Engineers
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey
VFA	Volatile fatty acids
WRATE	Waste and resources assessment tool for the environment
WTE	Waste-to-energy

Units

ft	Foot/feet
kPa	Kilopascal
lpm	Liter per minute
m	Meter
SCFM	Standard cubic feet per minute

Chapter 1
The Landfill's Role in Sustainable Waste Management

Abstract The management of municipal solid waste (MSW) in many countries throughout the world has changed significantly over the past 50 years, with a shift from uncontrolled dumping or burning to complex systems that integrate multiple processes to recover materials or energy and provide containment to reduce environmental impacts. A discussion of past landfilling practices and the evolution to modern landfilling is provided. Opportunities for designing and operating landfills in a more sustainable manner are discussed.

Keywords Landfill • Solid waste • Sustainability • Bioreactor

1.1 Sustainability and Waste Management

Over the past 50 years, much of the world has witnessed a remarkable evolution in the management of municipal solid waste (MSW; the garbage and refuse resulting from household, commercial, and institutional activities), from uncontrolled dumping on the land and indiscriminate burning, to integrated systems incorporating waste processing, recycling, and treatment. This progress parallels society's growing awareness of the need to protect human health and the environment, and the importance of resource and energy conservation. Governments, businesses, and individuals now recognize, and in many cases embrace, the adoption of sustainable practices in many aspects of daily life, including the management of solid waste.

While many definitions have been proposed, sustainability can be broadly defined as the ability to meet current societal needs without compromising the anticipated needs of future generations. The US Environmental Protection Agency further describes sustainability as follows: "Everything that we need for our survival and well-being depends, either directly or indirectly, on our natural environment. Sustainability creates and maintains the conditions under which humans and nature can exist in productive harmony, which permits fulfilling the social, economic and other requirements of present and future generations" (US EPA 2008). Meeting present and future environmental, social and economic demands constitute the three pillars of sustainability.

The terms "landfill" and "sustainability," as linked together in the title of this book, may suggest a contradiction to some, as landfills—places set aside for the

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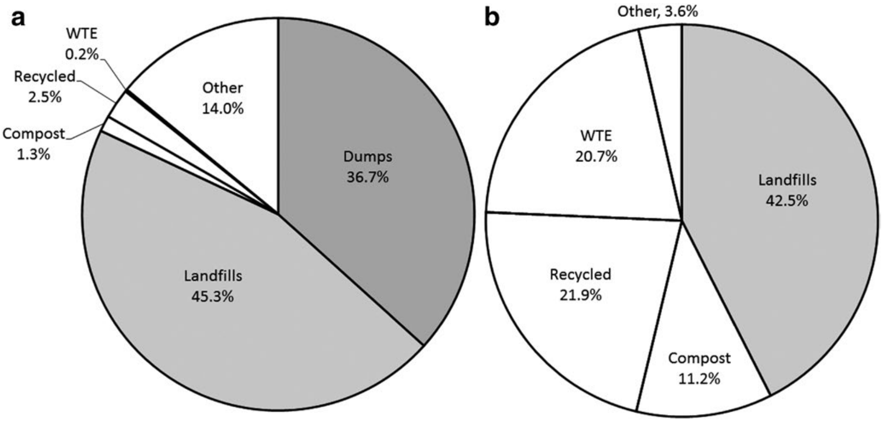

Fig. 1.1 Estimated MSW management in (**a**) middle and low income countries (total of 195 million Mg) and (**b**) high income countries (total of 588 million Mg); *Source* Hoornweg and Bhada-Tata (2012)

final placement of discards and throwaways—appear to be the opposite of a sustainable practice. Landfills, however, as a result of economic, social, and political realities, remain a major component of most integrated waste management systems around the world. As illustrated in Fig. 1.1, disposal of waste in landfills or dumps remains the predominant method for waste management worldwide (US EPA 2008; Hoornweg and Bhada-Tata 2012). Resultantly, engineers, scientists, and facility operators have endeavored to implement techniques and technologies to enhance the sustainability of this practice (Reinhart et al. 2012).

A common theme in sustainability revolves around shifting one's view of what would normally be considered a waste product to instead treating such materials as a resource or commodity. McDonough and Braungart (2003) coined the expression "waste equals food" as a tenet of green manufacturing and design, encouraging engineers to rework and develop services and goods that result in closed-loop material flows that are inherently benign and sustaining. Progress has been made in recovering wastes and utilizing them as a resource, but most of the world still relies on landfills as the predominant means of waste disposal.

The goal of sustainability and the realities of modern landfill dependence have led to the development of technologies that allow landfills to be operated in a more sustainable manner. In the developed world, modern landfills are constructed and operated with a goal of environmental protection using containment. These facilities generally meet some sustainability objectives by providing protection of human health and the environment in a cost-effective fashion. Some facilities have instituted practices to address additional sustainability objectives by treating the waste, recovering energy, or both. For much of the world, however, landfills are better referred to as open or uncontrolled dumps that pose immediate risks to human health and the environment.

This book evolved from efforts in the US to develop design guidelines for a solid waste management system referred to as a "landfill bioreactor," a facility that purposely encourages landfilled waste treatment in a controlled fashion. While basic guidelines for design and operation of landfill bioreactors have been available for more than 15 years (Reinhart and Townsend 1997), the growing implementation of this technology and concerns posed by poorly operated and designed facilities, demand the development of additional, more detailed design and operational guidance.

To address this knowledge gap, this book presents information that will be useful for owners, operators, planners, and designers of landfills—in addition to regulators charged with evaluating plans, designs, and operations of these facilities. The book also provides design and operational tools and guidance of interest to a wide variety of landfill operations, including facilities where leachate recirculation is practiced, sites where MSW is wet (either by nature or because of climate), and sites where optimizing methane recovery is paramount. The remainder of this chapter provides greater context on the historical development of landfill practices, the beginnings of sustainable landfilling practices, and the outline and organization of the rest of the book.

1.2 Non-sustainable Landfilling Practices

Prior to introducing practices for sustainable landfilling of MSW, it is useful to first describe what would generally be considered poor or unsustainable landfill operations; in some locations these might be more commonly described as open or uncontrolled dumps rather than landfills. Historically in developed nations, and currently in many parts of the developing world, MSW is disposed of not only in a manner considered unsustainable, but in one that poses risk of direct harm to human health and the environment. Figures 1.2, 1.3 and 1.4 illustrate common conditions

Fig. 1.2 Uncontrolled dumping of waste on a hillside in Eastern Europe

Fig. 1.3 Exposed leachate on the surface of a landfill in India

Fig. 1.4 Waste scavenging at an uncontrolled landfill in Central America

at dumps throughout the developing world, and the environmental and human health challenges they present.

Economic realities in many nations result in a large human presence at landfill sites, scavengers who are not officially associated with the daily operation of waste disposal. People, often including young children, sort through incoming waste for recovery of salable materials. It is not uncommon for waste scavengers and their families to live on or adjacent to the landfill itself. Potential immediate health risks include those posed by working in close proximity to waste vehicles and heavy equipment, exposure to harmful materials or chemicals, exposure to disease vectors, and explosions or fires that can occur because of gases produced from the decomposition process or incoming reactive wastes. In some cases, waste slides (slope failures) have occurred, burying and killing scavengers and their families.

Pollution of water and air resources commonly results from uncontrolled landfilling of waste. Leachate is the term used to describe the liquid resulting from water coming into contact with waste. Chemicals disposed of in the waste or byproducts from reactions in the landfill, dissolve (leach) into the water, and when this leachate emerges from the waste and, enters groundwater or a surface water stream, a risk is posed to those consuming or coming in contact with the affected water resource. Gases and particulate matter can also be released to the environment. Gases produced from the waste decomposition process, primarily methane, pose a potential risk of explosions and fires, and also act as a carrying mechanism for other chemicals in the landfilled waste, many of which may be toxic to humans. Particulates can be released from landfill fires or as dust disturbed as part of landfill operations.

Uncontrolled landfilling can pose a threat to ecological resources. Surface water resources contaminated as a result of waste disposal often have reduced dissolved oxygen levels, thus diminishing the ecological health of the water body and potentially resulting in the growth and spread of disease-carrying organisms. Without forethought in appropriate locations for landfills, important ecologic areas are destroyed as a result of waste disposal. A common example is the filling of wetlands as means of reclaiming land. Lastly, indiscriminant disposal of waste through land disposal represents a less than desirable practice from a materials and resource management perspective. Recovery of materials does take place by those sequencing the waste stream, but much more material recovery potential remains buried in the landfill, both in terms of resources and energy.

1.3 The Evolution of Modern Landfills

The first step in the evolution of modern landfills from uncontrolled dumps was the development of sanitary landfill practices designed to address immediate human health concerns. The implementation of sanitary landfilling involves several changes to operational practices that focus on minimizing the spread of disease and the occurrence of landfill fires. The placement of waste into defined cells, often constructed in distinct units and compacted in place with heavy equipment

Fig. 1.5 Waste compaction in organized cells is a fundamental component of sanitary landfill operation

Fig. 1.6 Cover soil application at sanitary landfills aids in reducing odor, vectors, fires and helps in the control of storm water and leachate

(see Fig. 1.5), allows more contained and controlled disposal. A critical element in sanitary landfill operation is the routine placement of cover soil on top of recently placed waste (see Fig. 1.6) to minimize fires, odors and disease vectors. Another key sanitary landfill feature includes site access control, which helps to discourage

Fig. 1.7 A barrier layer being placed as part of the construction of a landfill liner and leachate collection system

waste scavenging and properly define the facility's boundary through fencing or similar means.

While the evolution of sanitary landfill practices reduced many of the direct human health concerns associated with open dumps, it did not address the two major pollutant emissions associated with landfilled MSW: leachate and landfill gas (LFG). As regulators and scientists began to monitor groundwater quality surrounding landfills, the body of evidence indicating that leachate negatively affected groundwater quality grew (Sawney and Kozloski 1984; Reinhard et al. 1984; Schultz and Kjeldsen 1986). This resulted in many governments requiring MSW landfill construction to include barrier layers for preventing leachate migration out of the landfill (see Fig. 1.7) and drainage systems allowing the removal of accumulated leachate for treatment before disposal. Many of these technical requirements followed those previously developed for the management of hazardous wastes, a regulatory system designed upon the principle of cradle-to-grave management of wastes that posed an increased risk to human health and the environment. In lined landfill systems, leachate is removed from the landfill and treated prior to its return to the environment. Groundwater surrounding the lined landfill is monitored to assess whether the containment system functions properly.

Early LFG concerns focused largely on controlling subsurface migration into adjacent buildings and enclosed spaces, where methane produced from anaerobic waste decomposition could result in explosive conditions. This concern was partly addressed through the requirement of a bottom liner, and was often accompanied by soil vapor monitoring probes surrounding the lined landfill to assess gas migration. Another early gas concern arose from locations with regional air pollution concerns (e.g., California), and ultimately these and other issues with LFG (odor, toxic

Fig. 1.8 In foreground, a gas collection well is used to extract and control landfill gas for older waste, while in the background, new waste disposal continues

constituents, and global warming potential) resulted in widespread gas control regulations in developed countries. Typical gas control involves the construction of wells within the landfilled waste (see Fig. 1.8) that are connected together to an extraction system to draw gas from the landfill to a central location where the methane can be safely destructed (or otherwise managed).

As controlled landfill practices (e.g., those with leachate and gas control) became more common in developed countries, landfills became fewer and larger. In addition to basic sanitary principles such as compaction and cover soil, other operational practices were adopted. Such practices included the restriction on liquid wastes disposed of in landfills, and the control of storm water run-on and run-off, both designed in larger part to minimize the formation of leachate and the issues associated with leachate management. Regulatory requirements for managing landfills once waste disposal ended were also developed, including the construction of engineered closure systems (a closure cap) to prevent moisture infiltration and gas escape through the surface. Owners and operators were required to institute long-term monitoring and maintenance of the site to prevent future environmental issues.

1.4 Transition from Landfill Disposal to Treatment

Implementation of engineered controls for modern landfills and the development of operational strategies to minimize leachate formation had the desired result of greatly reducing water pollution from MSW landfills. A consequence of these actions, however, was the creation of many waste facilities that intentionally employ practices to mitigate waste stabilization reactions. As will be described in greater detail in the following chapter, once disposed of in a landfill, MSW undergoes a variety of biological and chemical reactions, particularly when waste is in contact with moisture. The gases and leachate that form during this active stage of waste reaction were a major motivating factor in the use of engineering and operational controls previously discussed. While the mitigation of the stabilization reaction benefits near-term environmental concerns, the potential for reaction over the long term still exists; these facilities are commonly referred to as "dry tomb" landfills.

The dilemma of modern MSW landfills is that the steps taken to address immediate concerns of leachate and gas result in facilities that will require continuous operating and monitoring, or else result in future emission problems. In the years following closure, if the integrity of the cap system is ever compromised allowing water to enter the landfill, the waste decomposition process can resume. If the landfill containment system is no longer functioning as designed, environmental contamination may result. Thus, while a dry tomb landfill reduces the environmental threats posed by unlined MSW dumps, it does not eliminate these threats completely, especially over the long term.

The landfill bioreactor was developed as an alternative approach where a landfill is operated to encourage waste decomposition, and thus limit the "active" life of the facility to those years when the site's containment components are in their best condition, and when it is actively being monitored. The landfill bioreactor is operated to control, monitor, and optimize the waste stabilization process rather than simply contain the wastes as prescribed by most regulations (Reinhart and Townsend 1997; Reinhart et al. 2002). The advantages of operating an MSW landfill as a bioreactor landfill may include: decomposition and biological stabilization in years vs. decades in dry tombs, reduced leachate disposal costs, cycling of nutrients and encouraging production of methane, a gain in landfill air space due to the rapid stabilization of waste mass, increased LFG generation over a shorter period which provides opportunities for greater collection efficiency, and reduced issues with the long-term care and monitoring of the facility.

Perhaps the most significant difference between a traditional engineered landfill and a landfill bioreactor is the operation of the system as "wet" through the addition of liquids. Increased moisture content promotes the biological waste stabilization process, and thus the landfill is operated in a manner similar to an anaerobic digester. In some cases, aerobic conditions may be promoted through forced or passive air addition. The landfill bioreactor concept has been tested in laboratory, pilot and full-scale settings (Buivid et al. 1981; Leckie et al. 1979; Pohland 1980), and lessons learned through these and other studies will be highlighted throughout this book.

1.5 Practices and Technologies for More Sustainable Landfilling

The evolution of landfills from disposal systems to treatment systems through landfill bioreactor and similar technologies, while motivated by multiple drivers, represents a major step toward more sustainable landfilling. The objective of such practices is to not only provide near-term environmental protection, but also to result in more sustainable operations that address longer-term concerns. Modern engineered landfills managed as waste treatment facilities, when integrated with other recovery components, offer a backbone through which sustainable practices can be accomplished. Whether they are called bioreactors or referred to by other descriptors, landfills that minimize environmental impact and promote waste treatment can be integrated with energy and materials recovery systems.

Many of the technologies used to promote more sustainable landfills focus on the methods to foster waste treatment. These technologies include systems for safely adding liquids and/or air to the landfill as a means of creating the environment conducive to waste treatment. The addition of liquids or air to landfilled MSW upon first consideration may appear to be a simple concept, but in reality, controlled, efficient and safe movement of fluids into and out of a medium as heterogeneous as MSW is challenging. Challenges include providing a sufficient amount of liquid to promote the environment conducive to rapid waste stabilization, as well as the necessity to safely remove liquids from the landfill to avoid deleterious outcomes such as leachate escape to the environment and physical failure of side slopes.

Other technologies involve the safe recovery of biogas from the landfill and the utilization of this resource for the production of energy and/or heat. Common practices include conversion of LFG to electricity using engines or turbines (see Fig. 1.9), and the use of gas directly or as a natural gas-quality fuel after appropriate treatment. LFG production rates increase with liquids addition, but experience has demonstrated that increased liquid levels in landfills often hinder the efficiency of gas collection. Sustainable landfill practices are thus those that promote efficient gas recovery at sites practicing accelerated waste stabilization.

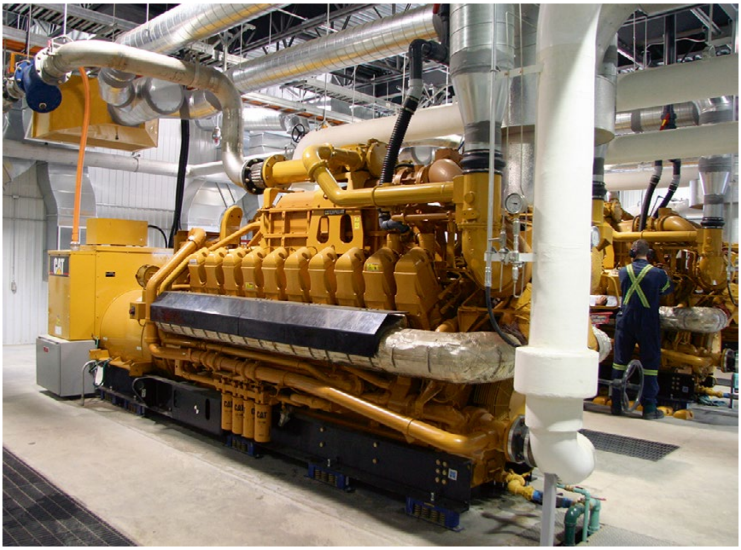

Fig. 1.9 Internal combustion engine producing electricity from landfill gas

Fig. 1.10 Landfill mining allows reclamation of metals, soil, and degraded organic matter

Additional sustainable landfill practices address how to best manage the landfill after waste disposal operations have ceased. Some operators, for example, add air to the landfill as a method of providing a final aerobic curing step and thus minimize future environmental emissions. The practice of reclaiming stabilized landfills through mining has been proposed; through this practice, resources can be recovered and the land requirement for future disposal is reduced (see Fig. 1.10). Technologies for utilizing landfill space for additional purposes, ranging from human enjoyment to recovery of solar and wind energy, also fall within the scope of technologies consistent with sustainable landfill practices.

1.6 Scope and Organization of Book

This book provides design and operation guidance for engineers and operators to implement sustainable landfilling practices at their facility. Methods for promoting rapid waste stabilization in a safe and controlled manner are a major focus. The methods described apply to facilities operated as landfill bioreactors, sites practicing leachate recirculation but not operated as bioreactors, landfills with high waste moisture content, and owners and operators that desire to collect LFG as efficiently as possible.

This book begins with an introduction of waste and landfill fundamentals, including a detailed discussion of the practice of landfilling and bioreactor landfills. Planning considerations for implementing more sustainable landfills, along with a review of the state of the practice of such facilities, are presented. Next, the focus turns toward liquids addition systems and other liquids management considerations. Later chapters of the book address concerns such as slope stability, LFG, and operation. The book ends with a discussion of final landfill disposition, the economics of sustainable landfilling practices, and the integration of other sustainable components such as landfill reclamation and energy recovery at integrated solid waste management facilities including a landfill as a component.

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Chapter 2
Waste and Landfill Fundamentals

Abstract Although this book focuses on sustainable approaches to landfilling of MSW, a presentation of fundamental MSW and landfill concepts is warranted. Elements of typical environmental control infrastructure are described, including bottom liner systems; leachate collection, removal, and treatment systems; gas collection systems; and closure systems. Sanitary landfill operation basics are presented, followed by a summary of waste stabilization processes and key aspects of sustainable landfilling systems, including a description of the bioreactor landfill concept.

Keywords Landfill • Liner • Leachate • Bioreactor • Stabilization • Sustainable

2.1 The Solid Waste Universe

This book focuses on sustainable practices for landfills managing MSW. Solid waste, however, refers to a broader universe of waste materials from residential, commercial, institutional, and industrial sources. Solid waste is not solely limited to discarded solid material; the term is often used to describe wastes in a semi-solid (e.g., sludge) or liquid form. Many solid wastes, because of practical or regulatory constraints, are managed as distinct and separate waste streams, including MSW, construction and demolition (C&D) debris, hazardous waste, industrial waste, agricultural waste, mining waste, and a myriad of special wastes.

In general, MSW refers to garbage and refuse produced from typical residential and commercial activities. MSW is the waste stream that must be routinely removed from households, businesses and institutions in a community, and although it might contain any number of different components, it is comprised primarily of the discards of daily life and business with which most of us are familiar. Common MSW components include paper (e.g., office paper, newspaper, and packaging), plastic, metal, glass, food scraps, plant trimmings, textiles, and bulky items (e.g., furniture, appliances). MSW is collected as part of a municipality's publicly operated or contracted waste collection services, or by private collectors hired by businesses or individuals, and as discussed in Chap. 1, the majority of MSW worldwide is disposed of in a landfill or open dump.

MSW generation and composition varies by region and country based on factors such as per capita income, dominant industries, and cultural practices. Waste genera-

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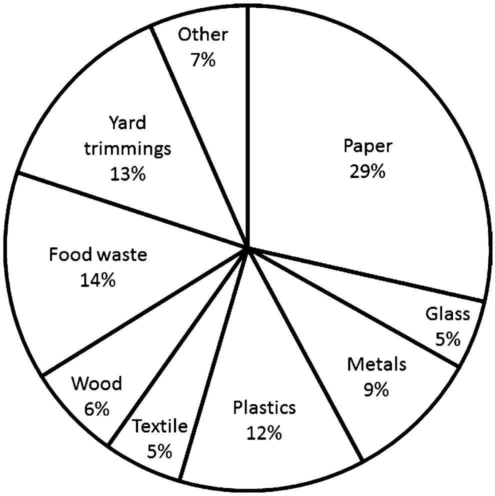
Fig. 2.1 2010 Municipal solid waste composition in the US (US EPA 2011)



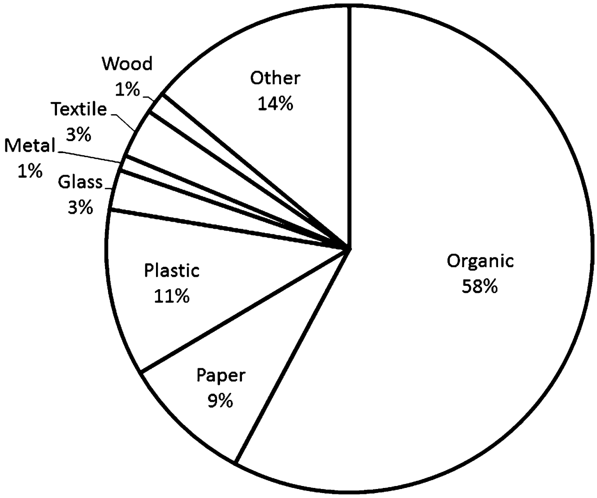


Fig. 2.2 Typical MSW composition in Chinese cities (Based on composition studies from 12 cities reported in Zhang et al. 2010)

tion rates strongly correlate with income level (Hoornweg and Bhada-Tata 2012), with greater average generation rates occurring in high income nations (2.1 kg/capita-day) compared to upper middle, lower middle, and lower income nations (1.2, 0.8 and 0.6 kg/capita-day, respectively). Figure 2.1 presents estimated MSW composition in the US in 2010 (US EPA 2011). The largest component of the US MSW stream is paper (29 %), with yard trimmings (13 %), food scraps (14 %), and plastics (12 %) also contributing heavily. This composition is representative of much of the developed world, with an abundance of packaged products and a greater quantity of discarded goods. This differs from many parts of the world, as indicated in Fig. 2.2,

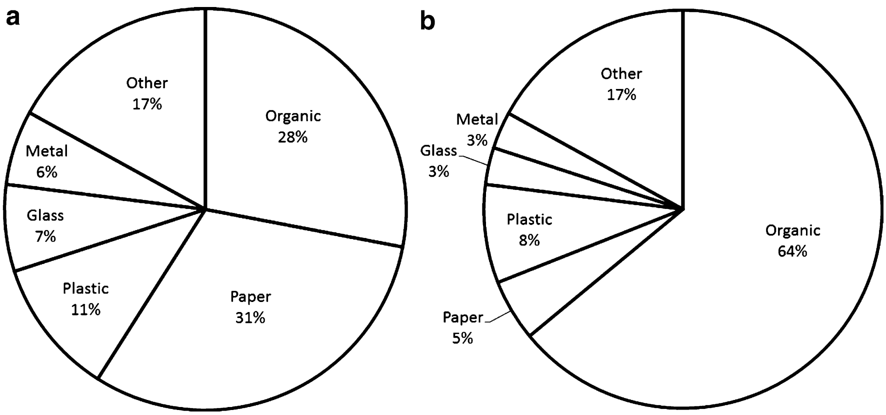


Fig. 2.3 Global MSW composition (**a**) High income countries (**b**) Lower income countries (Hoornweg and Bhada-Tata 2012)

which presents the typical composition of MSW in major Chinese cities (Zhang et al. 2010). Organic waste is the dominant component (58 %), with paper a much smaller contributor (9 %).

Waste composition is a critical factor when considering sustainable landfilling practices, as many of the potential problems with MSW landfills (e.g., water pollution potential, atmospheric emissions) result from the dominance of biodegradable materials in the waste. In higher income nations paper dominates, with appreciable amounts of food waste and plant trimmings also contributing (Fig. 2.3a). In lower income nations, food scraps and related organic materials dominate (Fig. 2.3b). Landfills managing either waste stream require sustainable practices to promote safe waste stabilization and control of emissions, although the manner in which some of this control will be achieved may differ. For example, landfills dominated by greater amounts of paper will need more liquids added to encourage stabilization, while in landfills dominated by food waste, sufficient moisture may already exist.

2.2 Landfill Components

As described in Chap. 1, modern sanitary landfills are designed and constructed to minimize impact to the environment. The disposal of wastes in landfills can pose potential problems to human health and the environment if such facilities are not properly located, designed, and operated. Some problems are catastrophic in nature, such as waste slides due to the instability of waste mass and explosions as a result of migrating gases. Other problems are more chronic in nature, such as long-term contamination of groundwater from leachate and impacts on global warming from the release of methane. These potential impacts can be mitigated through proper siting, design, construction and operation. To provide appropriate background for

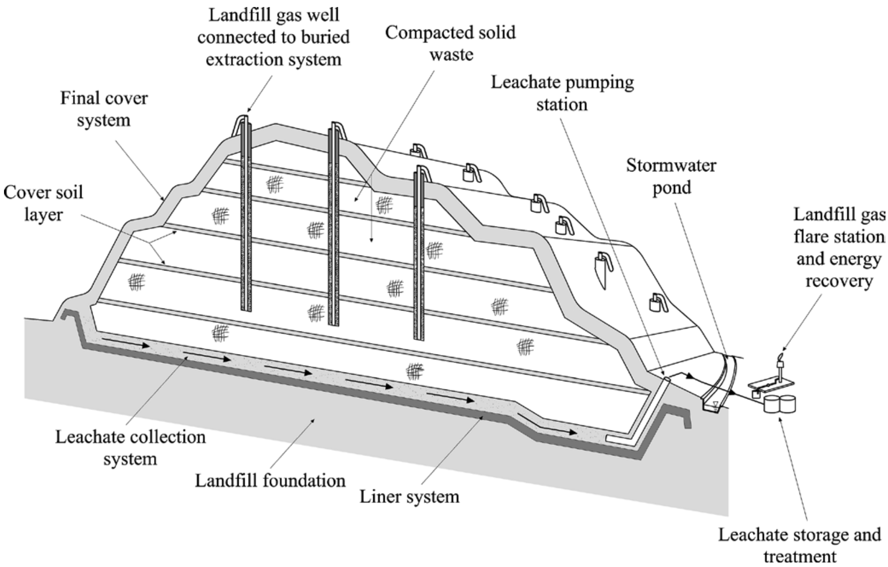


Fig. 2.4 Overview of major components of modern, engineered landfills

the later sections of this book, several major landfill components are discussed below, including liners, systems for leachate and gas management, and landfill management after waste disposal has stopped. Figure 2.4 provides an overview illustration of major landfill components.

2.2.1 Foundation and Liner

When water is exposed to waste, either through rainfall, groundwater inflow, or moisture contained in the waste, the water becomes elevated in dissolved chemicals and suspended particles from the waste and this liquid is referred to as leachate. In nearly all circumstances, land-disposed waste will result in the production of leachate. Landfill engineers and operators rely on barrier layers to prevent or minimize the migration of leachate to the environment. A barrier layer is often referred to as a liner, though a barrier layer at the top of a landfill—included to prevent gases from escaping and water from entering and forming more leachate—is typically referred to as a cap.

Prior to liner construction, the land upon which the landfill is to be constructed must be appropriately examined to ensure that the soils and underlying geology (the foundation) have sufficient strength to support the weight of the waste materials and associated infrastructure. Engineers and geologists must also evaluate the potential for seismic activity or sinkhole formation, as well as estimate the rate at which the foundation will settle or subside over time. In some cases, foundation

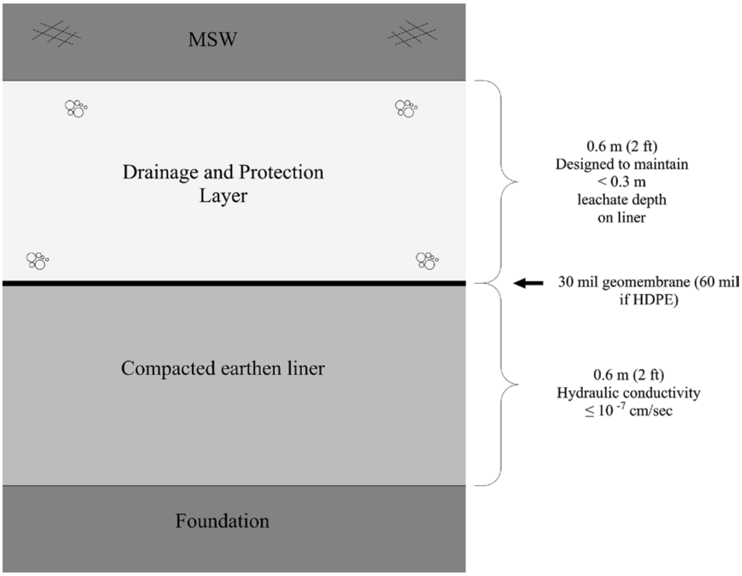


Fig. 2.5 Prescriptive federal Liner requirement for US MSW landfills

improvement will be required; examples include deep dynamic compaction and grouting. Existing soils may require excavation and removal, and often additional soils may be brought to the site. Prior to placement of liner materials, the foundation surface will be graded to meet the appropriate surface elevations needed for the designed drainage plan.

The two major categories of materials used in the construction of liner systems are low permeability earthen materials and geosynthetic materials. These two materials may be used independently or in combination to achieve the desired performance or regulatory requirements. In many nations, a prescribed set of design and construction criteria are mandated; Fig. 2.5 illustrates the minimum federal liner requirements for MSW landfills in the US, noting that federal rules allow states to develop their own criteria, which may be more stringent. With regulatory approval, engineers often utilize additional materials and design configurations to achieve fundamental containment objectives of this approach (Qian et al. 2002; Koerner 2005).

Earthen materials include natural soils with large clay mineral content, as these soils are necessary to reach target hydraulic conductivity requirements. Soils meeting necessary specifications are constructed in a series of smaller lifts (typically 0.15 m) to achieve the targeted thickness. During construction, an appropriate amount of water is added along with compaction energy to achieve desired density and hydraulic conductivity targets (Fig. 2.6a). In some cases, processed clay minerals are mixed with onsite soils to meet specifications. Products known as geosynthetic clay liners (GCL) come in rolls that can be transported from long distances when clay soils are not abundant locally.

Fig. 2.6 (**a**) Construction of compacted earthen liner. (**b**) Geomembrane liner panels. (**c**) Thermal fusion welding of geomembrane panels. (**d**) Thermal extrusion welding of geomembrane (Photo courtesy of Jones Edmunds)

Geosynthetic liner products, known as geomembranes, are manufactured from several different types of plastic polymers, the most common one in use for landfill bottom liners being high-density polyethylene (HDPE). Geomembranes are constructed by connecting adjacent panels of geomembranes (Fig. 2.6b) together through welding; HDPE geomembranes are attached using thermal welding. Thermal fusion welding is utilized for long seam lengths in a semi-automated fashion (Fig. 2.6c). Thermal extrusion welding is a manual process used for connections

Fig. 2.6 (continued)

where overlapping straight lengths of geomembranes is not available and when the geomembranes are attached to other plastic components (Fig. 2.6d). Rigorous testing of liner materials and seams must be included as part of geomembrane liner construction.

2.2.2 Leachate Collection, Removal and Treatment

As leachate migrates downward in a landfill under the driving force of gravity, it ultimately reaches the bottom liner system, at which point it must be removed from the landfill. This is accomplished using the leachate collection and removal system (LCRS). Requirements for removal and the design of the LCRS are dictated by regulatory requirements to minimize the potential for leachate migration through the liner system and to meet the performance needs of the design. As part of the LCRS design, the liner system is graded (sloped) to promote gravity drainage to a series of low elevations inside or outside of the landfill, from which the leachate is then removed by mechanical pumping (though in sites with sufficient elevation drop, gravity drainage may be used exclusively). Regulations often require a LCRS design that will result in the buildup of no more than a maximum depth (head) of leachate above the liner; in the US, this depth is 0.3 m (1 ft).

The engineer designs the LCRS to stay within maximum design depth of leachate by sloping the liner system, providing drains (large perforated pipes surrounding by drainage material) for rapid leachate removal, and by specifying a highly permeable drainage layer to be placed on top of the liner system and below the waste. A variety of drainage materials may be used. In areas where rounded stone is readily available, this material is commonly used because of its high hydraulic conductivity (Fig. 2.7a); layers of geotextile might be necessary to protect the geomembrane from damage by the rock and to keep overlying soil and waste from clogging the rock. Sand is also commonly used (Fig. 2.7b), though it is lower in hydraulic conductivity than stone and therefore the LCRS must be designed with greater frequency of drains. Geosynthetic drainage materials known as geonets provide rapid drainage with a small thickness, and coupled with geotextiles to prevent clogging; these products are commonly used in modern LCRS designs (Fig. 2.7c).

Using the sloped bottom liner and a series of drainage trenches, the engineer designs the LRCS so that leachate is routed by gravity to a designated set of low points, or sumps. These low points may be located within the lined containment unit, or they may be manholes or lift stations outside the lined area. Pumps are provided to extract leachate from the LCRS to the desired location for further management (Fig. 2.7d). The extracted leachate must be treated appropriately prior to discharge to the environment. If an appropriate treatment system is sufficiently close, leachate pumped from the landfill may be routed directly to an existing treatment facility. More commonly, leachate storage is provided on site (e.g., using ponds or tanks). In some cases, leachate is stored prior to subsequent transport offsite for treatment, though in some cases treatment operations are included on site.

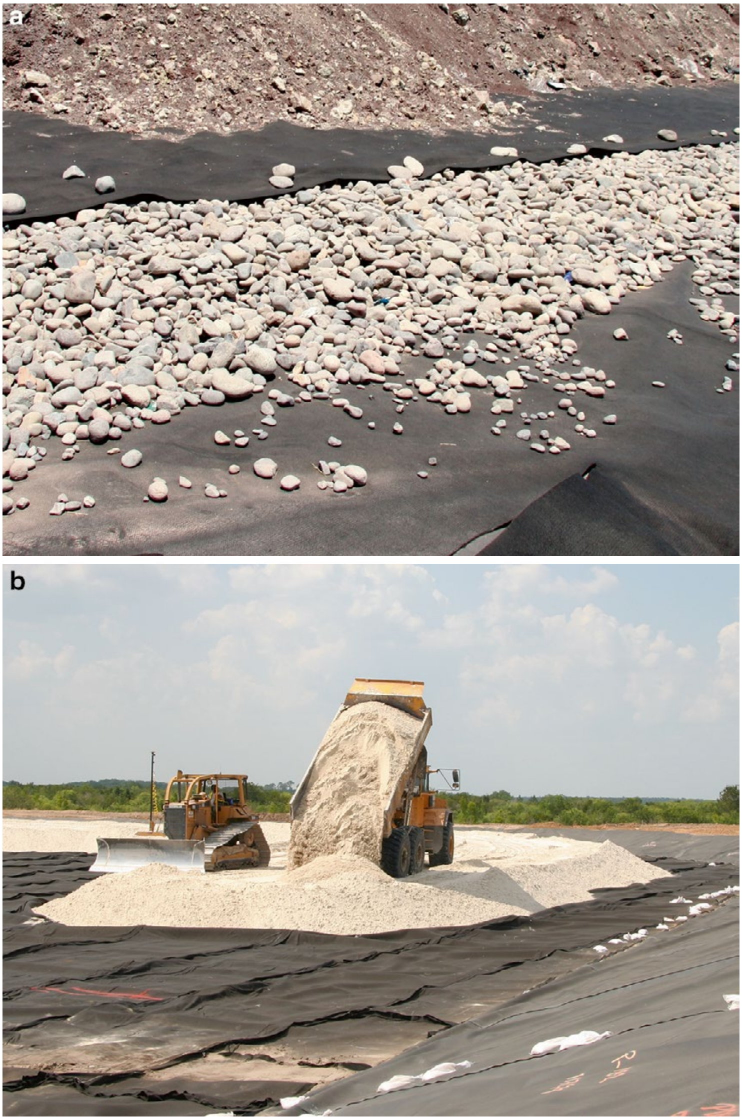


Fig. 2.7 (**a**) Rounded stone used as LCRS drainage material. (**b**) Sand placement for LCRS. (**c**) Geonet installation in LCRS. (**d**) Leachate pump station

Fig. 2.7 (continued)

2.2.3 Landfill Gas Control

Given the large amount of highly degradable organic matter in most MSW landfills, this material decomposes soon after waste disposal, which results in the production of biogas—a more detailed discussion of this process is provided in Sect. 2.5.

Under the anaerobic conditions that normally develop in landfills (due to the combination of compacting and covering the waste, and lining the bottom), large fractions of components such as food waste, paper, and yard trash are biologically decomposed to a gas that consists primarily of methane and carbon dioxide. The extent and rate at which this conversion takes placed is dictated by the waste type (e.g., the amount of food waste versus the amount of paper) and conditions such as moisture content, pH, and temperature. A focus of this book is on controlling the conversion process, but these reactions occur in all MSW landfills, and thus a common design component of many modern landfills is a gas collection and control system (GCCS).

The primary driving force for gas produced within an MSW landfill to migrate from the disposal unit is pressure. As gas is produced in the constrained volumes within the waste, pressure builds and the gas moves toward lower pressures outside the landfill. Thus, basic elements of most GCCS are extraction points that provide controlled pathways for gas escape from the landfill. These extraction points are most commonly vertical wells within the waste, though other configurations have been used. At some facilities, wells are naturally vented to the atmosphere (and possibly a flare), but when maximum gas recovery efficiency is desired, the wells are tied together using a series of connected manifold pipes, and this piping network is connected to mechanical blowers or fans to induce a vacuum in the well-field. The combined gas is then either flared or utilized in some beneficial fashion.

An important element of the GCCS is the extraction points where the operator has the ability to control the degree of vacuum placed at a given location. Figure 2.8

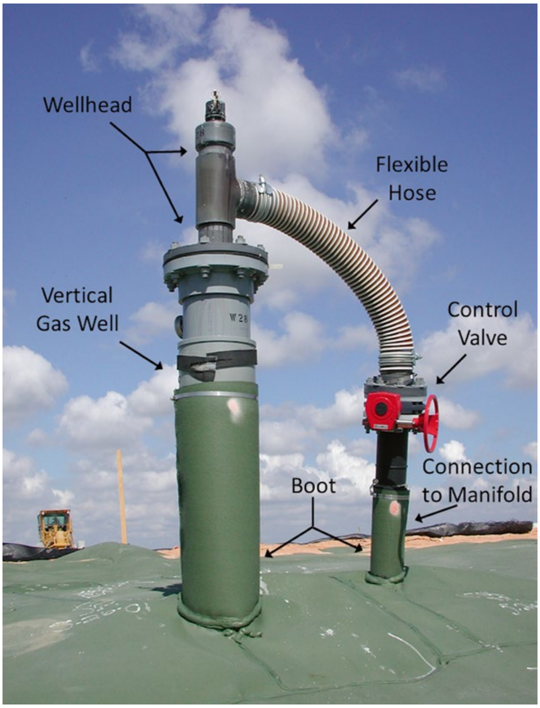


Fig. 2.8 Landfill gas extraction well at a facility covered with a geomembrane

illustrates a typical gas extraction wellhead, which includes the gas well penetration through the surface of the landfill; a wellhead to allow measurement of flow, pressure, and temperature; a control valve for adjusting pressure and flow; a flexible connection to the gas manifold; and appropriate connections to the surface cap that minimize air entrance into the landfill. Another important design and operation consideration for a GCCS is the management of condensate that forms in the pipes; this liquid must be appropriately removed or else it will interfere with gas transmission. Since gas condensate typically includes dissolved chemicals such as volatile organic compounds (VOCs) that may have deleterious health or environmental impacts, it is normally managed in a similar fashion to landfill leachate.

2.2.4 Landfill Closure

When waste is no longer disposed in a landfill, a final layer of soil—often accompanied by an engineered barrier layer—is placed on the surface (Fig. 2.9). This final cover system (often referred to as a cap) serves the purpose of minimizing water entry into the landfill and possibly decreasing the amount of gas exiting the landfill. In many respects, final cover systems are similar to bottom liner systems in that they contain multiple components with different functions. Compacted soil and/or geomembranes are used as a barrier, while highly permeable layers above the cap are designed to route water from the final cover as stormwater. Meanwhile, a highly permeable layer below the cap facilitates gas removal and direction to specified collection points. Some sites have implemented caps designed using the principles of

Fig. 2.9 Construction of a closure system at a landfill site

evapotranspiration, where a combination of favorable climatic conditions and engineered cap properties are used to prevent infiltration of rainwater through the cap.

In addition to the construction of a final cap, the process of landfill closure includes the integration of other control infrastructure including a landfill gas venting or collection system and a stormwater control system to prevent erosion of the cap surface. Most landfill caps include a grassed layer of topsoil to prevent erosion, but some facilities have implemented exposed geomembrane caps that are textured or impregnated with artificial grass.

2.3 Landfill Operation

Landfill operation not only includes the daily activities associated with the placement of waste in the landfill, it includes the execution of a variety of specialized tasks such as those related to leachate management and gas extraction (Bolton 1995). A modern landfill site will include a number of elements beyond the disposal unit, including a scale-house for weighing incoming materials, a system of roads for routing trucks to and from the waste disposal area, and facilities for employees and maintenance of equipment and vehicles. Other large areas may be devoted to surface water management systems, cover soil excavation and processing, and buffers from neighboring property. Many landfill sites also house other dedicated waste management operations such as yard trash processing, composting, recycling, and storage of appliances, tires, or other bulky material. In short, landfill facility operation is a multi-faceted endeavor.

Trucks carrying waste that enter the site for disposal are first weighed using scales and appropriate information is recorded for billing (Fig. 2.10a). Some landfills may simply have a receiving area where truck counts or truck load volume is recorded in lieu of scales. Waste vehicles are directed to dedicated disposal areas within the waste containment unit, commonly known as the working or active face (Fig. 2.10b). As waste vehicles unload their contents, landfill employees using a variety of equipment push the material to the desired location and compact the waste. Most landfill operators utilize large steel-wheeled compactors designed to maximize density after three or four passes over a layer of waste, (typically less than 1 m). As waste is unloaded from collection and transport vehicles, “spotters” examine the waste for improper materials; this is especially important for the first lift of waste placed in a new landfill to exclude materials that pose a puncture risk to the liner (Fig. 2.10c). Cover soil is hauled to the working face and then placed over a finished lift of waste by the end of the working day. In some cases, alternative cover materials to soil will be used, included mulch, tarps or foam.

Waste placement and compaction follows a predetermined filling sequence designed to fill the containment area in an organized manner than meets desired site objectives (e.g., slopes for stormwater control, placement of internal hauling roads). Strategic waste filling results in a final landfill configuration that meets designed targets for elevation, side slopes, stormwater control structures, and grading of the landfill top deck.

Fig. 2.10 (**a**) Trucks carrying waste that enter the site for disposal are first weighed using scales and appropriate information is recorded for billing. (**b**) Waste vehicles directed to dedicated disposal areas within the waste containment unit. (**c**) Spotting incoming waste. (**he**) Monitoring the gas system

Fig. 2.10 (continued)

In addition to waste tipping, compaction, and soil placement, the landfill operator is responsible for other operational features of the site such as operation and maintenance of the leachate removal and gas control systems. Leachate system operations includes ensuring proper operation of pumps, providing for appropriate maintenance, recording system data, and any operational needs of the leachate treatment and discharge components. In a similar manner, mechanical landfill gas extraction blowers must be maintained and the well field must be appropriately balanced to ensure efficient collection and to minimize possible risk of landfill fires (Fig. 2.10d).

Landfill operation does not end at closure. Throughout the life of the facility and after closure, groundwater and soil vapor samples must be collected and analyzed to meet regulatory permit requirements. Leachate collection and gas collection systems must be maintained. Post closure refers to the period following closure when necessary operation and monitoring of the landfill continues. Regulations typically mandate a minimum period of post-closure care; in the US, this period is 30 years. In addition to necessary monitoring, post-closure activities include operating the leachate and gas systems, maintaining the landfill cap and related features, and ensuring the integrity of all critical site features.

2.4 Waste Stabilization Processes

The importance of biological activity in landfilled MSW has been discussed multiple times in the introductory material provided thus far. Given that a major element of sustainable landfill operations is the control of the waste stabilization process and the byproducts resulting from it, as part of a discussion of landfill fundamentals, it is useful to describe the process in greater detail. Several researchers have provided descriptions of a progression of phases that a landfill will undergo after waste placement (Senior 1995; Palmisano and Barlaz 1996), with descriptions of changes in leachate and gas composition that result from each phase. A generalized depiction of these landfill phases is presented in Fig. 2.11.

Once waste is landfilled, the void spaces within the waste mostly contain air, and thus the initial phase of waste decomposition is often described as aerobic. Placement of daily cover, additional waste, and waste compaction may limit oxygen transfer, resulting in the termination of aerobic decomposition within a short period of time. For this reason, the portion of waste decomposed under aerobic conditions is relatively small with respect to the entire landfill stabilization process. The major gas components observed in the aerobic phase are oxygen, nitrogen (entrapped from the atmosphere) and carbon dioxide generated as a byproduct of aerobic decomposition.

As the oxygen trapped within the waste is depleted, the landfill conditions may change to anaerobic. With a lack of oxygen, waste may be decomposed by the bacteria that can use nitrate and sulfate (rather than oxygen) as an electron acceptor. In the acid phase, hydrolysis of macromolecules such as cellulose and protein enhances organic acid production and results in a decrease in pH. Although these organic acids can be consumed by methanogenic microorganisms, a great amount of organic acid can be accumulated due to the low growth rate of methanogens in comparison with the growth of acid formers. These cumulative organic acids and CO_2 (a byproduct of waste degradation) can depress the pH of the landfill. In addition, hydrogen gas can be produced as a byproduct of the degradation of butyric and propionic acid. Figure 2.12 provides an overview of anaerobic waste stabilization microbiology

As the redox potential of a landfill decreases, the growth of methanogenic microorganisms increases. Organic acid and hydrogen gas produced from waste

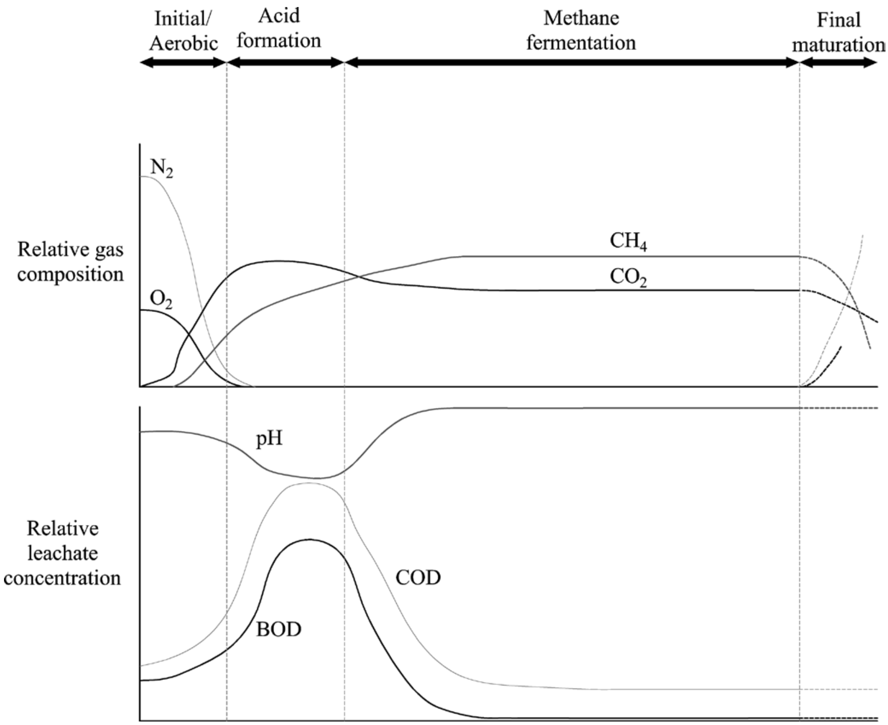


Fig. 2.11 Waste stabilization phases

degradation are rapidly consumed by methanogens, resulting in an increase of pH (7–8). In the methanogenic phase, CH_4 concentration in LFG is generally observed to be slightly higher than that of CO_2. This is because the ratios of CO_2 and CH_4 produced from organic acid- and hydrogen-using methanogens are different. Carbon dioxide also can be used as an electron acceptor and carbon source for hydrogen-using methanogens. In this phase, concentrations of organic matter substantially decrease, and the most landfill settlement (waste volume loss) is observed. Collectively, the methanogenic phase provides the best quality and quantity of LFG with respect to energy recovery.

In the final phase, although CH_4 and CO_2 in LFG are observed, the rate of LFG production is substantially diminished since the biodegradable portion of the waste is mostly depleted. The organic matter in the leachate changes to a complex form that may not be biodegradable, such as fulvic and humic acid. In some cases, oxygen and nitrogen can be observed in the gas due to air intrusion.

The changing environment within the landfill through the process of waste stabilization results in changing leachate chemistry with time. In addition to the pH variations described above, the chemical constituents change which affects the leachate treatment process and therefore technology selection. Table 2.1 describes general classes of leachate quality constituents and their progression through the

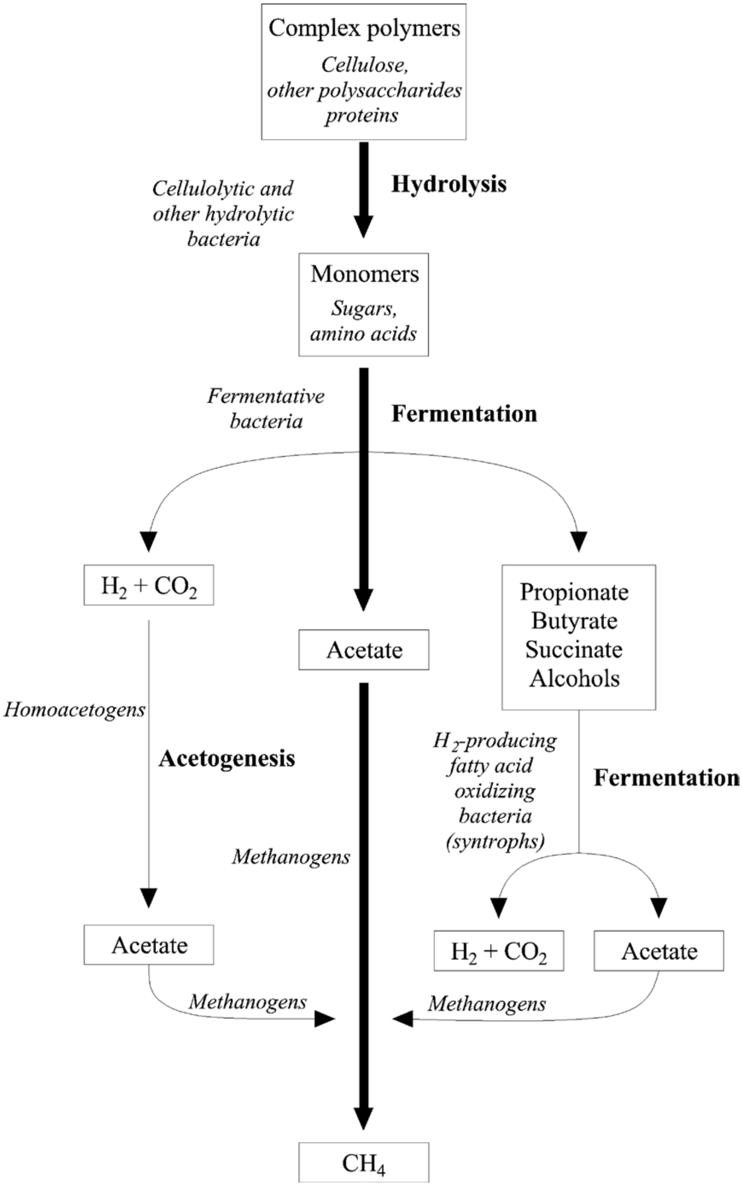


Fig. 2.12 Anaerobic waste stabilization microbiology

stabilization process. Dissolved constituents such as inorganic ions (e.g., chloride, sodium) and ammonia nitrogen become more concentrated with time. Perhaps most dramatic is the change in the organic chemicals during stabilization (as portrayed in Fig. 2.11). In the earlier acid phase, easily biodegradable organic chemicals make up much of the dissolved organic matter, as manifested by elevated measurement of both biochemical oxygen demand (BOD) and chemical oxygen demand (COD).

Table 2.1 Major leachate quality classes and changes during stabilization

Leachate constituent	Changes with stabilization
Organic matter	In the early phases of landfill stabilization, the concentration of organic matter is largely a result of the volatile fatty acids and other easily biodegradable chemicals. As the landfill progresses into an active methane-forming phase, most of the easily degradable organic matter is consumed within the landfill, and concentrations decrease. As activity progresses toward stabilization, leachate organic matter becomes dominated by large molecular weight chemicals that are recalcitrant to biodegradation
Inorganic ions	As the landfill ages, the ionic concentration tends to increase as leachate becomes less influenced by rainwater dilution and more wastes become exposed to moisture. Many inorganic ions such a chloride and sodium will be conserved in the system so when leachate is recirculated, concentrations will increase with time. Eventually, as more moisture flushes through the landfill, concentrations will decrease
Nutrients	Ammonium will exist at the dominant nutrient chemical and will behave in a similar nonreactive manner as other inorganic ions as the long as the environment remains anaerobic. At the points when air enters the landfill again, some of the ammonia may be biologically transformed to other nitrogen species
Trace chemicals	Trace pollutant concentrations are often sufficiently low that trends will be hard to observe, but the long-term trend with stabilization will be chemical specific. Some chemical constituents may biodegrade and others may be entrained with the waste (e.g., sorption, precipitation). Other trace elements will behave similar to inorganic ions

With a sufficiently active methanogen population, the biodegradable components are rapidly consumed, and thus leachate organic matter becomes dominated by organic matter recalcitrant to biological decay (this is manifested by lower BOD value and decreased ratio of BOD to COD). After stabilization, organic matter content retains a similar signature.

2.5 Landfill Bioreactor Fundamentals

The concept of a landfill bioreactor, or differently named facilities with similar objectives, centers on operating a landfill to encourage waste decomposition, and thus limit the "active" life of the facility to those years when the site infrastructure is in its best condition, and when it is actively being monitored. The operator attempts to control, monitor, and optimize the waste stabilization process rather than simply contain the wastes as prescribed by most regulations (Reinhart et al. 2002; Reinhart and Townsend 1997). The Solid Waste Association of North America (2002) defines a bioreactor landfill as:

> a controlled landfill or landfill cell where liquid and gas conditions are actively managed in order to accelerate or enhance biostabilization of the waste. The bioreactor landfill significantly increases the extent of organic waste decomposition, conversion rates, and process effectiveness over what would otherwise occur with the landfill.

Potential advantages of this approach include: decomposition and biological stabilization in years versus decades in “dry tombs,” reduced leachate disposal costs, a gain in landfill air space due to the rapid stabilization of waste mass, increased LFG generation that when captured can be used for energy, and reduced post-closure care.

Multiple MSW stabilization enhancement techniques such as leachate recirculation, air addition, co-disposal with sludges, low-density tipping and pretreatment of MSW have been investigated (El-Fadel 1999; Knox et al. 1999; Komilis et al. 1999; Reinhart and Al-Yousfi 1996; Reinhart and Townsend 1997; Townsend 1995). Out of all the techniques examined, increasing moisture content by leachate recirculation or addition of water and other liquids has been the most widely demonstrated. It has been applied in numerous lab-scale, pilot-plant and full-scale studies (Reinhart et al. 2002; Reinhart and Townsend 1997).

Leachate recirculation, also referred to as leachate recycling, was originally conceived as a method of managing leachate at solid waste landfills. This process involves the return of leachate intercepted by a landfill’s bottom liner and leachate collection system back into the landfilled solid waste. Cited benefits of leachate recirculation include leachate management, leachate treatment, accelerated landfill stabilization, and enhanced gas production. Numerous pilot studies have been performed demonstrating these benefits (Buivid et al. 1981; Leckie et al. 1979; Pohland 1980). Previous full-scale experiences have suggested that the typical volume of leachate available at a site is insufficient to increase the moisture content of the waste to the desired value in a reasonable time frame. Leachate recirculation, therefore, is often supplemented with the addition of other liquid sources such as water (surface water or groundwater), sludge from wastewater treatment plants, or other available liquid wastes. Thus, this practice can be generically referred to as moisture addition, liquids introduction or liquids addition. These terms are used interchangeably throughout this book.

The liquids addition approach is utilized because the addition of moisture to landfilled waste creates an environment favorable for the organisms responsible for waste decomposition (as described previously in Sect. 2.4). The moisture available in the waste is usually not sufficient to meet the microbial requirements, so design and operational modifications are needed to add liquids to the landfill waste. Leachate is the most common liquid supply, but other moisture sources can also be used.

Another method to accelerate the decomposition of disposed material is the addition of air, although this is less frequently employed in comparison to the liquids addition approach. The addition of air, and thus oxygen, promotes the aerobic stabilization of the landfilled waste. This is the same process that decomposes waste in a traditional waste compost system. Aerobic waste decomposition is a faster process in terms of reaction kinetics compared to anaerobic waste decomposition. The aerobic technique may be helpful for adopting bioreactor technology in cold regions. However, compared to the liquids addition approach, this technology can more readily pose hazards. This happens when increases in the temperature due to the activity of microorganisms, in addition to the combination of methane (a landfill gas) with oxygen, can cause waste combustion within the landfill and the formation conditions leading to a fire at or near the landfill surface.

As the waste decomposes, whether under anaerobic or aerobic conditions, the volume occupied by waste decreases resulting in a recovery of landfill air space may be realized (estimates of a 15–30 % gain in landfill air space upon stabilization are common). However, the additional disposal capacity is only gained if the landfill operator structured the filling sequence to utilize the recovered air space. If a landfill is operated as a bioreactor after a final cap has been placed and no additional waste is added, the air space likely will not be re-gained.

With accelerated waste decomposition, where primarily organic waste decomposes, the LFG generation rate increases. Therefore, in bioreactor landfills and similar facilities, gas generation rates are much higher than in conventional landfills; consequently LFG can potentially be recovered and used economically. If not properly controlled through design and operation of a LFG collection system, the enhanced LFG production rates may result in increased emissions to the environment. Under anaerobic conditions, both methane (CH_4) and carbon dioxide (CO_2) are generated, while under aerobic conditions nitrogen gas (N_2) and CO_2 dominate. A gas extraction system can be utilized within the life of the landfill and for years after closure, to collect and control the landfill, including potential conversion to energy. Since bioreactor landfills increase the rate of LFG generation, the increased quantity in a shorter time period can improve the practicality of the beneficial use of the gas (e.g., electricity generation).

Ultimately, a properly designed, operated, and maintained bioreactor landfill, or a facility operated in a similar manner that enhances waste decomposition, potential for offers considerable reductions in environmental impacts relative to conventional landfills. The waste is stabilized over a reduced timespan, when the landfill is still being monitored and when the landfill infrastructure is in its best condition. A means of leachate management can be provided, additional air space can be gained (potentially decreasing the necessity to construct a new landfill), and the viability of collecting and beneficially using the LFG is increased. However, this is only feasible if the bioreactor landfill is properly designed, operated, and maintained. Most of the rest of this book focuses on the technologies that can be used to meet such objectives.

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Chapter 3
Planning for Sustainable Landfilling Practices

Abstract Given the potential magnitude of sustainable landfilling technologies, proper planning is required to avoid common pitfalls and increase the odds of successful implementation. A series of region-specific (such as regulations) and site-specific (such as landfill dimensions and operational constraints and opportunities) planning considerations are presented. The concepts of operations and monitoring, closure and post-closure care, economics, and sustainability are presented in the context of sustainable landfilling and how differences in these different concepts (relative to traditional sanitary landfilling) must be planned for in advance.

Keywords Landfill • Planning • Sustainable • Bioreactor • Regulations • Liquid • Gas

3.1 The Importance of Planning

Proper planning is critical for any project the magnitude of a solid waste landfill. The introduction of sustainable design and operational elements to such a project demands additional emphasis on up-front planning. Preliminary considerations include decisions on the desired objectives of the landfill facility and the extent of additional components and technologies to be implemented. Some sustainable landfill practices may be limited by applicable regulations governing the facility, thus a strong understanding of the regulatory and permitting process is critical to planning. The facility must be designed and operated with due consideration of regulatory requirements, as well as other design and operational features necessary to safe and successful fulfillment of desired project goals.

While the objective of sustainable landfill practices and technologies may be greater long-term environmental protection, those considering these approaches should recognize that improper application of many of these technologies could result in deleterious impacts. For example, the addition of liquids to promote rapid waste stabilization is a major sustainable landfill technology and a major focus of this book, but uncontrolled liquids addition has the potential to result in greater emissions to the environment. If liquids are added at a flow rate or pressure greater than that which the

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landfill's containment infrastructure can accommodate, this can result in leachate outbreaks and waste side slope failures. At landfills where waste stabilization is accelerated, an inappropriately designed or operated LFG collection system may result in greater gas-phase emissions to the environment. These considerations must be planned for during the design process, even if they are not addressed specifically in the regulations.

In addition to the required engineering design of the facility and its components, implementation of sustainable landfill practices requires more demanding operational and monitoring considerations. These facilities require more control; this greater control is provided through a combination of greater operational attention, added control infrastructure, and additional collection of data used in the operation. As an example, a landfill operator who would normally only be required to monitor the safe and effective removal and disposal of leachate may be required to manage and monitor a system for pumping liquids back into the landfill. Other potential operational duties may include gas extraction, air addition, additional site or facility inspections, interfacing with new technology and equipment, and care and maintenance of energy conversion units.

The intent of this chapter is to introduce the planning elements required when pursuing sustainable landfill practices. A discussion of these considerations provides a good introduction to the detailed technical presentations in later chapters. In addition to discussing planning objectives, typical regulatory requirements, and design and operational issues, upfront considerations regarding the long-term fate of facilities integrating sustainable landfill technologies and economic considerations are discussed. Methods to examine sustainability of different waste management practices (e.g., life-cycle assessment) are also introduced.

3.2 Defining Project Objectives

Facility owners and operators must identify project objectives as part of the process of planning implementation of sustainable landfill technologies. Identified objectives may be constrained by a number of considerations, including regulatory limitations, specific site features, local infrastructure and markets, and economics. Whether the planning is for an existing landfill facility or a new operation may also greatly dictate which objectives are reasonable to address. Table 3.1 summarizes a list of potential sustainable landfill project objectives along with planning considerations. The considerations are discussed in greater detail, both later in this chapter and elsewhere in the book.

Table 3.1 Potential objectives for implementation of sustainable landfill projects

Potential project objective	Considerations
Protect water resources	Over the near term, this will normally be accomplished by appropriate design and operation practices for sanitary landfills. To address long-term concerns, waste stabilization technologies will help reduce potential impacts if implemented properly
Protect air resources	Although protection of air resources will normally be addressed through existing regulatory requirements, the implementation of sustainable waste stabilization technologies may require advanced technologies or modified timing of infrastructure construction to effectively capture and control gases that are produced
Provide rapid waste stabilization	Rapid stabilization is accomplished through the addition of liquids and/or air. There are numerous regulatory, design, operation, and economic issues to consider
Recovery of energy from landfilled waste	When anaerobic waste stabilization is promoted, biogas production increases which must be captured to realize one of the potential benefits of sustainable landfills. The economics and markets for beneficially used landfill gas must be examined ahead of time to assess the feasibility of sustainable landfilling technology and the associated landfill gas beneficial use technology
Reclaim landfill	If landfill reclamation following stabilization is a goal, planning must be conducted to identify key aspects such as timing of reclamation, degree of reclamation, and potential regulatory and operational impacts
Incorporate solar and wind energy	With advance planning, the implementation of additional energy-producing technologies could be facilitated. Planning of landfill layout and sequencing, cover soil types, surface water management, energy production potential, and other factors must be considered as part of feasibility evaluations

3.3 Regulatory Constraints and Considerations

The location, design and operation of modern engineered landfills are regulated by national, regional or local government agencies. The specificity of the regulations with respect to sustainable landfilling practices varies by jurisdiction and project planners and developers must consult the appropriate regulatory agency to determine necessary requirements. The following section highlights major landfill regulatory requirements in the US and Europe to provide context as to typical regulatory requirements and how these might impact the implementation of sustainable landfill practices.

3.3.1 U.S. Regulations

MSW landfills in the US currently fall under several federal regulations. Foremost among these are the RCRA Subtitle D landfill regulations found in 40 CFR 258 (US Government 2012a). In addition to other requirements, these rules contain location restrictions with regard to where a landfill unit may be constructed, design requirements for liners and leachate removal systems, groundwater monitoring requirements, corrective action requirements, and the need for financial assurance. While the terms "bioreactor" or "sustainable landfill" are not defined or used in the Subtitle D rules, several features of the rules have the potential to impact sustainable landfill practices. The Subtitle D rules prohibit the disposal of bulk liquid wastes, which are un-containerized liquid wastes or liquid wastes found in large containers; liquids wastes are defined as those wastes that do not pass EPA's paint filter test (US Government 2012a). Thus, the addition of wastewater or wet sludges to increase moisture content is prohibited, even if added for the purpose of landfill stabilization.

The Subtitle D rules do permit the recirculation of leachate and landfill gas condensate to the waste as long as the liner and LCRS design requirements are met (see Fig. 2.4). Since the introduction of liquids to a landfill will normally result in an increase in leachate collected by the landfill's LCRS, designing to meet the rules requirements of less than 30 cm of leachate head on the bottom liner is an important design consideration. The operating requirements of the rule also prohibit impairment of surface water quality as a result of the landfill's operation. Liquids introduction has the potential to result in surface leachate discharges on the face of the landfill, and if improperly managed, these seeps can be introduced to the landfill's surface water management system and potentially enter surrounding surface waters.

MSW landfills in the US are typically regulated at the state level, and thus some states allow alternative liner designs for MSW landfills. Most US states have their own MSW landfill rules based on the Subtitle D rules, and they are often stricter, though in some cases they may also provide more flexibility. State regulatory agencies often interpret Subtitle D differently with respect to bioreactor or sustainable landfilling operation. For example, the Subtitle D rules only permit recirculation of leachate and gas condensate to landfill with the Subtitle D composite liner system. In many cases, however, the volume of liquids provided by these two sources is insufficient to achieve optimal bioreactor conditions. Some state regulators, therefore, have permitted the addition of ground water to sites with a Subtitle D composite liner system; these states do not recognize groundwater as bulk liquid waste.

Since questions have been were raised regarding whether leachate can be recirculated over these alternative liner designs, the US EPA developed the Research, Development and Demonstration (RD&D) Rule to allow state regulators to issue permits to existing, new or lateral expansion landfills for which the owner or operator proposes to utilize innovative and new methods that differ from the operating criteria of the run-on control systems, liquids restrictions, and the final cover criteria found in Subtitle D. The variances in landfill operation are limited to the introduction of liquids other than leachate and gas condensate to the landfill, and allowing rainwater to run on to the landfill while preventing rainwater run-off from the landfill surface if in contact with the waste.

Few regulations addressing landfill gas control are specified in Subtitle D, but detailed design and operational requirements are provided under the Clean Air Act. Landfills of a given size (in terms of volume or mass of waste) must install a GCCS if estimated emissions of non-methane organic compounds (NMOC) exceed a defined threshold of 50 Mg/year (US Government 2012b). Recognizing that landfills practicing accelerated waste stabilization could produce a large volume of gas prior to a regulatory trigger for capture, the National Emissions Standards for Hazardous Air Pollutants (NESHAP) provided requirements for bioreactor landfills to capture gas sooner than conventional municipal landfills (US Government 2012c). In this rule, a bioreactor was defined as:

> An MSW landfill or a portion of a MSW landfill where any liquid, other than leachate or landfill gas condensate, is added in a controlled fashion into the waste mass (often in combination with recirculating leachate) to reach a minimum average moisture content of at least 40 % by weight to accelerate or enhance the anaerobic biodegradation of the waste.

Although the NESHAP rules for bioreactors differ slightly depending on whether the landfill is a new or existing source, generally bioreactors as defined under NESHAP must have LFG collection components installed before initiating operation of the bioreactor and must begin collecting either within 180 days of bioreactor operation or after the waste moisture contents reaches 40 % (by weight), whichever is later.

3.3.2 European Union Regulations

Directives and policies in the EU have been put in place that are similar to US regulations, with technical requirements such as liner systems and other protective measures to minimize risk to human health and the environment as a result of land disposed waste. While many EU nations have migrated away from landfilling as a primary method of managing MSW, as a whole, landfilling remains a common practice. As of 2010, more than half of EU member states landfilled greater than 50 % of the municipal waste generated in their country (EEA 2013).

With a goal of reducing reliance on landfills, the EU has passed several directives to promote resource recovery and landfill diversion. For example, the EU Landfill Directive of 1999 (Council of the European Union 1999) provided a timeline for minimizing the amount of biodegradable waste disposed of in landfills. Those nations meeting this directive first process their waste through waste-to-energy (WTE) systems or mechanical biological treatment (MBT) prior to landfill disposal. The EU's Waste Framework Directive of 2008 established a target to recycle 50 % of municipal waste by the year 2020 (European Parliament and Council of the European Union 2008).

3.4 Engineering Design Considerations

3.4.1 Design Differences with Sustainable Landfill Practices

Landfills implementing sustainable technologies must still comply with existing design requirements of standard engineered landfills and, where applicable, additional regulations. The incorporation of technologies to achieve rapid waste stabilization require new design features, and in some cases the presence of sustainable

Table 3.2 Potential impacts of sustainable landfill practices on standard landfill design elements

Landfill design element	Impact of incorporating sustainable landfill practices on design element
Foundations	The increased unit weight of the waste created by the introduction of liquids and by the more rapid stabilization of the MSW can impact the earthen foundation upon which the landfill is constructed. The designer should factor this unit weight into the design of the landfill foundation. Greater slopes in the leachate collection and removal system may be required to ensure gravity drainage can still occur since greater differential settlement of the foundation may be predicted based on the increased unit weight of the landfill
Liner systems	Liner systems are normally comparable to standard engineered landfills, though possible increases in temperatures resulting from accelerated biological activity (especially if air is added) may need to be considered
Leachate collection systems	The leachate collection system needs to be designed to accommodate the larger volumes of leachate that are expected as a result of liquids introduction. Other design elements, such as foundation settlement and gas extraction systems, should be considered in tandem with leachate collection system design. A well-designed and constructed leachate collection system is one of the most critical features of a sustainable landfill
Stormwater control systems	The possibility of surface seeps as a result of liquids introduction should be considered in the design of stormwater collection systems. Systems designed to mitigate and control seeps can minimize the mixing of leachate with stormwater
Slope stability	The addition of liquids to landfills can impact the pore water pressure existing within the waste mass, which in turn can lead to changes in the shear stresses within the landfill mass and cause slope stability concerns. Waste characteristics may also change as waste decomposes due to liquids introduction. Designers should factor added water pressures into slope stability analyses.
Leachate management systems	The recirculation of leachate will be a part of a site's liquids management system. Leachate storage volumes should be examined as part of a water balance that considers leachate production and recirculation rates. Leachate treatment technologies that complement sustainable landfill technologies should be considered based on site-specific factors
Gas extraction systems	Liquids introduction not only increases the rate of gas production, it also may impact the efficacy of many of the standard landfill gas collection techniques. Gas collection systems need to be designed to accommodate both enhanced gas production from liquids addition and the increased volume of liquid within the waste
Capping and closure system	The approach to capping and closing a landfill using sustainable landfilling technologies during active filling and/or after closure should consider the liquids introduction and other sustainable landfilling infrastructure and impacts from waste settlement

landfill technologies may require innovative designs of standard sanitary landfill features Reinhart and Townsend (1998). Table 3.2 provides a summary of the potential impacts of incorporating sustainable landfill technologies on the design of standard landfill components. More detailed design considerations are provided for many of these in later chapters of the book.

3.4.2 Liquids Management

Given the importance of liquids management to sustainable landfill practices, specific planning considerations pertaining to this aspect are discussed here. Table 3.3 lists and describes various design elements of a liquids introduction system. The three components needed to add liquids to a landfill unit are a liquids

Table 3.3 Design elements for liquids introduction systems

Design elements	Key considerations for liquids introduction
Total volume of liquids to add	The total volume that needs to be added to increase the waste moisture content to a target value should be based on volume (or mass) of waste deposited in the landfill (or part of it) under consideration, the initial waste moisture content and the target waste moisture content.
Sources of liquids	The liquids source can be leachate or other liquids, depending on permit limits.
Liquids introduction rates	The liquids introduction rates should be based on the rate at which liquid becomes available for addition to the landfill, anticipated impacts on leachate collection system, waste hydraulics, and other considerations such as slope stability, desired management of leachate generated at the end of operations, and the potential for seeps.
Type of liquids introduction system	The objective of liquids introduction, compatibility with other landfilling operations, cost-benefit analyses and other site-specific regulations should be considered when selecting the liquids introduction system.
Sizing and configuration of devices	Sizing and configuration of individual liquids introduction devices should be based on cost-benefit analysis and additional functions that a liquids introduction device is envisioned to serve such as gas extraction or addition of air for aerobic operation.
Spacing between devices	Spacing (lateral and vertical) should be based on the expected zone of impact of the individual device over the duration of operation of the device, which depend on media properties and injection pressure (or flow rate).
Materials of construction	The materials (pipe size and material, perforation size and spacing, trench media) for construction of liquids injection devices should be specified to meet its functional requirement (delivery of liquids to the waste without significant pressure loss), and structural requirements (sustaining overburden pressure and stresses from differential settlement and withstand the biogeochemical environment of the landfill).
Operating pressures and flow rates	The pressure that a liquids injection device would be subjected to should be specified based on slope stability analysis, surface and side slope seeps consideration, and pumping system limitations (in the case where the operator would attempt to use an existing pump rather than purchasing a new pump for liquids introduction). The achievable flow rate depends on injection pressure, liquids introduction device size and media properties.
Operating strategies	Operational strategies (or constraints) such as continuous versus intermittent operation of a liquids introduction system, compliance with specific conditions of the existing operational permit, compatibility with operation of the other landfill components such as a gas extraction system among others should be considered while designing a liquids introduction system.

storage unit, a conveyance mechanism to deliver liquids from the storage unit to the landfill unit, and a scheme to apply liquids to the landfilled waste mass—collectively referred to herein as the liquids addition system. Possible storage systems for the liquids include ponds, tanks, or other storage units that are located outside the lined landfill area. Liquids can be delivered from the storage system to the landfill in a variety of fashions. In the simplest form, liquids can be hauled to the landfill in a tanker truck and discharged directly to the surface (to infiltrate at the working face) or to an impoundment area (e.g., a pond). Liquids can also be delivered to points of interest through a piping network.

The design of a liquids introduction system includes the estimation of the volume of liquids that need to be added to increase the moisture content of the waste from an initial value to a target value, identifying sources of liquids available, selection of the type of liquids introduction system, developing detailed specifications on sizing and configuration of the liquids introduction devices, selecting spacing between individual devices, and identifying materials of construction. Liquids can be applied to the landfilled waste using a multitude of surface and subsurface techniques. Surface applications include drip irrigation, spray irrigation, infiltration ponds, and trenches, while subsurface applications consist of buried horizontal injection trenches, planar or blanket systems, or vertical wells. The systems that add liquids via surface application are less complicated to design than those that add liquids via subsurface application. The design process for surface liquids introduction systems involve the specification of a liquids application rate, the area of liquids application, and a piping and pumping system to accomplish liquids introduction. Conversely, the design process for subsurface liquids introduction systems entails the specification of the sizing and configuration of individual injection devices, spacing between these devices, injection pressure (or flow rate), material selection (e.g., trench bedding media, pipe diameter and thickness), and pumping system design. Design methods and considerations for a variety of liquids addition strategies are presented in Chaps. 6 through 9.

The design of a leachate collection and removal system (LCRS) is one of the most important design elements for all landfill designs, especially for landfills with high moisture contents or those where liquids are deliberately added into the waste. A well-functioning LCRS can effectively reduce the potential for groundwater impacts resulting from leachate leakage and slope failure due to increased pore-water pressure and changes in waste characteristics. The main components of a LCRS include a liner system sloped to promote gravity drainage, a perforated collection pipe network, drainage media to route the collected liquids to targeted conveyance points, and pumping systems to remove leachate from the landfill. More liquids are expected to be collected by the LCRS in bioreactor landfills and similar operations because of the added liquids. Therefore, the LCRS must have adequate drainage capacity to handle the increased leachate flow; Chap. 10 focuses on LCRS design.

As part of the design and permitting process of a bioreactor landfill, other design elements may also need to be considered and integrated into the design elements discussed above, such as seepage control and leachate management. Leachate seeps are usually observed as wet spots on the surface of landfill side slopes, especially in landfills where liquids are added under pressure. Leachate seepage can be odorous and attract vectors, in addition to causing other environmental issues, such as leachate migration beyond the lined limits of the landfill, storm water contamination, cover soil erosion, gas emissions through the cover, and potential slope stability issues. Design engineers for landfills practicing liquids addition need to balance the use of pressurized liquids addition for moisture distribution with the need to minimize leachate seepage problems.

A leachate treatment and management system is another primary design element that needs to be considered. One objective for operating a landfill as a bioreactor is leachate treatment. Leachate recirculation, to some extent, can reduce the organic chemicals in the leachate through biological degradation. It is important for a design engineer to understand the degree of treatment if external leachate treatment is needed to meet desired treatment limits, particularly in cases where the leachate production rates at the site exceed the design leachate recirculation rates. In addition, the amount of leachate produced at a bioreactor is generally greater than a conventional landfill when outside liquids are added. Therefore, a leachate storage system of sufficient capacity is critical to bioreactor landfill leachate management. The enhanced leachate production rate due to bioreactor operations should be factored into the leachate management design process. Leachate management techniques, from seep control to storage and treatment, are presented in Chap. 11.

3.4.3 Managing Landfill Gas

Promoting rapid waste stabilization increases the LFG generation rate, and planning for such an outcome is a major consideration in sustainable landfill project development. Operating a landfill as a conventional landfill or as a bioreactor landfill generates the same amount of landfill gas over the long term, as the total amount of gas that can be produced is a function of the waste mass and its characteristics. The increased LFG generation rate associated with landfills practicing enhanced stabilization techniques can be beneficial to the landfill owner because the accelerated gas generation may make beneficial use of the gas more economically feasible, and provides an opportunity to collect gas in the early years of a site's active gas collection system. However, the increased gas generation rate presents design and operational challenges.

The main design elements for a gas collection system include gas extraction devices, larger gas conveyance pipes, condensate collection, storage and conveyance system, and a vacuum source. If the generated landfill gas is not efficiently collected, the accelerated gas generation rate will increase landfill gas emissions to the atmosphere. The efficiency of a landfill gas collection system depends on design elements such as the density and type of collection devices (e.g., horizontal, vertical, surface collection, leachate collection system integration), the presence or absence of a bottom liner system, landfill cover characteristics, applied vacuum, and condensate management. To maximize gas collection, the impact of installation timing of LFG collection components coupled with the starting time for liquids addition should be examined to accommodate the expected increased LFG generation rate following initiation of liquids addition. Early installation of landfill gas collection systems can capture the additional gas that is generated, thus reducing emissions and enhancing the viability of a beneficial use project to take advantage of the increased landfill gas quantity.

LFG collection system designs for sustainable landfills must also consider the change in waste properties due to added liquids, primarily the density of the waste which can be increased following liquids addition. The increased density causes a greater overburden on the deeper layers of waste, thus making LFG collection more difficult in these areas. Accordingly, a greater vacuum is required to collect an equivalent amount of gas; a greater applied vacuum or different design approach must be accounted for to reduce the potential for air intrusion. In addition, enhanced moisture may result in other operational problems, such as well flooding and a decrease in waste permeability to gas flow, which can decrease GCCS operational efficiency. Chapter 13 provides an overview of GCCS fundamentals and addresses specific concerns related to sustainable landfill operations.

3.4.4 Other Design Considerations for Sustainable Landfills

While liquids addition to promote anaerobic stabilization has been the most widely discussed and implemented technique for sustainable landfill operation, other opportunities may need to be considered in the design and planning process. Other considerations include waste processing and placement objectives, the types of wastes accepted for disposal, and waste mixing considerations (e.g., mixing wet wastes with dry wastes). A sizable impediment to waste stabilization through liquids addition is the inability to uniformly wet the waste. Thus waste processing through shredding prior to disposal and the deliberate reduction in waste compaction have both been proposed as techniques to promote even moisture distribution. The co-disposal of some wastes may limit effectiveness of sustainable practices (e.g., when ash layers limit liquids reaching MSW) and in other cases enhance it (e.g., when biosolids are mixed with MSW to provide moisture and nutrients).

Air addition has been proposed as a tool for more sustainable landfill operation. While it poses a greater risk with respect to landfill fires, air addition provides for more rapid waste stabilization. Air addition has been selectively used for targeted benefits, such as warming cold landfills to prime them for subsequent anaerobic stabilization and for stabilizing landfills at their end of life. The use of air addition at landfills is the focus on Chap. 14.

Planning in the design process must also include necessary engineering to ensure necessary facility integrity in the short and long term, and to provide future opportunities to maximize sustainable landfill practices. With the addition of liquids, the formation of elevated gas pressures, and the changing nature of stabilized waste, the engineer must assess and address potential concerns with respect to slope stability (discussed in Chap. 12). Some future opportunities may be maximized through upfront planning. For example, future waste reclamation and reuse of landfill cells will be much easier if the liner system is designed with this process in mind (landfill reclamation issues are presented in Chap. 17). Feasibility of future energy recovery opportunities, such as landfill gas, solar energy, and wind power, may be greater if site infrastructure is designed from the beginning with these objectives considered (Chap. 19).

3.5 Operation and Monitoring

The implementation of sustainable landfill practices will in most cases result in additional operation and monitoring requirements beyond standard engineered landfills (Chap. 15). With the role that liquids play in such systems, the measurement and tracking of the site's water balance will be critical. Not only will this include standard measurements such as leachate generation and rainfall, but also liquids added (often measured on a per device or areal basis), liquid levels and pressures in the landfill, and liquid measurements associated with the LCRS. Additional gas measurement requirements may be needed as GCCS operations may be implemented earlier, additional devices may be used, and the level of control needed may necessitate more frequent monitoring.

Routine inspection of all landfill elements becomes more critical when practices such as liquids or air addition are employed. As described previously, leachate seeps to the landfill side slope should be anticipated and as part of the site's operation plan, routine inspection for seeps must occur and a contingency plan to manage seeps must be in place. Seeps and other surface changes act as indicators of system performance and can signal potentially more serious issues such as side slope and cover failures. Since subsurface fire formation is a major concern with air addition, monitoring gas composition and internal landfill temperature is critical and demands additional operator effort.

As will be described in Chap. 16, the landfill operator can use multiple measurement parameters and techniques to assess the performance of the sustainable landfill system. Table 3.4 lists some of the potential monitoring alternatives that might be implemented. A major part of the planning of sustainable landfill practices will be determining the level of staffing that will be required to achieve monitoring objectives and the degree of instrumentation and monitoring necessary. These determinations will consider existing regulatory and permit requirements, performance objectives, costs, and the acceptable operational risk level. Planning considerations will include determining how much of the operation and monitoring can be accomplished with permanent landfill staff and how much to turn over to outside contractors.

Table 3.4 Monitoring options and considerations for sustainable landfills

Monitored parameter	Considerations
Leachate generation	Leachate volumes will be monitored at most landfill sites, but tracking the water balance in systems where liquids are added is more critical. More frequent and spatially distinct monitoring may be necessary
Leachate quality	Tracking leachate quality is a helpful tool to assess stabilization activity within the landfill. It may also be useful in determining how best to operate the liquids addition system. These data may also be helpful in determining when to end the post-closure care period
Gas production	As gas is a major focus in landfills that are accelerating waste stabilization, measuring gas quantity and quality earlier, more frequently and in more places may be advantageous or required
Gas quality	Gas quality is an important indicator of system operation and is of extra importance at sites where gas is beneficially utilized and when assessing the potential presence of potential landfill fires
Waste settlement	Surface topographic measurements are often conducted on an annual basis at modern landfills. Since settlement can help evaluate the progress of landfill stabilization, more frequent and spatially distinct measurements may be advantageous
Waste quality	Most landfills will not have a need for collection and analysis of solid waste samples. Landfills practicing rapid stabilization techniques may benefit from assessing the degree of waste stabilization with time—a waste sampling program may be developed so that the sampling locations and analytical techniques allow for a statistically meaningful tracking of waste degradation. Additionally, degraded waste quality following completion of sustainable landfilling at a site may be measured if the beneficial reuse of the material is contemplated
Moisture	While moisture content may be determined with water balance information, devices and instruments exist for measuring internal moisture content of waste at distinct locations. Installation and monitoring of such devices have been used by some operators to track the progress of moisture distribution as a result of liquids addition (i.e., tracking the presence of moisture). Limitations exist with respect to using moisture measurement devices that provide an accurate quantitative reading
Temperature	When air addition is practiced, monitoring of internal landfill temperature (i.e., waste temperature) is important to avoid subsurface landfill fires. Temperature of collected landfill gas is also an important indicator required by US regulations
Energy production	For facilities where energy production results from landfill gas, solar or wind, additional monitoring of system performance and output will be required

3.6 Closure and Aftercare

Under normal landfill operation, the facility is operated such that waste is deposited and compacted to reach a final configuration and then closed with an engineered capping system. Engineers and operators must also assess at what point to close distinct areas of the landfill and what types of cover systems to use. These decisions become even more important in facilities operated with sustainable practices such as rapid waste stabilization, reclamation and energy recovery systems. The focus of Chap. 17 is on landfill management at end-of-life and opportunities for more sustainable practices.

The standard approach of closing once a predetermined design elevation is reached may not be the best choice for landfills practicing accelerated stabilization. One objective of rapid stabilization is to recover additional disposal capacity (airspace), thus premature construction of a cap may prevent utilization of this additional capacity. In addition, closure systems that rapidly settle will be more subject to damage and thus necessitate repair. Thus as part of planning, the engineer and operator must consider whether to overfill the waste anticipating future settlement or planning a temporary cover or capping system that later will be removed to allow addition placement—the planning process should assess whether overfilling is a practice permitted under state or local regulatory rules.

While premature capping of a landfill area may be disadvantageous for facilities undergoing rapid stabilization, an engineered cover or cap has benefits for such systems. Gas collection can be enhanced, as can the control of leachate seeps from the side of the landfill. Thus, options such as temporary capping systems and partial closure of target areas should also be considered.

A targeted benefit of sustainable landfill operations is to minimize the environmental, economic, and social impacts as much as possible. Planning for the future of the facility early in the process allows the engineer and operator to maximize future use of the site and to minimize future cost and impact. An alternative route to closing the facility may be to reclaim all or part of the stabilized waste and cover soil through a large-scale mining operation. The mining plan should consider potential quality and use of the excavated materials and likely outlets for their reuse. Consideration must be given to the design and construction of the system to best allow such recovery and possible reuse of landfill infrastructure.

3.7 Economic Considerations

An integral part of sustainable landfill planning will be an evaluation of economics throughout the life cycle of the facility. With respect to initial capital and operating costs, implementation of many of the technologies for a sustainable landfill will be greater relative to a standard engineered landfill. Infrastructure for achieving rapid waste stabilization will incur added costs to the construction, and as described, additional operation and monitoring will be required. Although site-specific, some benefits and savings will be relatively easy to quantify. These include potential leachate disposal savings and energy sales, though forecasting current values into the future has risk as leachate treatment costs and energy costs change with time, sometimes unexpectedly.

Table 3.5 Economic considerations for sustainable landfills

Economic factor	Considerations
Construction cost	Sustainable landfills require additional infrastructure beyond that which is needed for a traditional landfill. Some opportunities exist to reduce the magnitude of additional cost through re-purposing components (e.g., using leachate recirculation pipes as gas collectors)
Operations cost	Cost of operations may be greater than or less than that of a similarly-sized and operated traditional landfill, depending on site-specific factors. For example, cost savings by avoiding off-site leachate management may exceed the cost increase of additional monitoring and maintenance by site personnel
Closure cost	The cost to close a sustainable landfill is not expected to differ from a traditional landfill, as the closure components (e.g., geosynthetic caps, vegetative layers) would be substantially similar
Post-closure care cost	The principles of the sustainable landfill include reducing long-term environmental impacts; however, broadly characterizing and quantifying these impacts is difficult given there is not a sufficient body of evidence to compare post-closure care costs of traditional landfills to sustainable landfills
Energy revenue	Sustainable landfills have the potential to realize greater revenues from accelerated production and subsequent early collection of LFG. Revenue or potential to implement other renewable energy technologies at landfills such as wind or solar is not expected to differ substantially when comparing the sustainable landfill to the traditional landfill

Other costs are more difficult to quantify. For example, additional disposal capacity gained through accelerated waste stabilization depends largely on whether the landfill is operated and configured in a manner to recoup the airspace. Potential savings from lower monitoring and operating costs in the future and reduced liability are much more difficult to quantify. Table 3.5 presents a series of economic factors and a discussion of considerations for each. Economic considerations of sustainable landfilling practices are discussed in Chap. 18.

3.8 Life-Cycle and Sustainability Considerations

The incorporation of sustainability goals when contemplating the use of enhanced landfill technologies may be of interest to site owners or operators. The concept of life-cycle analysis (LCA) has been applied to waste and materials management systems over the last 20 years (Gentil et al. 2010). LCA tools allow investigators to examine life-cycle impacts of various emissions from waste management activities over long time horizons—often, results from LCA can be used to help support decision making and planning for waste management. Examples of emissions of interest examined as part of an LCA include greenhouse gas emissions, toxicity impacts, materials flow impacts, and several others. A depiction of key aspects of LCA is presented in Fig. 3.1. The figure shows typical components including initial inputs

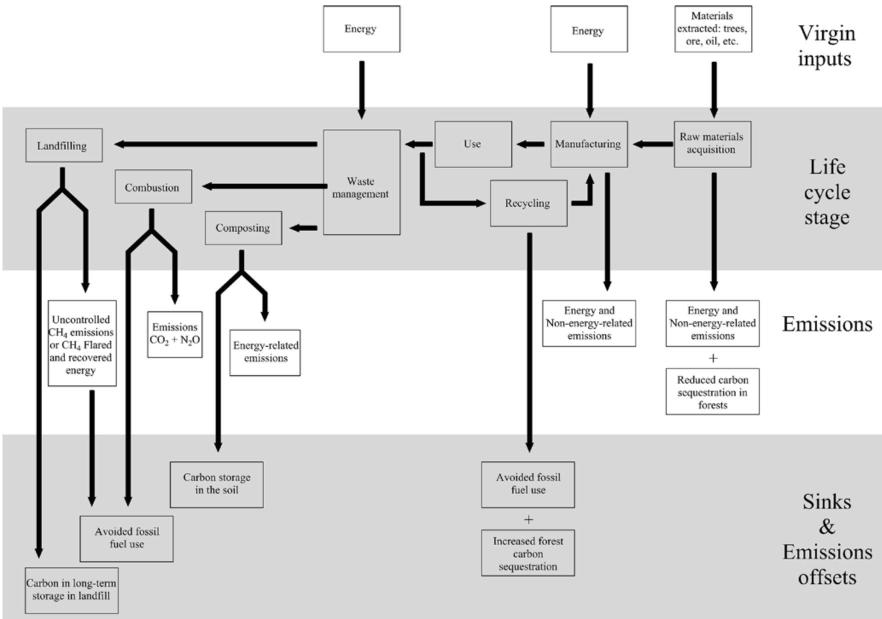

Fig. 3.1 Generalized depiction of key aspects of LCA for waste management systems, which are often represented by charts showing different processes, material and energy flows, and relationship of different processes to one another

(typically materials and energy), processes and actions that occur during the life cycle of a given material, emissions, and potential sinks or offsets that decrease the impact of the emissions. Life-cycle models can examine entire systems such as that shown in the figure, or models can allow very close examination of one or a few elements (e.g., landfilling processes only). Advancements in computing, analytical capability, and availability of site monitoring data have led to rapid expansion of the study of LCA in waste management in recent years, which are available to landfill owners, operators, and engineers to evaluate potential impacts based on a series of site-specific inputs to assess potential environmental, economic, and social impacts over short to long time horizons.

Different of computer-based tools have been developed over the years to examine the life-cycle impacts of waste management systems. A summary of recently-developed or recently-updated models is provided in Table 3.6.

Detailed procedures and approaches to conduct an LCA are beyond the scope of this book, but a discussion about major factors related to sustainable landfills that can impact LCA results is warranted. For example, methane has a large greenhouse gas potential compared to carbon dioxide, so uncontrolled methane emissions can have a substantial impact on life-cycle greenhouse gas emissions for a given landfill. Implementation of sustainable landfilling technologies (including early and effective gas control) can show very favorable lifetime greenhouse gas emissions compared to a traditional landfill, but the reverse may also be true if early or

Table 3.6 Listing of LCA computer models with a focus on waste management processes

Model name	Developer	Description
EASEWASTE (now EASETECH)	Technical University of Denmark	Allows LCA of integrated waste management operations including transportation, composting, resource recovery, and landfilling based on resources consumption and environmental emissions from these operations for municipal solid waste
Municipal solid waste—decision support tool (MSW-DST)	US Environmental Protection Agency, RTI International, and NC State University	LCA tool designed to aid solid waste planners in evaluating the economic and environmental aspects of integrated municipal solid waste management operations including collection, transfer, materials recovery, composting, waste-to-energy, and landfill disposal
WRATE (Waste and Resources Assessment Tool for the Environment)	Environment Agency UK	LCA of integrated municipal solid waste management operations including collection, materials recovery, composting, waste-to-energy, and landfill disposal

effective gas collection is not implemented at a sustainable landfill. This type of an analysis could be conducted and the lifetime greenhouse gas emissions (and the associated life-cycle benefits) could be incorporated into the decision-making process when contemplating the use of (and degree of) sustainable landfill technologies employed at a given site.

LCA tools can also be used as part of planning associated with landfill reclamation. Jain et al. (2014) provided inventory data that could be used by solid waste engineers and LCA modelers to assess the relative benefits of mining landfills. This type of analysis could incorporate considerations including greenhouse gas emissions over the life cycle of a landfill and the benefits of materials recovery (e.g., metals) during landfill mining.

Ultimately, the use and integration of LCA modeling in waste management decision-making is still a developing field. But the proliferation of landfill operating and monitoring data (both for traditional and sustainable landfills), coupled with the continued expansion of computing capabilities and models that can utilize new and large data sets, will help to inform future assessments and help to enhance opportunities to incorporate the principles of sustainability into waste and materials management decision-making, in which sustainable (and traditional) landfills will play a key role.

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Chapter 4
State of Practice

Abstract The potential benefits of sustainable landfill practices have been illustrated historically through a series of laboratory, pilot-scale and operating facility experiments and demonstration. A series of case studies throughout the world are presented which illustrate the variety of goals, design approaches, constraints, and opportunities that may exist for a sustainable landfilling project. The chapter begins with a discussion of the transition of the sustainable landfilling concept from smaller-scale efforts (laboratory studies and pilot-scale testing) to full-scale implementation. Experiences from a number of North American full-scale operations are highlighted, followed by a discussion of sustainable landfill technology research and implementation from Asia, Australia, and Europe.

Keywords Landfill • Leachate • Case study • Leachate • Gas

4.1 The Evolution of Sustainable Landfill Research and Application

As described in Chaps. 1 and 2, until relatively recent history, landfilling of municipal waste was performed with little control or regard for human health and the environment. However, even prior to widespread requirements for engineered controls for environmental discharges from landfills (e.g., leachate, gas), researchers and practitioners began to recognize the important factors influencing the decomposition of municipal waste, such as moisture content and temperature (Eliasen 1945; Farquar and Rovers 1973). This awareness led to laboratory and pilot-scale research experiments conducted to evaluate how conditions in a landfill might be controlled to better achieve desired environmental outcomes.

Table 4.1 summarizes several different laboratory and pilot-scale studies conducted over the past four decades examining advanced landfill control techniques that support more sustainable landfill operation. These experiments provided evidence that suggested full-scale facilities in fact could be influenced by different operational techniques to achieve more rapid waste stabilization. The experiments and demonstrations also provided a fundamental understanding of many properties of landfilled waste and their importance in the stabilization process. Lessons learned

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Waste Management Principles and Practice, DOI 10.1007/978-1-4939-2662-6_4

Table 4.1 Laboratory and pilot-scale research conducted to examine municipal waste decomposition behavior and sustainable landfill concepts

Investigator	Experience and results
Georgia Institute of Technology	Researchers at the Georgia Institute of Technology constructed and operated simulated landfills (one open, one sealed to the atmosphere). Leachate organic strength was observed to decrease drastically over a 6-month period after liquids addition commenced, over a 3-year period, and gas production was found to occur over a 3-month accelerated period. Additional column laboratory scale experiments assessed the fate of trace pollutants and observed that heavy metals were attenuated in the simulated landfills practicing leachate recirculation while trace organics were attenuated from leachate based on their linear partitioning coefficients for the solid phase (Pohland 1977; Pohland et al. 1987; Reinhart et al. 1991)
Sonoma County, California	Pilot-scale field test cells filled with MSW at the Sonoma County Landfill were used to examine varying operational strategies for moisture management. Researchers concluded that moisture movement was critical to rapid leachate stabilization and that initially high moisture addition alone was not sufficient alone. Leachate recirculation was observed to result in more rapid waste settlement to accelerate geotechnical stabilization (EMCON Associates 1975; Augenstein et al. 1976)
University of Wisconsin-Madison	Researchers at the University of Wisconsin-Madison evaluated CH_4 production in small-scale (208-L) MSW landfill reactors over 2 years. The development of a strong methanogenic community was determined to be the limiting factor for waste degradation. Seeding (microbiological) the waste with anaerobically-degraded refuse and buffering the waste were both found to be effective in stimulating CH_4 production; conversely, sewage sludge and acetate addition, as well as O_2 depletion did not stimulate CH_4 production. The presence of initial nutrients was determined not to be limiting (Barlaz et al. 1987)
University of South Florida	Researchers at the University of South Florida performed short-term (several month long) simulated landfill experiments to explore the concept of aerobic landfill operation. Test columns with continuous air addition (leachate aeration prior to recycle and air injection to waste) were observed to enhance waste stabilization (measured by waste settlement) and improve leachate quality compared to anaerobic test columns; post-degradation waste was more compacted, which acted to prevent airflow into the waste mass (Stessel and Murphy 1992)
Yolo County, California	Two test cells (10,000 ft^2) were filled with MSW and monitored; one cell was operated with liquids addition (referred to as the "enhanced cell") and one was not. Surface settlement was greater in the cell with moisture addition (15.5 % versus 3 % for a 12 m waste thickness); the mean biochemical methane potential (BMP) measured for the enhanced cell was 24.0 mL CH_4/dry-kg waste for the first roughly 3.4 years. Analysis of borings in the waste collected after approximately 4 years found high moisture content in the wetted cell as well as a lower ratio of cellulose to lignin, suggesting greater waste decomposition (Mehta et al. 2002)

(continued)

Table 4.1 (continued)

Investigator	Experience and results
Delaware Solid Waste Authority	Two 4,000 m^2 (43,056 ft^2) test cells were filled with MSW and monitored over a 6-year period; one cell was operated using leachate recirculation and one was not. Time capsules exhumed from each cell demonstrated dramatic differences in waste degradation with significantly more decomposition occurring in the recirculation cell compared to the dry cell. The lack of dramatic leachate quality differences between the cells was reported to result from poor moisture distribution within the leachate recirculation cell. Gas production was greater in the wetted cell, although this gas production was much lower than the predicted gas production potential (Morris et al. 2003)
University of Southampton (UK)	Researchers at the University of Southampton studied the compressibility, hydraulic conductivity, and other properties of MSW in a purpose–built compression cell. This device allowed overburden pressure to be applied to the top of the waste, similar to that which would occur under field conditions as additional waste is landfilled and waste thickness is increased. Density, field capacity, and hydraulic conductivity changes as a function of overburden pressure were assessed. Results showed that in areas with built-up biogas, the pore water pressure will affect waste bulk density and drainable porosity less than areas with low gas accumulation—a behavior that was not accounted for in standard compression models (Hudson et al. 2004)
Various Studies in Turkey	Laboratory-scale landfill reactors in Turkey were used to examine leachate recirculation and landfill aeration. Decomposition of the waste was similar for aerobic recirculation and non-recirculation cells, while leachate quantity (although not quality) differed, aerobic operation was found to decrease waste moisture content. Within operated anaerobic cells leachate recirculation was found to have a significant impact on leachate generation quantity (increased) and COD (decreased). The reactors operated with aeration resulted in the best leachate quality characterized by the lowest observed organic matter and nitrogen levels (i.e., lowest COD and TKN concentrations). Trace metal concentrations were also lower in aerobic reactors (all leachate concentrations were below regulator limits), and levels decreased to below regulatory limits in anaerobic reactors after the reactors reached the methanogenic phase. Aerobic reactor leachate had higher fractions of non-biodegradable COD than anaerobic reactors (by 10 percentage points) (Bilgili et al. 2007a, b, 2008)
University of Florida Simulated Landfills	Researchers at the University of Florida compared simulated bioreactor landfills (lysimeters) operating under aerobic and anaerobic conditions. Landfill gas analysis showed minimal CH_4 production from aerobic lysimeters (<1 % of generated CO_2) with greater decomposition (62 % vs. 54 % of biodegradable lignocellulosic waste) of recalcitrant lignin based materials (e.g., office paper, cardboard). Leachate organic strength decreased more rapidly in the aerobic experiment compared to leachate from the anaerobically operated simulated cell, with 90 % BOD reduction over 160 days vs. >700 days for the anaerobic lysimeters. Waste volume loss and settlement were typically between 30 % and 40 % and 16 % to 22 %, respectively; volume loss was used to calculate mean decay rates of 0.378 $year^{-1}$ for aerobic and 0.0185 (acid phase) and 0.22 $year^{-1}$ (methanogenic phase) for anaerobic lysimeters, respectively (assuming first order kinetics). Heavy metals behaved differently within the two environments, with the relative mobility found to be dependent on the metal examined; Al, Cu, and Pb were significantly higher in aerobic reactors, which the opposite was true for As, Fe, and Zn. The acid-forming phase tended to have higher levels of metals for the aerobic reactors, levels were consistent in anaerobic reactors (Kim 2005; Kim et al. 2011)

in these studies led to successful full-scale implementation of techniques at many operating landfills. The sites described this chapter were selected for evaluation to reflect a variety of operational techniques (e.g., anaerobic and aerobic, horizontal and vertical liquids addition devices) and results.

The remainder of this chapter is devoted to reviewing a number of case studies where sustainable landfill practices have been implemented worldwide. The sites described this chapter were selected for evaluation to reflect a variety of operational techniques (e.g., anaerobic and aerobic, horizontal and vertical liquids addition devices) and results.

4.2 Full-Scale Case Studies: North America

Several full-scale landfills have been operated using sustainable landfilling techniques in North America. Investigators have reported on different key aspects of sustainable landfill operation and science, including gas production (Faour et al. 2007), biological and chemical aspects of leachate and gas (Barlaz et al. 2010), and bioreactor practice or performance in general (Benson et al. 2007; US EPA 2007; Bareither et al. 2010; Kumar et al. 2011). The focus of this section is to present summaries of some of the better documented North American case studies in the technical literature.

Reviewers tend to agree that increased moisture content, to near field capacity, is the dominant factor in the promotion of the accelerated waste degradation observed in sustainable landfills (Benson et al. 2007; Kumar et al. 2011). Accelerated decomposition can be characterized by greater waste decay rates, which is often described through the landfill gas decay constant; normally accelerated stabilization occurs after some lag period following liquids addition initiation. Summary reports including leachate quality data tend to agree that over time, as sustainable landfill operation progresses, the strength of leachate tends to decrease over time (as represented by a decreasing ratio of BOD:COD), while ammonia levels tended to stay elevated, even after many years in some cases (Benson et al. 2007; Barlaz et al. 2010). Enhanced and/or accelerated settlement has been observed in most reported studies that collected routine measurements of surface elevations. Overall, sustainable landfill sites in North America have shown an ability to perform within landfill regulatory limits and guidelines (Benson et al. 2007; US EPA 2007; Bareither et al. 2010).

4.2.1 Delaware Solid Waste Authority

The Delaware Solid Waste Authority (DSWA) has practiced leachate recirculation at several of its operating landfills since the early 1980s (Watson 1987). Operators employed multiple methods of leachate recirculation at the Central Solid Waste Management Center (CSWMC) in Sand Town, Delaware, which accepted waste until 1996. Morris et al. (2003) summarized results of long-term monitoring at the site.

Leachate recirculation methods at CSWMC included (i) vertical leachate recirculation wells, (ii) surface application using spray irrigation, and (iii) surface wetting. The vertical wells were constructed of 1.2-m diameter perforated concrete manhole sections filled with coarse aggregate and a perforated PVC pipe distribution manifold. These devices were extended upward as landfilling operations progressed. Liquids addition into the vertical wells was employed only during the operational years of the landfill (Morris et al. 2003). Spray irrigation was performed both during the operational years and post closure, and was estimated to remove up to 30 % of the leachate by evaporation (Watson 1987), but could not be operated during periods of inclement weather. This method caused the most odors of all the methods evaluated and spray irrigation was avoided under windy conditions.

Several methods were utilized for surface application of leachate at the site. In one method, areas of the site surface were bermed off and utilized as seepage beds. Liquids could be added during weather conditions with high winds but not during wet weather (Watson 1987). After closure, leachate recirculation at the surface was performed using buried stormwater infiltration chambers that were connected to a leachate distribution manifold (Morris et al. 2003).

Leachate constituent concentrations were monitored before and after closure (Morris et al. 2003). Leachate organic strength (as characterized by BOD concentrations) decreased over time, and the BOD:COD ratio was <0.1 in the later stages of leachate monitoring (see Chap. 15 for more discussion of BOD:COD significance including data from a DSWA landfill). Ammonia concentrations remained elevated over the majority of the site's monitoring period, although concentrations decreased in the later stages of landfill monitoring as continued flushing via leachate addition and disposal.

4.2.2 Alachua County Southwest Landfill

Research on leachate recirculation and augmented waste stabilization began at the Alachua County Southwest Landfill (ACSWL; located near Gainesville, FL, US) in 1990. Figure 4.1 presents a plan view of the facility. This facility represented one of the first lined MSW landfills in the Southern US and was equipped with a leachate pretreatment system consisting of lime addition and aeration; treated leachate was hauled off-site to a domestic wastewater treatment facility via tanker truck. To reduce leachate management costs and to promote rapid waste stabilization, the County and researchers from the University of Florida implemented and evaluated several different types of liquids addition systems (surface and subsurface) and monitoring of multiple parameters of interest (some of the data from this site are presented in Chap. 16 on monitoring).

Liquids addition was conducted in a lined landfill cell that was constructed and began operation in 1988. Initially, liquids introduction at the site was performed using a perforated manifold system, similar to that of a drip irrigation system, placed on the surface of the landfill (Fig. 4.2). Leachate was pumped to the manifold

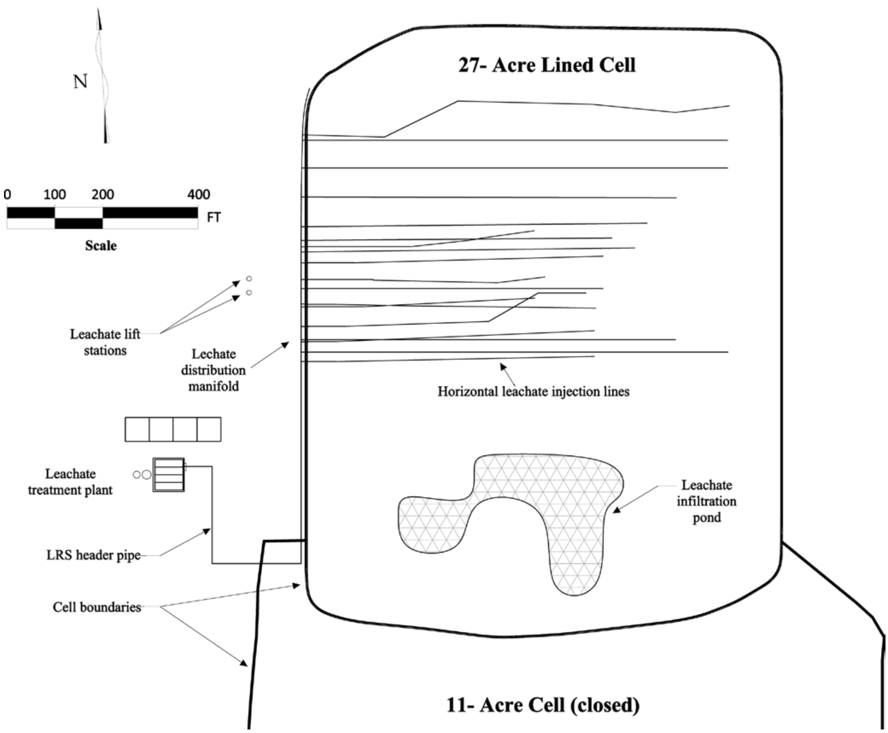

Fig. 4.1 Plan view of Alachua County Southwest Landfill

Fig. 4.2 Original surface drip irrigation system at ACSWL

Fig. 4.3 Excavation of surface infiltration pond at ACSWL

system from a submersible pump placed in the leachate storage tanks. The manifold system was designed to distribute the liquids uniformly over the application area, but once initiated it was recognized that the rate of leachate application was larger than the achievable rate of liquids uptake into the waste, resulting in excessive leachate ponding and runoff.

The limited rate of leachate infiltration through the surface of the landfill from the drip irrigation system led to the use of surface infiltration ponds (Townsend et al. 1995), which provided a greater storage volume and more consistent infiltration rate into the waste. The ponds were constructed by excavating a depression into the waste on the surface of the landfill (Fig. 4.3) in combination with constructed perimeter walls comprised of newly-compacted waste. Liquids were added via a piped connection to the leachate tanks; a constant depth of liquid was then maintained in the ponds during operation (Fig. 4.4). Hydraulic performance of the ponds was closely monitored by tracking the water balance on a daily basis (Townsend 1992); leachate infiltration rates ranged from 6×10^{-6} to 9×10^{-6} cm/s (5,500–8,300 gallons per acre-day). Using the infiltration data and the liquid depths in the infiltration ponds, the vertical hydraulic conductivity of the underlying waste was estimated to range from 3×10^{-6} to 4×10^{-6} cm/s (Townsend et al. 1996).

Throughout the research, waste samples were collected by augering into the waste with a solid-shaft open-flight auger, both before and after liquids addition (Jain et al. 2005a). The results demonstrated that the infiltration pond technique resulted in favorable moisture distribution and waste decomposition (Townsend et al. 1996; Kim and Townsend 2012; see Chap. 16). Observed disadvantages of surface ponds included floating waste (typically occurring after several months of operation as a result of biogas becoming trapped under plastic film), and the requirement of a large area of landfill surface. Given the relatively high amount of rainfall in Florida (approximately 50 in. per year), additional moisture entered the ponds over time,

Fig. 4.4 Completed surface infiltration pond system ACSWL

Fig. 4.5 Construction of horizontal leachate recirculation line at ACSWL

especially when stormwater from surrounding areas entered the ponds. When ponds were constructed or modified by compacting waste to extend the perimeter berms, seeps would sometimes occur at the base of the newly added berms. Experience with these infiltration ponds is discussed further in Chap. 7.

The next phase of leachate recirculation at the site was performed using buried horizontal trenches containing perforated pipe and a bedding material of shredded tires (Fig. 4.5). Most of the trenches were constructed using an excavator to dimensions of approximately 1 m deep by 1 m wide (3 ft by 3 ft), with lengths from 110 to 240 m (360–780 ft). Shredded tires were placed on the bottom half of the trench, followed by the placement of perforated PVC pipe (in most cases 7.7-cm (3-in.) diameter pipe), and the remaining trench volume was filled with shredded tires. The top of the trench was then covered by waste excavated from the trench and topped with cover soil. This buried trench system, referred to as horizontal injection lines (HIL), was used for leachate recirculation for the remaining life of the landfill and after closure (in 1998), but was studied in greatest detail from 1992 to 1995 (Townsend 1995; Townsend and Miller 1998).

Leachate was added to individual injection lines at a rate ranging from 0.003 to 0.005 m^3/s (50–100 gpm) and the resulting injection pressure was recorded. Leachate recirculation rates were highest at the beginning of daily injection cycles, and as leachate recirculation progressed, achievable flow rates decreased and injection backpressure increased. After a non-operational rest period, leachate recirculation flow rates would return to higher levels, but soon returned to previous lower rates and higher back pressures; this trend continued, with increasing cumulative injection volume over time. Townsend and Miller (1998) described the hydraulic performance of individual injection lines; results of this work are discussed further in Chap. 9.

Gas collection infrastructure was installed at the site in 1994. Large gas pressures were observed in the HILs and the injection system was reconfigured to operate with the dual purposes of leachate recirculation and gas collection (Fig. 4.6). The HIL pipes were configured so that leachate could be added as desired, such that when no leachate was recirculated, gas could be extracted using an independent gas manifold connected to the landfill's blower flare station. Although leachate recirculation activity resulted in high gas production rates, flooded conditions surrounding the trenches precluded effective gas extraction (Townsend et al. 1994). In many cases, when connected to the gas collection manifold, leachate would periodically surge into the gas collection line, resulting in larger amounts of liquids to manage than would typically result from extracted gas condensate alone.

Another observation at the site was the presence of large gas pressures in the LCRS. This led to the retrofit of the LCRS for gas collection, a technique which was found to be much more effective than gas collection from the buried injection trenches (Townsend and Miller 1997). The operation of the leachate lift stations was modified to minimize gas escape through the manholes, thus promoting a greater gas capture rate from the LCRS.

The landfill was closed in 1998 and capped with a final cover system that included a geomembrane. Leachate recirculation into the landfill using the buried horizontal lines and a surface trench system continued as of 2014. Early research efforts at the site examined the use of membrane treatment to create a diluted leachate stream that could be spray irrigated on the site and a concentrated stream that would be recirculated back to the landfill (Townsend 1992). Leachate is currently treated using reverse osmosis (RO) following this approach; with the RO permeate land-applied to the vegetated final cover system and the concentrate recirculated.

Fig. 4.6 Combined liquids addition and gas extraction system connected to horizontal trenches at ACSWL (white pipe is gas extraction manifold and gray pipe is liquids addition manifold)

4.2.3 Yolo County Landfill

The Yolo County Planning and Public Works Department followed up a successful demonstration of bioreactor landfill concepts in a side-by-side pilot-test cell comparison begun in 1994 (see Table 4.1) with full-scale implementation of several sustainable landfill technologies. Three different landfill cells were constructed to operate with liquids addition, with 6- and 3.5-acre (2.4 and 1.4 ha) cells operated anaerobically and a 2.5-acre cell operated aerobically (see Fig. 4.7 for an overall site schematic). Leachate recirculation systems in the full-scale cells were constructed as they were built with horizontal injection lines buried in the waste (four injection line layers in the 3.5- and 6-acre anaerobic cells and three injection line layers in the 2.5 acre aerobic cell) (Yazdani et al. 2002, 2006). Instrumentation layers were integrated as part of a supervisory control and data acquisition (SCADA) system for improved air and leachate injection control capabilities and access to

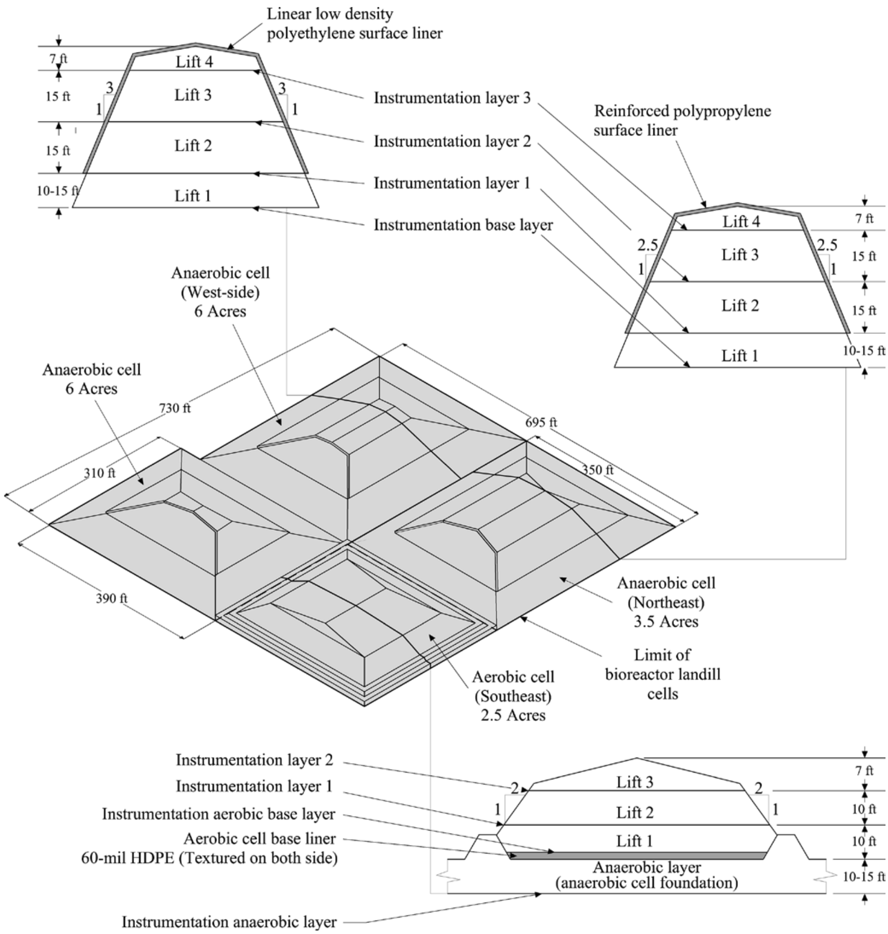

Fig. 4.7 Configuration of aerobic and anaerobic bioreactor cells at the Yolo County Landfill

instrumentation data from the sensors embedded within the waste (Yazdani et al. 2006). When completed, the anaerobic cells were covered with a geomembrane cap (Fig. 4.8).

Instruments were placed throughout the landfill to measure temperature, moisture content, and fluid pressure. As illustrated in Fig. 4.9, instruments were placed adjacent to liquids addition and gas extraction manifolds. Pressure data from sensors installed at the bottom of the full-scale bioreactor cell indicated that the maximum head on the liner (HOL) was within regulatory limits (peaking typically around 0.9 in. (2.3 cm)). Sampling tubes were also installed for the collection of gases within the landfill for measurement of major gas components. Field-scale gas tracer tests were performed to characterize moisture content of the waste and gas flow patterns. Liquids addition was performed using horizontal trenches installed

Fig. 4.8 View of Yolo County Landfill northeast anaerobic bioreactor cell; upon completion the slopes were covered with a geomembrane cap ballasted by tires (Photo courtesy of Ramin Yazdani)

Fig. 4.9 Instrumentation and associated cables placed next to gas collection piping during construction at Yolo County Landfill (Photo courtesy of Ramin Yazdani)

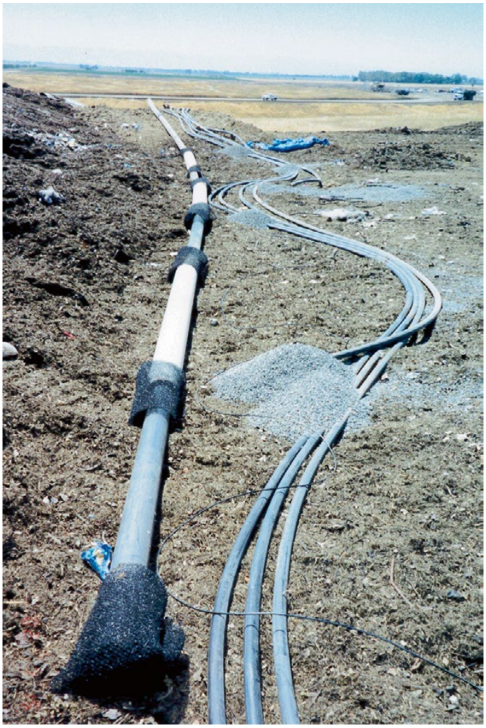

Fig. 4.10 Liquids addition trench with shredded tires at Yolo County Landfill (Photo courtesy of Ramin Yazdani)

into the landfill as it was constructed (4.5–7 m [14.8–23 ft] spacing) to achieve a moisture content of approximately 40 % in the anaerobic bioreactor cells. Figure 4.10 shows a liquids addition trench using tire shreds as a bedding media. Liquids percolation rates were used to estimate an apparent permeability of 3×10^{-5} cm/s (Yazdani et al. 2006). Gas collection pipes were installed in a similar manner, with perforated PVC or HDPE pipe (10–150 mm [0.39–5.91 in.] in diameter) installed horizontally on top of waste lifts and spaced 11.9–13.7 m (39–44.9 ft) apart. Shredded tires were used as a bedding material. Air addition in the desired cell was accomplished by placing sufficient vacuum on the gas extraction pipes to pull air into the landfill through the permeable soil cover; extracted air was pulled through a biofilter (comprised of wood chips and limestone for buffering capacity) for treatment (Yazdani et al. 2006).

The anaerobic bioreactor landfill cells were successful at accelerating CH_4 production, initiating peak generation rates approximately five times earlier than control cells that were operated conventionally. A 6-acre bioreactor landfill cell equipped with an exposed geomembrane facilitated a ninefold increase in CH_4 capture, with overall capture rates estimated to be greater than 90 %.

Sustainable landfilling operation at the site resulted in waste volume reduction, surface settlement, waste stabilization, and a reduction in fugitive greenhouse gas emissions. Enhanced landfill gas production correlated with increased waste temperatures in bioreactor cells of approximately 5–15 °C compared to conventional cells (reaching 110–140 °C) (Yazdani et al. 2006). Settlement rates for anaerobic cells reported in Yazdani et al. (2006) were 8.5 % and 4 % (as of September 2004) for the 3.5- and 6-acre anaerobic cells, respectively, and reflective of the greater time period over which the 3.5-acre cell had to settle.

Results from the aerobic cell testing revealed that even where air was added to specific areas within the landfill, anaerobic decomposition was always present, particularly where measured moisture content was highest (Yazdani et al. 2010). This observation was attributed to rapid depletion of injected O_2, indicative of waste with an O_2 demand in excess of supplied quantities, as well as the formation of "immobile zones" (i.e., dead zones where airflow did not penetrate) and preferential flow pathways (short circuiting through bedding media in trenches) was also reported (Yazdani et al. 2010). Even so, data collected from the aerobic cell results showed that an overall greater fraction of organic waste was decomposed via this method compared to the anaerobic cell operation (Yazdani et al. 2006).

4.2.4 New River Regional Landfill

The New River Regional Landfill (NRRL) located in Raiford, FL, US, is owned and operated by the New River Solid Waste Association (NRSWA) and receives a mix of residential and commercial waste from surrounding municipalities. The NRRL site occupies approximately 500 acres (202 ha) in total area and consists of six contiguous lined landfill cells totaling approximately 82 acres in size. In 2001, the NRSWA retrofitted approximately 10 acres (Cell 1 and part of Cell 2) with sustainable landfilling infrastructure (Fig. 4.11) including leachate recirculation, air injection, landfill gas extraction, and monitoring equipment. Several research experiments were performed in this area of the site and NRSWA has continued implementation of sustainable landfill practices in other areas of the site.

The liquids addition system of the original bioreactor landfill area consisted of 45 vertical well clusters (Fig. 4.12) that were used to recirculate leachate (and groundwater) and add air to the landfill (Jain et al. 2005a). Each cluster consisted of three wells with approximate depths of 20, 40, and 60 ft. The injection wells within each cluster were approximately 2 ft apart, and each cluster approximately 50 ft from other clusters (Fig. 4.13; additional construction photos of the wells are provided in Chap. 8). Pumps located in the facility's lined leachate ponds provided liquids to the injection well-field. Added liquids included leachate collected from the lined landfill units on site as well as groundwater, pumped into the ponds as needed to fulfill the liquids addition requirements. Approximately one-half of the well field was constructed with aid addition infrastructure. Two positive displacement blowers located at the landfill gas blower flare station provided the pressurized air.

Thirty-one 3-ft deep by 3-ft wide horizontal gas collection trenches were constructed at 120-ft spacing on the landfill surface (including side slopes) beneath a

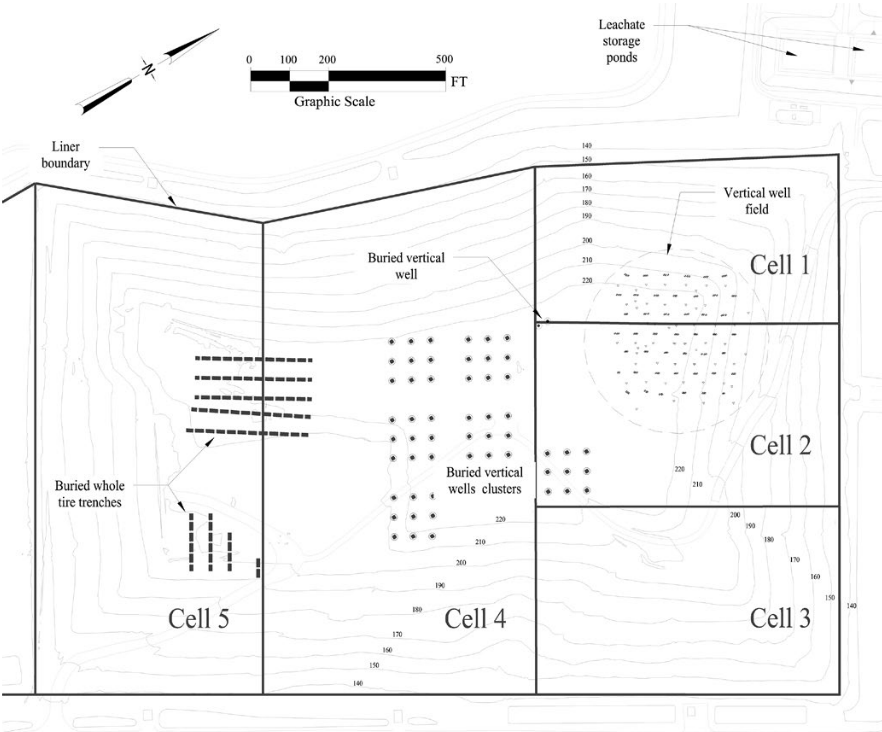

Fig. 4.11 Plan view of New River Regional Landfill

Fig. 4.12 Cluster of vertical wells at NRRL after construction and prior to liquids or air addition

Fig. 4.13 Vertical well field at NRRL

40-mil linear low-density polyethylene (LLDPE) textured exposed geomembrane cap (EGC). Once the EGC was installed, gas monitoring wells, leachate/air-injection wells, and monitoring ports were cut through the cap and expansion boots were installed to accommodate settlement (a total of 300 penetrations). Figure 4.13 shows the surface of the landfill after installation of the EGC and indicates the location of the cluster wells.

Instruments were installed around the injection clusters and at several depths to monitor moisture content, temperature, and gas composition. A composite sensor bundle for monitoring moisture (based on electrical-resistance technology), temperature, and gas composition (referred to as MTG sensors) was fabricated and installed (Gawande et al. 2003). Vertical holes were drilled at 15-, 30-, and 50-ft depths and an MTG probe was placed at the bottom of each borehole by temporarily attaching the instrument bundle to temporarily attached access pipe (Fig. 4.14). The instruments were separated from the access pipe using a small diameter pipe (Fig. 4.15) and the access pipe was used to add sand followed by a bentonite clay seal before removal (then the access pipe was removed). Upon placement of the EGC on the site, the cables were routed through a penetration in the geomembrane (Fig. 4.16) bundled, and the penetration sealed. Forty-two clusters and a total of 138 MTG probes were installed (Kumar et al. 2009). Twelve time-domain reflectometry (TDR) probes were installed at five cluster locations for comparison purposes (Jonnalagadda et al. 2010). In most cases, the instruments were connected to data-loggers for continuous monitoring.

The bioreactor research at the site was started in 2003 with a series of short-term air-injection tests to estimate air permeability of the waste (Jain et al. 2005b).

Fig. 4.14 Recently augered cluster of boreholes with instruments placed at bottom of borehole. Each instruments bundle was temporarily attached to the end of a pipe

Fig. 4.15 The pipes were dislodged from the instrument bundles using a small diameter pipe to the provide separation force required

Fig. 4.16 Instrument cable routing through the geomembrane

Air was added to 134 vertical wells installed at three different depths at flow rates ranging from 5 to 50 scfm, and the corresponding steady-state pressures were recorded and used in an analytical fluid flow model to estimate air permeabilities of 1.6×10^{-13} to 3.2×10^{-11} m^2. The estimated air permeability decreased significantly with increasing waste depth, which was attributed to the lower porosity of waste in deeper sections caused by higher overburden pressures, moisture contents, and landfill gas pressures.

Leachate recirculation tests were conducted in 2003 and 2004 to estimate the saturated hydraulic conductivity (Jain et al. 2006; see Fig. 4.17). The tests were conducted at 23 locations using the borehole permeameter test and the saturated hydraulic conductivity (K_s) of the landfilled waste was estimated to range from 5.4×10^{-6} to 6.1×10^{-5} cm/s. Similar to air permeability, the hydraulic conductivity of the waste decreased with depth, the likely result of greater overburden pressures associated with increasing waste depth in the landfill. The decrease in hydraulic conductivity with depth suggested that a single screened well was sufficient to achieve uniform distribution and that a cluster of multi-depth wells was unnecessary.

Jain et al. (2014) reviewed the performance of the vertical well system for liquids addition. Over a 5-year period, 25,000 m^3 of leachate was added to the well field. The performance was evaluated in terms of fluid conductance (defined as flow rate per unit well screen length per unit liquids head above the well bottom), which was found to range from 5.6×10^{-8} to 3.6×10^{-6} m/s. Liquid depths within the well had to be maintained below the landfill surface to avoid surface seepage; therefore, the system operation was labor intensive, especially for wells installed at the shallow depth. Concrete collars to minimize seeps under pressurized addition of liquid were tested, but leachate surface seeps were still problematic.

Fig. 4.17 Addition of liquids into a vertical well cluster at NRRL and measurement of flow rates and liquid depths

The ability of the resistivity sensors and TDR clusters to monitor moisture content was evaluated (Kumar et al. 2009; Jonnalagadda et al. 2010). Sensors used to detect landfill moisture showed that the extent of lateral moisture movement ranged from 8 to 10 m. When the spatial average moisture content of the landfill following the experimental period was calculated, the resultant value was very high, suggesting that obtaining true moisture content magnitude from in-situ sensors can be complicated by various factors (e.g., channeling of liquids). From these observations, it was concluded that in-situ moisture monitoring devices are well suited to detect the presence of moisture, but not necessarily to calculate an exact in-situ moisture content. The resistivity sensors, which were less expensive to construct and install compared to the TDR sensors, performed comparably to the TDR sensors and in general proved to be more reliable.

In 2004 and 2005, air injection tests were conducted to examine the change in landfill gas quality upon initiation of aerobic decomposition conditions (Powell et al. 2006). The concentrations of CH_4, CO_2, O_2, and trace chemicals (nitrous oxide (N_2O), a suite of volatile organic compounds, CO, and H_2S) were measured both before and during air addition. A significant increase in CO was observed in 9 out of 14 monitoring points after initiating air addition, and this increase was concurrent with a decrease in the ratio of CH_4 to CO_2. A significant decrease in H_2S was observed at 6 of 14 monitoring points, but no noticeable effect on N_2O and volatile organic concentrations was observed. The results suggested that aerobic decomposition conditions can be accomplished within compacted MSW and that certain problematic gases (e.g., H_2S) can be controlled.

Another key observation regarded the increase in temperature shortly following air addition. Since the landfill was heavily instrumented, a high resolution of temperature dynamics was available, which showed substantial increases within days of initiating operation. Ultimately, the temperature increases resulting from air addition were found to be limiting to long-term operations, even when measures such as significant liquids addition prior to air addition were implemented (Powell 2005). Additionally, the insulating environment of the landfill resulted in higher sustained temperatures, even upon cessation of air addition. These results underscore the importance of removal of the heat generated from aerobic decomposition reactions if aerobic operation is contemplated at sustainable landfills.

The performance of the air addition system was reviewed by Ko et al. (2013). Approximately 49 million standard cubic feet (1.4 million m^3) of air were added to 78 wells in the NRRL well field. Similar to the studies conducted by Powell (2005), consistent long-term aerobic conditions could never be established as air injection resulted in undesirable elevated temperature. Gas concentrations measured throughout the experiments showed both CH_4 and O_2 present at potentially flammable mixture ratios, but not in the explosive range. While air addition could play some role in bioreactor landfill operation, results from these tests suggested that maintaining aerobic conditions as the dominant waste-decomposing environment within typical large landfills can be difficult and limited by resulting temperatures.

The degree of waste stabilization from sustainable landfill operations at NRRL was evaluated by Kim and Townsend (2012). Waste samples were collected before and after liquids addition using a solid-shaft open-flight auger and analyzed for moisture content and the biochemical methane potential (BMP). The results showed that areas where leachate was recirculated had higher waste moisture content and lower BMP compared to areas where leachate recirculation did not take place, demonstrating that the sustainable landfilling operations resulted in an environment where biodegradation of waste was enhanced (more details are provided in Chap. 16).

Several other research experiments were conducted at the site in support of sustainable landfill operation. Timmons et al. (2012) documented the use of total earth pressure cells for measuring the overburden pressures at the base of the landfill resulting from overlying waste. Kadambala et al. (2011) examined the use of vibrating wire piezometers placed within the waste surrounding a vertical liquids addition well and observed pore pressures measured in the area surrounding the wells to be significantly lower than those encountered in the well itself. Pore pressures increased rapidly following the initiation of leachate recirculation, but only slowly dissipated after liquids addition ceased. Additional data from this experiment were used to assess the degree of waste anisotropy (Singh et al. 2014); pore pressure and liquids flow data supported that the waste was indeed anisotropic with respective to hydraulic conductivity, and the magnitude of anisotropy decreased with waste depth.

The occurrence of leachate seeps around the wells as in-well liquid levels approached the landfill surface suggested that clay plugs and grouting placed around the well during construction did not sufficiently limit surface seeps. Additionally, differential settlement around verticals wells at the surface of the landfill created a

Fig. 4.18 Installation of a vibrating wire pressure transducer into a buried vertical well at NRRL

maintenance problem. Kadambala et al. (2011) evaluated the use of buried vertical wells as a method to avoid seepage issues; vertical wells were constructed on the surface of the landfill and connected via a buried manifold in a surface trench (Fig. 4.18). Another lift of waste was then placed above the top of the manifold, which allowed for the successful addition of liquids into vertical wells under pressure without resultant surface seeps (see Chap. 8 for more details).

4.2.5 Crow Wing County Landfill

Leachate recirculation at the Crow Wing County Landfill in North Central Minnesota started 1998 (Doran 2007; US EPA 2007). The site, which began waste acceptance in 1991, receives approximately 40,000 tons of MSW per year, has four lined landfill units (Fig. 4.19), and introduces leachate to the landfill by spray application to the working face, spray application to intermediate landfill cover, and buried horizontal trenches (Doran 2007; US EPA 2007; Burns and McDonnell Engineering Company Inc. 2014). All cells are equipped with a composite bottom liner consisting of compacted clay and a 60-mil HDPE geomembrane. The recirculation pipe design consists of alternating 4-in. and 5-in. perforated pipes bedded in shredded tires. Approximately 3.5 million gallons (13,200 m^3) of leachate are recirculated annually, with a range of 1.9 million to 5.0 million gallons (7,200–18,900 m^3) (Burns and McDonnell Engineering Company Inc. 2014). The waste moisture

Fig. 4.19 Crow Wing Landfill site plan

content prior to initiating leachate recirculation activities was 19 %. The moisture balance at the site is updated annually and was 22 % in 2013, with a maximum of 25 % observed in some locations (Burns and McDonnell Engineering Company Inc. 2014).

Leachate is stored at the site using four treatment ponds that are configured in series and provide a total storage capacity of approximately 3.9 million gallons. Leachate is recirculated into the buried horizontal trenches, at rates which range from 25 to 50 gallons per linear ft of trench per year. Recirculation is practiced between March and October to avoid the colder winter months and potential issues with freezing conditions (Burns and McDonnell Engineering Company Inc. 2014).

The leachate management hierarchy at the site consists of, in terms of decreasing preference, treated leachate spray application to an on-site spray field, leachate recirculation into the landfill, and off-site hauling. Historical measurements of the collected raw leachate quality show that the BOD:COD ratio has dramatically and rapidly decreased in each of the four cells to <0.2 within 3–5 years of initiating leachate recirculation (Burns and McDonnell Engineering Company Inc. 2014). An ex-situ leachate treatment system via ponds serves to reduce ammonia by nitrification (and subsequent conversion of nitrate to nitrogen gas via denitrification after leachate is recirculated back into the landfill). As of 2013, no leachate has been managed via off-site hauling since 2002, demonstrating that the combined system of leachate recirculation and on-site treatment has been effective over a long period as the primary leachate management options.

An active GCCS was constructed at the site in 2008 and consists of gas collectors within the waste as well as plumbing to capture gas from leachate recirculation devices and the LCRS (Burns and McDonnell Engineering Company Inc .2014). Collected LFG is managed via a flare and an on-site boiler and the quality has historically ranged from 45 to 50 % CH_4 at a flow rate of 200 standard cubic feet per minute (5.7 m^3/min).

As for operational observations, some seepage occurred during early stages of recirculation activities near locations of former access roads. A robust leachate collection toe drain around the perimeter of the cells was found to alleviate seepage issues, although the drains were found to intercept stormwater during large rain events. To mitigate leachate seeps, sandy soils were used for an intermediate cover and a recirculation line perforation setback distance of 15 m was maintained (US EPA 2007).

Historical airspace monitoring at the site found that the airspace utilization factors for the cells increased over time, for cell 1, from 1,004 to 1,341 lb/yd^3, an effect attributed to the leachate recirculation activities and subsequent waste degradation and settlement, which was calculated at 20 % of total waste height after 5 years of recirculation operations (US EPA 2007). Given the high degree of settlement observed, flexibility in infrastructure piping (including flexible stainless steel and excess 5 ft. engagements at pipe ends) was key in reducing operational issues as leachate recirculation and subsequent settlement progressed (US EPA 2007).

4.2.6 Polk County North Central Landfill

The Polk County North Central Landfill (PCNCL) in Winter Haven, FL, US was the site of intensive research on sustainable landfill operation, particularly as related to the controlled addition of liquids into buried horizontal trenches and galleries. The county had historically operated several MSW landfills and had on occasion practiced leachate recirculation through surface ponding as a means of leachate management. Motivated in large part by rising leachate disposal costs, the county modified its existing lined Phase II landfill unit to operate as a sustainable landfill (Fig. 4.20). Landfill gas from the site is conveyed to a neighboring industrial facility for direct beneficial use.

Beginning in 2000, the landfill began installing a series of horizontal trenches for liquids addition. The majority of these trenches were constructed using an excavator to approximate dimensions of 1 m deep by 1 m wide (3 ft by 3 ft), with lengths up to 220 m (720 ft). Ten-centimeter (4-in.) high density polyethylene (HDPE) pipes were used; 0.95-cm diameter pipe perforations (0.375-in.) were placed at a frequency of 2 for every 0.6 m (2 ft) of pipe and were each oriented 45° from either side of the vertical and placed in the downward direction. A variety of bedding materials were used, including shredded automobile tires and crushed glass; in

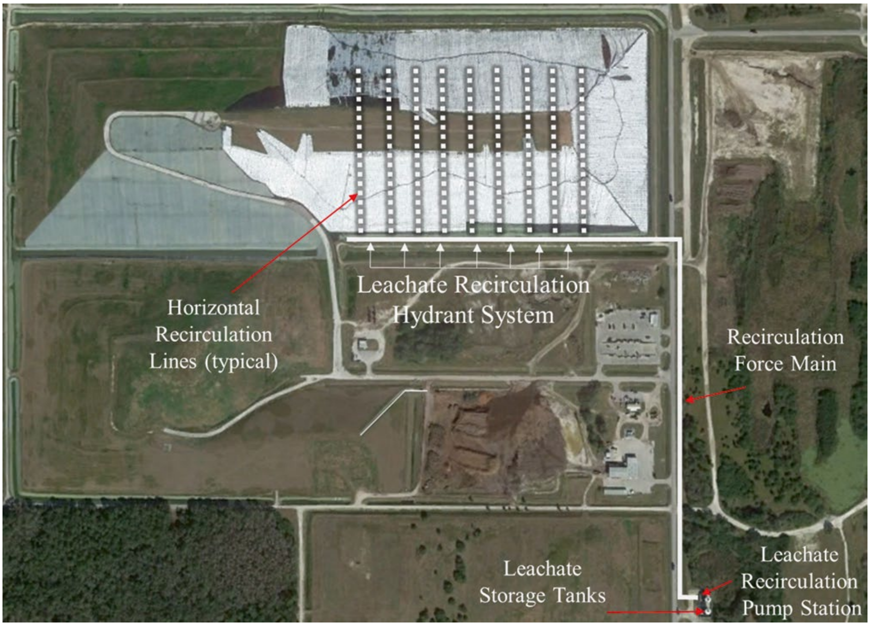

Fig. 4.20 Plan view of Polk County North Central Landfill (PCNCL)

several cases no bedding material was used and excavated waste was placed back into the trench after pipe installation. In a few cases, injection lines were installed using a trenching device that pulled the pipe in place directly into the waste with no bedding (see Chap. 9). Figure 4.21 shows a segment of HDPE pipe being thermally welded after placement on top of the shredded tire bedding media. Figure 4.22 shows the segmented construction of a horizontal injection trench; in some cases, only sufficient lengths of trench were installed to keep up with the incoming waste placement needs, and construction was continued at a later time.

More than 100 buried horizontal trenches were installed at the site. Perforations for the HDPE pipes stopped at least 30 m (100 ft) before the pipe exited the side slope of the landfill. At the transition from perforated to non-perforated pipe, a plug of clayey soil was placed as bedding around the trench to prevent short-circuiting of leachate to the side slopes. After exiting the landfill, the pipes were routed to the base of the landfill where they were connected to a manifold system via hydrants (Fig. 4.23). The site's leachate tanks served as the source of liquids; a variable speed pump system was installed specifically for the purpose of liquids addition and permitted the addition of liquids into aspecfied hydrant at a constant flow rate. The pumping system was integrated with a SCADA system. The SCADA system, along with the pump station, flow meters, and pressure transducers, allowed continuous control (e.g., opening and closing valves for specific recirculation lines) and recording of operational data (e.g., liquids addition pressure, flow rate, added volume, and run time). The permit conditions for the site mandated a maximum injection pressure

Fig. 4.21 Thermal welding of HDPE pipe in horizontal trench at PCNCL

Fig. 4.22 Partially constructed horizontal trench for liquids addition at PCNCL (shredded tires used as a bedding media)

Fig. 4.23 Delivery pipes transmitted liquids from manifold system to individual horizontal trenches at PCNCL

Fig. 4.24 Installation of buried pore water pressure transducers surrounding horizontal injection lines

cut off to avoid slope stability concerns and the system was configured so that liquids flow into a given line would cease when the pressure threshold was reached.

In the vicinity of selected injection trenches a series of vibrating wire pressure transducers were installed, both within the trench, below the trench, and within the waste at various radial distances from the trench (Fig. 4.24). Each pressure transducer was inserted into a sand bag saturated with water to prevent damage and to allow pressure from the waste to be transmitted to the transducer quickly. The transducer wires were encased in PVC pipes filled with polyurethane expanding foam to prevent damage and preferential liquid flow. Larson et al. (2012) conducted air addition tests using 13 pressure transducers to measure the vertical air permeability of landfilled waste overlain by 3–6 m of waste plus a cover soil layer. The vertical air permeability was determined to range from 2×10^{-13} to 8×10^{-13} m^2 for the topmost 3–6 m of compacted waste.

Liquids addition was performed for a period of 5 years and more than 100,000 m^3 (25 million gallons) were added to the landfill. Larson (2007) found that fluid conductance values (flow rate per length of pipe per unit pressure head; see Chap. 9) were similar for shredded tires and crushed glass. In the first stages of liquids addition, fluid conductance values for trenches with bedding were greater than in trenches without bedding media, and were greater for trenches closer to the surface than those deeper in the landfill. As liquids addition proceeded, these differences became less pronounced. In follow-up work incorporating additional injection lines, Kumar (2009) observed that fluid conductance increased with increasing cumulative injection volume and decreased with increased overburden waste depth.

Kumar (2009) also examined the spatial variation of pore water pressure in the waste as a result of pressurized liquid addition using the buried transducers. At a constant flow rate of 0.057 m^3/min, liquids were intermittently added through horizontal lines in trenches filled with bedding media of shredded tires, crushed glass, or excavated waste. Within the trench, pressure distributions were more uniform for trenches with bedding media compared to those without. For instruments in the surrounding waste, pore pressures were found to dissipate a short distance from the trenches; a drop of 4 psi approximately 25 ft from the trenches was observed (Kumar 2009). Cho (2010) conducted additional evaluations at the site with similar results. Additionally, flow and pressure data were used to estimate waste properties; estimated horizontal and vertical hydraulic conductivities ranged from 3.0×10^{-4} to 7.0×10^{-4} cm/s and 1.0×10^{-5} to 1.9×10^{-5} cm/s, respectively, resulting in corresponding anisotropy values from 37 to 280.

Two large liquids addition horizontal blankets were also installed at the PCNCL. Each blanket was constructed with a bedding depth of approximately 0.5 m over a 30 m by 60 m area. One blanket utilized shredded tires as a bedding material (Fig. 4.25) and one used crushed glass. Prior to installation of the blanket, landfill surface soils were scraped. Then, two liquids addition pipes and multiple pressure transducers were placed within the bedding. After bedding material placement, no additional cover was added, and the subsequent waste lift was placed directly on the bedding. The horizontal blankets allowed large amounts of liquids to be added with little pressure buildup. Both liquids addition pipes were damaged for one of the blankets, so liquids addition was not possible through the blanket, demonstrating the critical need for robust construction, pipe redundancy, and operational care to avoid damage that would preclude liquids addition to large-area drainage blankets.

Fig. 4.25 Permeable blanket of shredded tires used for liquids addition (under construction)

In addition to the technical lessons learned at PCNCL with regard to the performance of horizontal liquids addition systems, other observations were made in support of the design and operation of future systems. The system was designed so that one hydrant would support individual trenches or several trenches at different depths. As high backpressures often limited the volume of liquid that could be added, an improved design would allow single hydrants to operate multiple trenches at the same depth. Fluid conductance values of trenches located deep within the landfill are relatively low and this limits the introduction of liquids at high pressures. Adding liquids to these lines early in operation before waste depths grow large would allow for more efficient use. When high pressures are used in these deep lines for a continued operational period, they cause leachate seepage because the waste under the side slopes will be more permeable due to decreased overburden waste depths. Leachate seeps at the base of the landfill was a major issue at PCNCL; this necessitated construction of a toe drain to assist in collecting leachate and transmitting it to the LCRS (Fig. 4.26). Some of the design and operational recommendations with respect to managing seeps presented in Chap. 11 are a result of lessons learned at this site.

4.2.7 Outer Loop Landfill

The Outer Loop Recycling and Disposal Facility (OLRDF) is located in Louisville, KY, USA, and is owned and operated by Waste Management of Kentucky, Inc. The facility consists of several different waste management units, including several landfill cells operated as bioreactor landfills (Fig. 4.27). One landfill area was

Fig. 4.26 Toe drain beneath liner at the base of the PCNCL

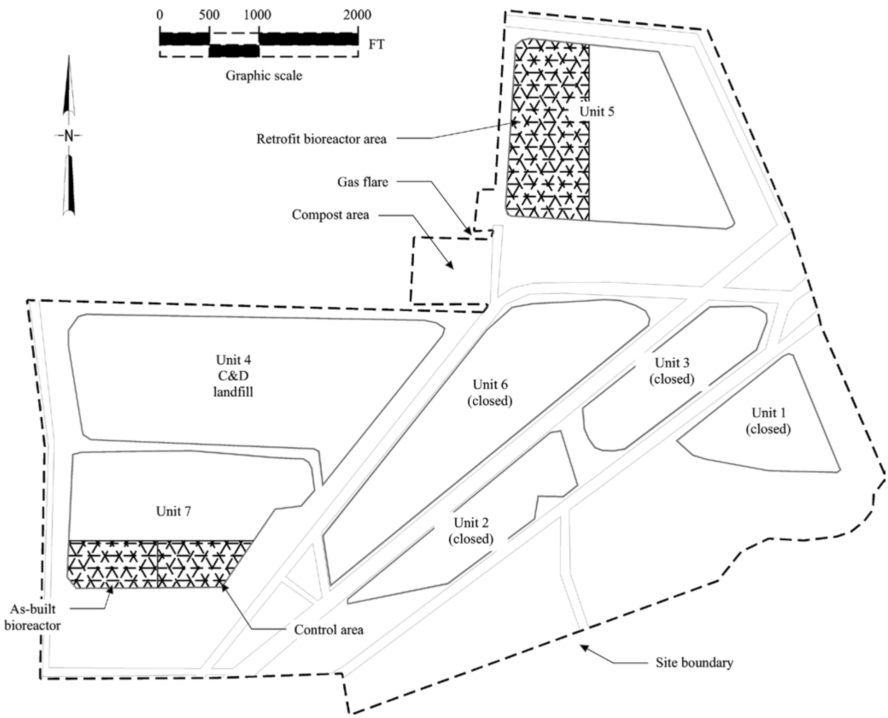

Fig. 4.27 Plan view of Outer Loop landfill

constructed with recirculation infrastructure after the bulk of waste filling was complete (retrofit cell). In another unit, liquid and air addition devices were incorporated into the waste mass as the routine landfill operation and waste filling took place (as-built cell). These units, along with a reference cell (Control cell) where no enhancement techniques were practiced, were studied for more than a decade (Hater and Green 2003; US EPA 2006; Abichou et al. 2013a, b). Each type of cell (retrofit, as-built, and control) was built with a quasi-duplicate to facilitate data comparison.

Liquids addition to the retrofit cell was accomplished using deep surface trenches bedded with tire chips; leachate was treated via external nitrification prior to injection into the retrofit cell to counteract ammonia buildup (US EPA 2006). Added liquids included leachate and industrial liquid waste streams. Industrial liquids were frequently added at or near the working face of the landfill using mobile drip irrigation systems that could be connected to incoming tanker trucks (Fig. 4.28). In the as-built cells, perforated pipes were placed in horizontal trenches constructed on top of waste lifts as the landfill was filled (Fig. 4.29). After a lift of waste was placed on a piping layer, air addition commenced continuously for 30–90 days. The intent of air addition was to shorten the acid phase of anaerobic waste decomposition by consuming easily degradable organic waste aerobically. Both leachate and industrial liquids were introduced after air addition ceased (Hater and Green 2003; US EPA 2006).

Monitoring at the site, documented in detail for periods of operation up to 2006 in several site reports, included solid waste composition (including moisture content), leachate volume and constitution, gas production potential of solids, collection rate, and quality, and surface settlement analysis.

Fig. 4.28 Surface drip liquids addition system at Outer Loop landfill (Photo courtesy of Waste Management Inc.)

Fig. 4.29 Construction of horizontal liquids addition trench at Outer Loop landfill (Photo courtesy of Waste Management Inc.)

Waste samples collected from 2000 through 2005 showed that the median ratio of cellulose and hemicellulose to lignin (i.e., C+H/L, degradable to non-biodegradable) in Retrofit Cells decline was correlated to waste age falling from approximately 1.5 (1–2 year old waste) to 0.7 (waste age 10 years), in comparison to C+H/L in waste from Control cells where median levels ranged from approx. 1.3 to 2.4 with no observable correlation to waste age. A decreasing temporal trend for median C+H/L was observed in As-Built cell A (US EPA 2006). Moisture content measurements were found to exhibit large spatial variability, particularly within bioreactor cells and temporal variation with respect to waste age was inconclusive (US EPA 2006).

Leachate quality and quantity data reported by US EPA (2006) showed that bioreactor cells operated with leachate head-on-liner less than the regulatory limits. The BOD:COD ratio in leachate from as-built cells was indicative of accelerated organics decomposition. The pre-recirculation leachate treatment provided effective removal of ammonia as observed in leachate collected from Retrofit cells (US EPA 2006).

Several years of LFG collection data from the operational period of the bioreactor cells showed a statistically significantly greater gas production rate in the as-built cell compared to the control cell (Tolaymat et al. 2010). Mean methane yield, estimated based on the measured BMP of freshly buried waste was 54.8 m^3 CH_4/Mg wet waste; this L_o was used to calculate methane first-order generation rates of 0.11 $year^{-1}$ for the as-built bioreactor cells and 0.06 $year^{-1}$ for the control cell by Tolaymat et al. (2010). The enhanced gas generation rate calculated for the As-Built cells has important implications for active operations and post-closure operations. In the case of active operations, the result underscores the importance of early gas collection for sustainable landfills to reduce fugitive emissions and enhance the viability of beneficial landfill gas use projects if infrastructure and capacity are available. As for post-closure care implications, the measured decay rate of the As-Built cells would produce 90 % of the total CH_4 production potential in 22 years compared to the Control cell which would take 41 years to produce 90 % of the total CH_4 potential. The implications of enhanced gas productions for landfill operation are further discussed in Chap. 3.

Measured settlement for the as-built cell was more pronounced than for the control cell, which was consistent with solids composition data that suggested accelerated decomposition of waste in the as-built cells occurred relative to the control cells (US EPA 2006; Abichou et al. 2013a). Abichou et al. (2013a) reported liquids introduction to the retrofit cell produced overall settlement rates ranging from 5 to 8 % of the column height (actual settlement depths of 60–100 cm across the landfill surface of the Retrofit cell) over 8 years of operation. In comparison, the average long-term total settlements of as-built and control cells were considerably higher at 37 % and 19 %, respectively.

4.3 International Experience

Sustainable landfill technologies have been reported by researchers at sites around the world. In some regions (e.g., Europe and Japan), regulations and practical constraints limiting landfilling of unprocessed waste reduces the potential application of sustainable landfill research targeting enhanced waste degradation (i.e., the practices previously described for US studies), given that one of the primary goals of bioreactor operation is to accelerate decomposition (a form of "processing"). In other countries (e.g., China), more recent requirements for controlled landfills have resulted in an increase in research and practical application of sustainable landfilling technologies. This section describes research experience reported in the literature for three international regions.

4.3.1 Europe

Current EU directives limit landfilling of unprocessed domestic waste, although many countries are still only in the early phases of implementing this requirement. Significant research and practice on enhanced landfill stabilization techniques have been reported in EU countries in the past, and research on stabilizing older, closed landfills using aeration to minimize harmful environmental emissions continues. Several patented landfill waste stabilization or curing technologies (e.g., AEROflott®, DEPO+®) have been developed and/or applied (Ritzkowski and Stegmann 2012).

Fig. 4.30 Off-gas treatment system at German landfill undergoing aeration (Photo courtesy of Marco Ritzkowski)

In addition, many EU researchers continue to provide research contributions on a fundamental scale pertaining to full-scale sustainable operation; European landfill aeration projects are discussed in greater detail in Chap. 14. Figure 4.30 shows the off-gas treatment system for an aerobic landfill project in Germany.

A full-scale project that commenced in the late 1980s at the Brogborough Landfill in Bedfordshire, England examined various enhancement techniques to improve landfill gas quality and production (Knox 1998; Caine et al. 1999). In addition to a control cell, five test cells were examined to investigate the effects of waste density, air injection, waste amendments, and leachate recirculation on gas production. Among monitoring results, the addition of sewage sludge was found to promote early gas generation and a faster rate of gas production.

A landfill test site was operated at the Dewsbury Landfill, UK (i.e., Landfill 2000) from April 1991 to March 1995 (Knox 1999; Reynolds 2011). Two cells, each 36 m long by 23 m wide with a maximum depth of 5 m, were constructed; each contained approximately 1,000 tons of untreated domestic waste and approximately 12 % sewage sludge. Sewage effluent (10 % by volume) was added to one cell and the leachate produced was subsequently recirculated back into the waste at a rate of 3 m^3/day, for a mean hydraulic retention time ranging from 130 to 210 days (Reynolds 2011). The second cell served as the control, with no recirculation (Knox 1999; Reynolds 2011). The quality of the landfill gas was higher in the leachate recirculation cell (50–60 % CH_4 v/v compared with 45–50 % CH_4 v/v in the non-recycle cell) (Knox 1998). Knox (1999) reported that cells were too shallow to develop high enough temperatures for optimal accelerated waste degradation; specific LFG yields for the Brogborough and Dewsbury Landfill typically were around

20 m^3/ton MSW (wet weight), lower than those peak values reported in small, lab-scale studies by approximately an order of magnitude (Knox 1999).

A full-scale investigation was conducted at the Sanitary Landfill of Lingen, Germany; two cells (each approximately 1 ha) were operated as bioreactors to examine in-situ leachate treatment and leachate recirculation (Kumar et al. 2011). One cell was constructed with a layer of pre-composted waste placed at the bottom, and the other was used as a control without the pre-composted layer. Leachate recirculation was performed in both cells, and a comparison of leachate composition over a 4-year monitoring period showed that the use of a compost layer was much more effective in reducing leachate strength (BOD and COD).

4.3.2 Asia

Like Europe, several countries in Asia have moved largely away from managing unprocessed domestic waste in landfills (e.g., Japan, Taiwan). One notable sustainable landfilling technology from Asia has been the semi-aerobic landfill concept developed in Japan (Lee et al. 1994; Matsufuji 2004). This technique will be discussed in detail in Chap. 14, but in brief, the technique includes air venting introduced at the base layer of the landfill, and at times into the waste itself, as a means of providing leachate treatment within the landfill and promoting waste stabilization (Matsufuji 2004). Figure 4.31 shows the liner and LCRS of a semi-aerobic landfill in Japan.

Fig. 4.31 Semi-aerobic landfill in Japan (Photo courtesy of Yasushi Matsufuji)

Much research on sustainable landfill technologies has been recently completed or is underway in China. Qu et al. (2008) described research on leachate heavy metals content as affected by full-scale recirculation of leachate using horizontal injection pipes into a landfill. Heavy metal concentrations in leachate were reduced dramatically (typically by about one order of magnitude, to less than Chinese regulatory thresholds) after 5 months of landfilling by the time the methanogenic stage was reached. The decreased metal concentrations were attributed primarily to increased pH, lower metals concentrations were correlated with decreased leachate COD content (from up to 40 to 6.5 g/L) (Qu et al. 2008). Zhang et al. (2008) compared two landfill cells, one of which employed leachate recirculation. The flux of CH_4 was increased in the recirculation cells, however sandy cover soil was found to sufficiently oxidize methane prior to discharge to the atmosphere, particularly where gas collection wells had limited collection efficacy (the area of influence was <5 m from a gas collector). Liu et al. (2012) reported success in treating landfill leachate high in NH_3–N (2.12–3.21 g/L) achieving COD removal of 85–90 % (from influent ranging from 13.2 to 52.3 g/L) with an expanded granular sludge bed; high NH_3–N is an issue commonly observed in bioreactor leachate with the potential to cause methanogenesis inhibition, which can be undesirable at sites where LFG to energy infrastructure is in place.

4.3.3 Australia

Interest in bioreactor and sustainable waste management technologies in general has increased in Australia concurrent to awareness of environmental and economic costs of landfilling (Clarke 2000; EPA Victoria 2010). Clarke (2000) reported that the organic fraction of MSW in Australia ranged from 60 to 70 %, and that enhanced degradation to target this fraction may provide benefits to Australian landfills. EPA Victoria (2010) reported bioreactor landfills as a feasible technology for enhanced waste degradation (within 5–10 years of waste placement) and has provided guidelines specifically for bioreactor landfill design and operation, which includes inert waste placement at the landfill's base, temperature monitoring, minimization of low permeability layers within the waste, and liquids application to produce the most uniform waste moisture distribution possible.

After demonstration at the pilot-scale, a full-scale bioreactor cell, located at the Lyndhurst Sanitary Landfill, Victoria, Australia was constructed (Yuen et al. 1997). The site was approximately 180 m by 75 m (1.5 ha), with a volume of waste in the test cell of 180,000 m^3 with waste depths ranging from 10 to 15 m. The cell was divided into two sections of approximately equal area, with the western half designated as the control section (i.e., dry landfilling) and the eastern half as the test section (i.e., wet landfilling by leachate recirculation) separated by a clay berm wall. The cell was equipped with a bottom liner consisting of compacted clay, and leachate was added to wells and trenches by gravity (Yuen et al. 2001). A total of 2.5 million liters of leachate were injected through the recirculation system between

July 1996 and October 1997, increasing the overall volumetric moisture content from 27 to 31 % in the test section, while the moisture content in the control cell did not vary (Yuen et al. 2001). The researchers observed that achieving uniform moisture distribution in the waste was difficult because of the heterogeneous nature of the landfilled waste, and pointed out limitations associated with applying recirculation test results observed at small-scale test cells to a full-scale landfill (Yuen 2001).

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Chapter 5
Landfill Constituent Relationships and Dynamics

Abstract MSW landfills are complex, dynamic systems, with a combination of phases (solid, liquid, and gas) interacting with and impacting one another in different ways throughout the life of a landfill. A discussion of these phases and fundamental properties of landfilled waste—which are key to understanding sustainable landfilling processes and design parameters that impact the performance of sustainable landfilling technologies—is provided alongside a substantial amount of supporting data from numerous peer-reviewed studies. Concepts such as waste properties (e.g., density, porosity, and moisture content), liquids movement, gas and air movement, and solids movement, are presented sequentially to give the reader the necessary foundation in waste behavior and dynamics.

Keywords Landfill • Sustainable • Bioreactor • Modeling • Leachate • Gas • Density • Hydraulic conductivity • Shear strength

5.1 Landfill Components and Their Movement

MSW landfills, by their very nature, are dynamic systems. Liquids move through the waste mass in response to moisture infiltration from rainfall, drainage of liquids already entrained within the waste, or liquids purposely introduced to manage leachate or promote rapid waste stabilization. Solid waste components are converted to various gases as a result of biological decomposition, and the gases move through the waste mass in response to internal pressure buildup and external atmospheric changes. The waste mass itself changes over time as waste mass is lost, mechanical stresses redistribute, and liquid and gas content changes and redistributes. This chapter provides a discussion of the fundamental relationships among solid, liquid and gas phases. As appropriate, magnitudes of pertinent waste characteristics are summarized. A basic discussion of liquid, gas, and solid movement at landfills is also described. The objective of this discussion is to provide sufficient fundamentals to prepare the reader for subsequent, more detailed discussions on these phase dynamics presented later in the book, and to provide the reader with necessary background to understand the potential applications of some of the more advanced constituent dynamics simulation tools that are available.

T.G. Townsend et al., *Sustainable Practices for Landfill Design and Operation*, Waste Management Principles and Practice, DOI 10.1007/978-1-4939-2662-6_5

5.2 Fundamental Properties of Landfill Waste

5.2.1 Phase Relationships

Many of the basic characteristics of landfilled waste that play a role in the design of sustainable landfill technologies relate one landfill constituent to another. Borrowing from classic soil mechanics literature, it is helpful to illustrate the relationship of these different phases in a constituent phase diagram (see Fig. 5.1).

The three primary phases are solid, liquid and gas. The solid phase consists of the waste components and cover soil. Water represents the liquid phase, although this water (i.e., leachate) will contain dissolved and suspended materials. At some point in a landfill's life, the gas phase may be predominantly represented by chemicals similar to atmospheric air, but over much of the landfill's existence, gaseous products of biological reactions will dominate the gas phase (e.g., methane, carbon dioxide). The phase diagram provides nomenclature for mass components on the left side, while volume components are represented on the right side. In the following sections, some of the more important material properties are described, with many of these defined by the mass and volume components in Fig. 5.1.

5.2.2 Density

Density relates the mass of a material to its respective volume, and following conventions illustrated in Fig. 5.2, is defined as:

$$\rho_T = \frac{M_T}{V_T} \tag{5.1}$$

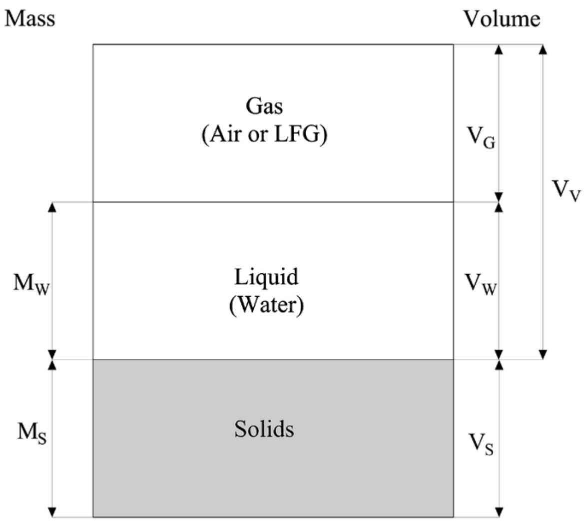

Fig. 5.1 Phase diagram of landfill constituents

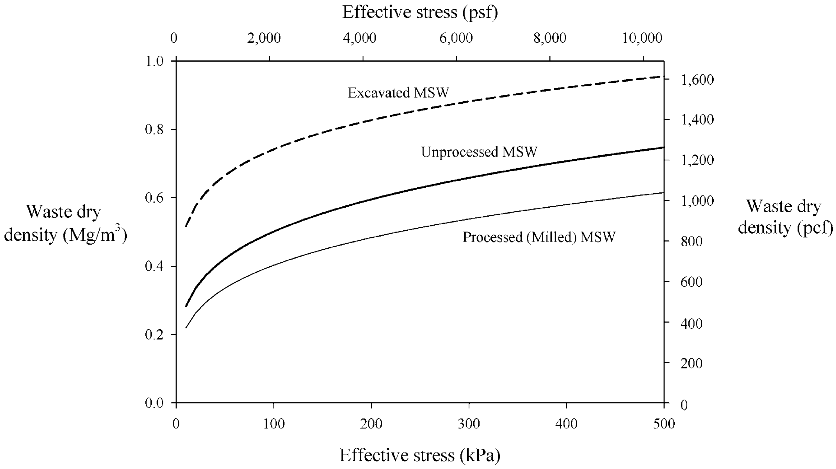

Fig. 5.2 Dry density of processed, unprocessed and landfill excavated MSW as a function of applied stress as measured by Beaven (2000)

where ρ_T refers to the total density (i.e., bulk density) of the media (kg/m^3 or lb-m/ft^3), M_T is the total (wet) mass of the media (kg or lb-m) (the mass of gaseous phase is insignificant compared to solid and liquid phases), and V_T is the total volume of the media (m^3 or ft^3). A related term, specific weight, relates the weight of material to its respective volume:

$$\gamma_T = \frac{W_T}{V_T} \tag{5.2}$$

where γ_T is the total specific weight of the material (kN/m^3 or lb/yd^3) and W_T is the total (wet) weight of the media (kN or lb). Density and specific weight relate to one another as follows:

$$\gamma_T = g\,\rho_T \tag{5.3}$$

where g is the gravitational constant. The term density will be more commonly used in this book as a generic tem referring to both parameters. In engineering calculations involving force or weight, specific weight is the correct parameter to use.

The density of waste plays an important role in many landfill design procedures. It is especially important in sustainable landfill operation where a primary objective is waste transformation (stabilization), a process through which density changes. It is also important to recognize the role that cover soil plays in determining the density of the landfilled mass (waste plus soil). Soil is substantially denser than most municipal wastes. As the relative amount of soil increases in a landfill (which will happen as waste decomposition proceeds), the density of the landfill increases.

Several researchers have measured waste density under a variety of conditions using different approaches (Watts and Charles 1990; Cowland et al. 1993; Zornberg et al. 1999; Oweis and Khera 1998). Table 5.1 presents a summary of the density and specific weight of several different municipal waste sources under different landfill conditions. Multiple factors impact the density of landfilled materials. Since newly-deposited and relatively dry municipal waste may have a density less than water, added liquids increase density. When waste decomposes

Table 5.1 Densities and specific weights of the primary materials in a landfill under common landfill conditions

Material	ρ_T (kg/m^3)	ρ_T (lb-m/ft^3)	γ_T (kN/m^3)	γ_T (lb/yd^3)
Water	998	62.4	9.77	1,685
Soil	1,680–1,920	105–120	16.4–18.8	2,835–3,240
Newly compacted waste (no soil) (Kavazanjian 2001)	610–710	38–44	6–7	1,030–1,198
Excavated landfill waste (near the surface of the landfill) (Zornberg et al. 1999)	1,017–1,220	64–76	10–12	1,716–2,059
Excavated landfill waste (deep in the landfill) (Cowland et al. 1993)	1,330–1,530	83–96	13–15	2,245–2,582
Crude, domestic waste, retrieved from the tipping face of a landfill (Powrie et al. 1998)	500–1,180	31.2–73.7	4.90–11.6	842.8–1,989
Landfilled waste and cover soil (Hull et al. 2005)	1,150	71.8	11.3	1,938
Landfilled MSW most recently deposited 2 years prior to sampling (sample depths: 1.5–6 m) (Chiemchaisri et al. 2007)	240–1,260	15–78.7	2.35–12.4	404.5–2,124
Landfilled samples extracted via borehole every 1 m depth from a landfill closed in 1985 (Al-Yaqout et al. 2007)	1,088–2,350	67.9–147	10.67–23.05	1,834–3,961
Transfer station collected MSW (Penmethsa 2007)	906.5–1,071	56.8–66.8	8.89–10.5	1,528–1,805
Landfilled MSW (Alaska), soil, and subgrade soils (Hanson et al. 2008)	530	33.1	5.2	893.7
Landfilled MSW (Michigan), soil, and subgrade soils (Hanson et al. 2008)	999	62.4	9.8	1,685
Landfilled MSW extracted via borehole (Machado et al. 2010)	1,326–1,785	82.8–111	13–17.5	2,235–3,009
Large-scale MSW bioreactor lysimeter (Bareither et al. 2012a)	510–714	31.8–44.6	5.0–7.0	860–1,204
Landfilled MSW in Spain (Yu et al. 2012)	1,530–2,141	95.5–134	15–21	2,579–3,609
Landfilled MSW densified in-place via rolling and dynamic compaction (Yu-xin et al. 2013)	1,590–2,130	99.3–133	15.6–20.9	2,680–3,590

and ultimately settles, density will increase as the moisture content increases, the fraction of less dense materials is reduced (e.g., paper), and the relative abundance of cover soil increases.

Waste density is heavily influenced by overburden pressure, that is, the pressures imposed by overlying materials (waste and cover soil) due to their weight. It is well understood that landfilled material deep in the disposal unit, especially after a degree of stabilization has occurred, will be much denser than recently-compacted waste on the surface. Several researchers have measured the relationship between density and applied stress; the experimental devices used for these measurements, often described as an oedometer or a compression cell, allow measurement of waste density (and other parameters of interest) under conditions of different applied vertical stresses. Beaven (2000) conducted a comprehensive evaluation of waste characteristics resulting from the application of various pressures in a large-scale compression cell (2 m diameter), with the capability to convey leachate. The cell holds approximately 3,000–6,500 kg of waste (at field capacity) and is equipped with piezometers to monitor the leachate head within the cell. Three different waste streams were assessed using this device: a new sample of MSW (i.e., unprocessed), a processed sample of new MSW (shredded), and a waste sample excavated from a landfill (partially degraded). Waste samples were either loaded at a specified in situ density (0.5 ton/m^3) or at a low pressure (approximately 5 bars), at a waste height of 2.5 m, and then subjected to increasing applied pressure (up to five successive load increases from the initial 40 kPa) to characterize waste dry density in response to increased applied pressure. The results of this characterization are presented in Fig. 5.2; units of force are presented in both kPa and lb/ft^2 (psp), while units of density are presented in both Mg/m^3 and lb-m/ft^3 (pcf). Beaven (2000) also measured other waste parameters as a function of applied pressure (e.g., effective porosity, leachate volume extracted from waste during compression) and several of these will be presented later in this chapter.

Dry density is a useful way of presenting density data, as wet weight densities can be subsequently estimated for different moisture contents; it is important to note, however, that the degree of compaction that can be achieved will be influenced by the moisture conditions during testing. Figure 5.3 presents the wet-weight densities at different applied loads measured by Beaven (2000) under conditions where the waste was at field capacity. McKnight (2005) used a smaller-scale oedometer (a hydraulic press (10-ton cylinder jack and hand pump) coupled with a steel cylinder to contain the waste sample (0.43-m diameter)) to measure the relationship between density and applied pressure for samples of differing ages and states of decomposition excavated from a landfill in Florida, US. Results from these experiments are presented in Fig. 5.4, and include for comparison data points for soil, cardboard, compost, and lines from Beaven's experiments.

Density estimates such as those presented in Table 5.1 and Figs. 5.1, 5.2, and 5.3, along with waste and facility-specific density information, can be used to provide better inputs for estimating landfill capacity, designing LCRS and landfill foundations (Chap. 10), and projecting materials recovery amounts in landfill mining operations (Chap. 17).

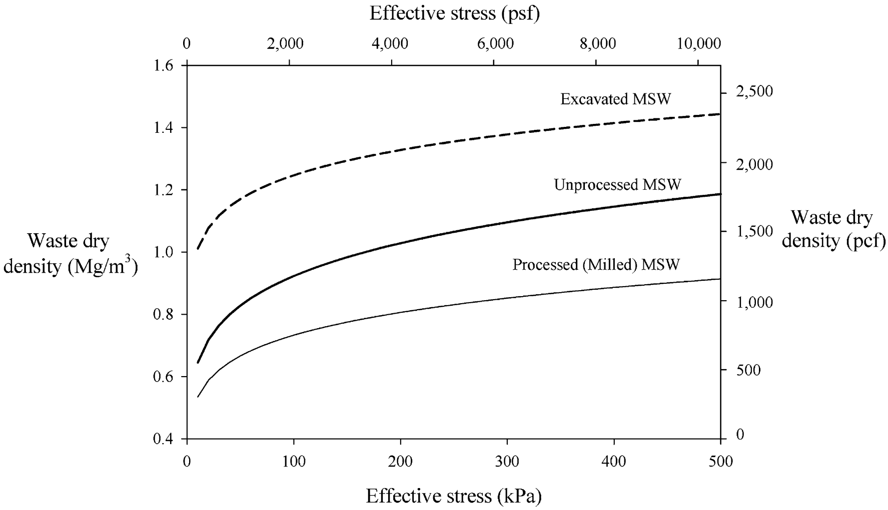

Fig. 5.3 Wet density (at a moisture content of field capacity) of processed, unprocessed and landfill excavated MSW as a function of applied stress as measured by Beaven (2000)

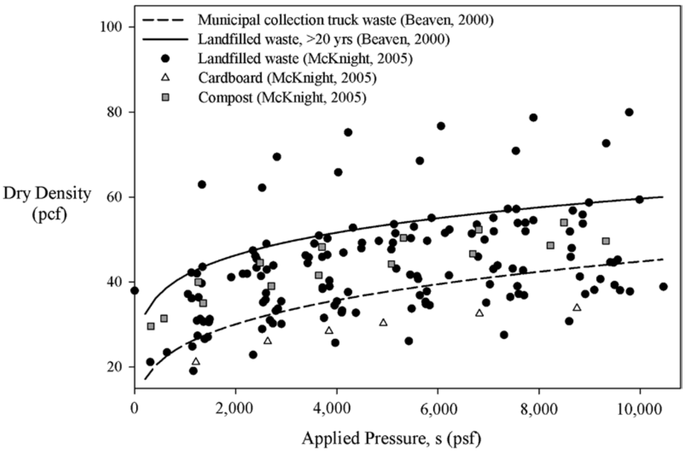

Fig. 5.4 Dry density of excavated landfill waste samples (McKnight 2005) as a function of applied load. For comparison purposes, data from Beaven (2000) and measured for compost and cardboard included

5.2.3 Porosity

Porosity is the fraction of the volume of the void space to the bulk volume of a porous medium, and is defined as:

$$\eta = \frac{V_V}{V_T} \tag{5.4}$$

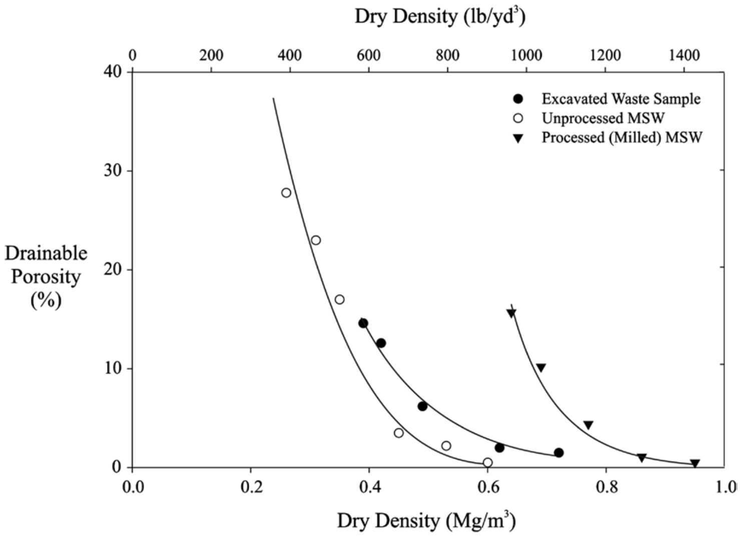

Fig. 5.5 Drainable porosity measured as a function of applied stress as measured by Beaven (2000)

Several attempts have been made to measure the porosity of MSW. Like density, porosity will be influenced by applied stress (overburden pressure), with an observed decrease as stress increases. Korfiatis et al. (1984) constructed a column of waste to investigate infiltration rates and porosity by measuring the volume of water required to saturate the waste and found porosity values to vary from 50 to 60 %. Zeiss and Major (1993) investigated porosity variations as a function of the degree of compaction and found that porosity ranged from 47 % at high compaction to 58 % at lower compaction. Zornberg et al. (1999) investigated porosity in relation to confining pressure in a landfill undergoing vertical expansion and estimated a range of 49–62 % based on the specific weight of the waste and the applied overburden pressure.

The term drainable porosity is also used in some cases to describe void space, and as defined by Beaven (2000) is the volume of water released from a unit of volume of fully saturated material that is allowed to drain freely under gravity. Also referred to as effective porosity, the drainable porosity is analogous to the concept of specific yield in hydrology. Figure 5.5 presents the range of drainable porosity measurements reported by Beaven (2000) as a function of applied pressure.

5.2.4 Moisture Content

The term moisture content refers to the amount of water (mass or volume) contained in a matrix (soil, waste) relative to the total mass of that medium. Moisture content may be defined differently depending on the application or discipline, thus it is important to verify the definition of any moisture content value provided. Most engineers and facility operators, when discussing the moisture content of solid waste, refer to a weight-based definition, relative to the total weight of the media:

$$\mathrm{MC} = \frac{\mathrm{M_W}}{\mathrm{M_T}} \tag{5.5}$$

where MC = gravimetric moisture content (wet weight basis), M_T = bulk weight of the landfilled waste, and M_W = weight of moisture. This value is measured by weighing a wet sample of waste, drying the waste in an oven and measuring the weight of moisture (normally water) that evaporated, and dividing the moisture weight by the total weight. Typical values of wet-weight moisture content for MSW (as disposed) are provided later in this section. In some applications it may be common to encounter a moisture content that relates the weight of water in a medium to the dry weight of solids. This parameter is referred to herein as water content, and is defined as

$$w = \frac{M_W}{M_S} \tag{5.6}$$

Where w = water content, M_W is the mass of water, and M_S is the mass of dry solids. This term is routinely used to characterize soil relationships such as soil compaction.

The volumetric moisture content (θ) refers to the volume of water occupied by the volume of a medium. Volumetric moisture content is the parameter used when modeling liquids flow through a porous media, and is defined as:

$$\theta = \frac{\mathrm{V_W}}{\mathrm{V_T}} \tag{5.7}$$

where θ = volumetric moisture content; V_T = total volume of the landfilled waste; V_W = volume of water (or liquids). The following relationship allows conversion between MC and θ.

$$\mathrm{MC} = \frac{\rho_{\mathrm{W}}}{\rho_{\mathrm{T}}} \theta_{\mathrm{w}} \tag{5.8}$$

Where ρ_T = bulk density of the landfilled waste and ρ_W = density of water.

The moisture content of waste when disposed depends on the composition of the waste, climatic conditions, and landfilling practices such as surface water management. Table 5.2 presents initial MC of MSW from several locations as reported in the literature.

Table 5.2 Reported moisture content of as-disposed MSW

Location and reference	Moisture content (wet weight basis)	Remarks
New Jersey (Korfiatis et al. 1984)	44.3 %	Samples collected from a local landfill
United States (Tchobanoglous et al. 1993)	15–40 %	Municipal waste in compactor truck or normally or well-compacted in a landfill
Pennsylvania (Gabr and Valero 1995)	23.1 % (near surface) to 56.5 % (20 m deep)	Samples collected from a waste profile from a landfill opened in 1940
Florida (Townsend et al. 1996)	31.3 % (13), 29.7 % (6), 27.6 % (11)	Samples were collected from control and bioreactor area prior to leachate recirculation
California (El-Fadel 1999)	26–46 %	Samples collected before leachate recirculation
California (Zornberg et al. 1999)	3.5–50 % (average 28 %)	80 Samples collected from a landfill
South Korea (Jang et al. 2002)	36.0 %	Borehole extracted samples from a municipal landfill
California (Mehta et al. 2002)	11.8–26.7 %	11 Samples
Florida (Jonnalagadda 2004)	23 % (11.5–36.8 %)	51 Samples from a lined MSW landfill before leachate recirculation
New Jersey (Hull et al. 2005)	28.3 % (18.8–41.6 %)	98 Samples from 13 gas extraction well borings
Florida (McKnight 2005)	24.1–43.4 %	17 Samples from a part of 40-ha unlined landfill
New York (Harris et al. 2006)	26.0–44.2 %	Eight samples, collected via hollow-stem auger
	36.4–76.4 %	12 Samples, collected via bucket auger
Kuwait (Al-Yaqout et al. 2007)	2.1–37.9 % (mean approx. 13.5 %)	13 Borehole extracted samples from a landfill
Thailand (Chiemchaisri et al. 2007)	39.6–60.1 %	Landfilled MSW most recently deposited 2 years prior to sampling
		Mean of three samples collected
Illinois (Reddy et al. 2009a, b)	30.6 %	Four 1.5-year-old samples collected from the landfill with boreholes at 20 m depth (samples >5 kg)
France (Stoltz et al. 2010a, b)	35.8 %	Fresh MSW (sample 150 kg)
California (Zekkos et al. 2010a, b)	21.1 %	Samples extracted from landfill via bucket auger (samples 5–10 kg)
Texas (Hossain and Haque 2012)	15 %	MSW collected from a transfer station
China (Yu-xin et al. 2013)	Compacted: 5.3–22.7 %	In situ landfilled MSW from boreholes
	Non-compacted: 6.0–35.9 %	

Table 5.3 Volumetric field capacity (θ_{FC}) reported for MSW

Reference	Field capacity, volumetric (Vol/Vol)	Density (kg/m^3)
Fungaroli (1971)	0.294–0.346	384–410
Rover and Farquhar (1973)	0.30–0.31	315–339
Wigh (1979)	0.325–0.375	391–596
Fungaroli and Steiner (1979)	0.31–0.61	299–437
Walsh and Kinman (1982)	0.32–0.40	474–480
Zeiss and Major (1993)	0.123–0.143	165–304
Zeiss and Uguccioni (1995)	0.08	141
Zeiss and Uguccioni (1997)	0.09–0.13	267–458
Zornberg et al. (1999)	0.48–0.53	878–1,184
Powrie and Beaven (1999)	0.40–0.45	320–720
Jang et al. (2002)	0.26–0.45	800–1,200
Bareither et al. (2012a)	0.35–0.48	510–714

Saturation, or the degree of saturation, is defined as the ratio of water volume in a unit volume of soil (or other media) to its porosity. Porosity is the volume of void spaces per unit volume of porous media and is the maximum volumetric moisture content that a unit volume of soil can hold. If all of the available void spaces in waste are filled with water, the waste would be considered saturated and its volumetric moisture content would be equal to its porosity.

As will be discussed in detail in Chap. 6, a common target moisture content for achieving enhanced waste stabilization is field capacity, which is the moisture content that a media can retain under the influence of gravity, not saturation. Any additional water above field capacity will eventually drain from the media (Bear 1979; Corey 1994). Field capacity is important for several design techniques involved in landfill liquids addition systems, and as such, a number of researchers have attempted to quantify this characteristic. Table 5.3 summarizes the results of several of these studies.

The field capacity of landfilled waste depends on various factors such as waste composition, waste particle size distribution, waste age, and the degree of compaction. Field capacity generally increases as the organic fraction (e.g., paper, food, and textile) in the waste stream increases (Qian et al. 2002). Vaidya (2002) showed that field capacity of waste increased with an increase in cellulose content and percentage of volatile solids. When wastes are exposed to higher levels of applied stress, the waste particles consolidate, resulting in increased density (Figs. 5.2, 5.3, and 5.4) and reduced porosity (Fig. 5.5), and in turn, reduced field capacity. Figure 5.6 presents wet weight field capacity (MC_{FC}) measured at different dry densities by Beaven (2000). Figure 5.7 presents MC_{FC} as a function of dry density reported by several investigators; a best-fit line for these data is also presented in this figure.

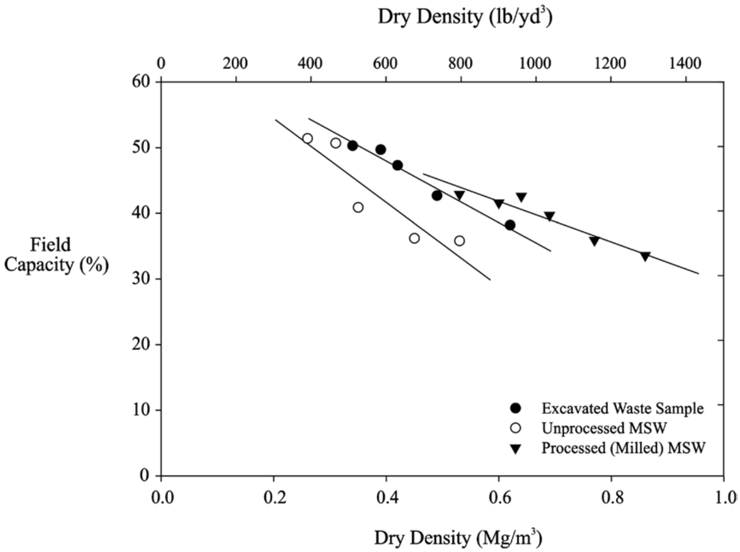

Fig. 5.6 Field capacity (% volume) measured for processed, unprocessed and landfill excavated MSW as a function of dry density (Beaven 2000)

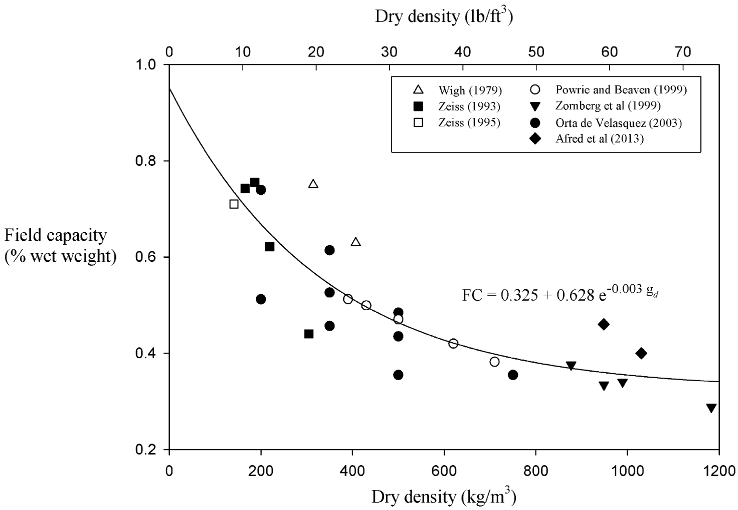

Fig. 5.7 Waste field capacity as a function of dry waste density (based on several different studies)

5.3 Moisture Movement

As liquids addition is one of the fundamental techniques for achieving enhanced waste stabilization, engineers rely on design approaches and tools that predict the movement of moisture through porous media. A detailed discussion of fluid flow fundamentals and predictive techniques is beyond the scope of this book, and the reader is referenced to the many excellent works on fluid flow through porous media (e.g., Bear 1972; Fetter 2001; Pinder and Celia 2006; Todd and Mays 2005). The objective of the following section is to provide sufficient background so the designer of sustainable landfill technologies understands the underlying physics of how moisture moves within a landfill and the tools that can be used in design.

5.3.1 Saturated Flow and Hydraulic Conductivity

Conditions within a landfill with high moisture levels, either from added liquids or inherent with waste and precipitation, will, in some places, likely be saturated. The designer must understand, however, that unsaturated conditions may dominate much of the landfill. A discussion of fluid flow fundamentals, however, will relate to most engineers best by first starting with a description of saturated fluid dynamics.

Darcy's law states that the saturated flow rate through a porous media (Q) is proportional to the cross-sectional area of flow (A) and the hydraulic gradient ($\partial h/\partial l$), which in turn relates the change in potentiometric head over a unit length. As such, Darcy's law for one-dimensional flow may be written as:

$$q = \frac{Q}{A} = -K\frac{\partial h}{\partial l} \tag{5.9}$$

where Q is the total flow rate (L^3/T) through a cross-sectional area A (L^2); $\partial h/\partial l$ is the pressure gradient (unitless, potentiometric pressure head, h/path length, l); q is the specific discharge (L/T; also commonly referred to as the Darcy flux or Darcy velocity); and K is a proportionality constant called the hydraulic conductivity (L/T).

The specific discharge does not correspond to the actual velocity of the moving fluid. The true velocity (v) would be greater, and may be determined from specific discharge as follows:

$$v = \frac{q}{\eta} \tag{5.10}$$

where v is the velocity (L/T) and η is the porosity (unitless).

While some landfill moisture problems may be one-dimensional (e.g., vertical (downward) flow as a result of gravity), many of the liquid movement scenarios that the engineer may wish to predict or simulate occur in multiple dimensions. Thus, specific discharge using Darcy's law for all three dimensions (x, y, z) can be defined as:

$$q_x = -K_x\frac{\partial h}{\partial x} \tag{5.11}$$

$$q_y = -K_y \frac{\partial h}{\partial y} \tag{5.12}$$

$$q_z = -K_z \frac{\partial h}{\partial z} \tag{5.13}$$

where q_x, q_y, and q_z represent the specific discharge in the x, y and z directions, and K_x, K_y, K_z represent the hydraulic conductivity in the x, y and z directions. As will be discussed later in this section, the hydraulic conductivity of landfilled waste differs depending on the direction considered (i.e., waste is anisotropic with respect to hydraulic conductivity).

The law of conservation of mass can be used to derive a governing equation for the fluid flow scenarios of interest. For example, when conserving mass around a three-dimensional control volume, the following equation can be written:

$$-\left[\frac{\partial \rho q_x}{\partial x} + \frac{\partial \rho q_y}{\partial y} + \frac{\partial \rho q_z}{\partial z}\right] = \frac{\partial \rho \theta}{\partial t} + w \tag{5.14}$$

where $\partial(\rho\theta)/\partial t$ refers to the increase in storage in the control volume, the combined term $-\left[\frac{\partial \rho q_x}{\partial x} + \frac{\partial \rho q_y}{\partial y} + \frac{\partial \rho q_z}{\partial z}\right]$ represents net flow of the fluid into the control volume, w refers to the fluid generation rate by the control volume (e.g., gas generation by waste), and t is time.

There are three modes by which the fluid storage of a porous media can change. First, as the name suggests, a porous media possesses void spaces from which fluid can be stored or withdrawn. Second, porous media is compressible (i.e., undergoes a change in volume with a change in pressure). An increase in the fluid pressure in the pores causes the pores to expand and store more fluid volume. An increase in pore pressure results in media compression and a consequential reduction in porosity. Finally, the storage can change because of the compressibility of fluid. Under larger pressure, fluid compresses (i.e. density increases) and occupies a smaller pore space volume and, as a result, more fluid mass can be stored in the same volume of pore space (Bear 1972, 1979). The significance of each of the three modes for fluid storage depends on the pressure driving fluid flow. For flow of a compressible liquid in compressible media (e.g., water flow in a confined aquifer system), $\partial(\rho\theta/\partial t) = \rho S_s \partial(h/\partial t)$ (S_s is the specific storage). Substituting Darcy's equation in (5.14), this relationship for flow of compressible fluid in compressible media (assuming variation in ρ with respect to x, y, and z are negligible) may be further described as:

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right) = S_s \frac{\partial h}{\partial t} + w \tag{5.15}$$

With an appropriate governing equation and boundary conditions in hand, a flow problem can be assessed either by solving the equation analytically or numerically. Examples of governing equations used to solve moisture flow problems in landfills will be presented later.

At this point it is appropriate to discuss hydraulic conductivity of landfilled waste. Hydraulic conductivity is the proportionality constant that describes the relationship between the fluid flow rate and the hydraulic gradient. It may be defined as the specific discharge per unit hydraulic gradient in an isotropic medium and depends on the fluid properties and physical properties of the medium. The fluid properties of the liquids that affect the hydraulic conductivity are viscosity and density. The physical properties of the porous medium that affect the hydraulic conductivity are primarily pore size and shape, pore size distribution, tortuosity, specific surface, and porosity (Bear 1972). A summary of reported laboratory measurements and field measurements of saturated hydraulic conductivity of MSW are presented in Table 5.4 and Table 5.5, respectively.

The saturated hydraulic conductivity of solid waste depends on the density of the media (and thus as seen in the previous sections, the applied stress). Waste hydraulic conductivity is known to be reduced in deeper sections of the landfill. Figure 5.8 presents the waste hydraulic conductivity measured by Beaven (2000) as a function of dry density. Obscurations of deceased hydraulic conductivity of landfilled MSW will be highlighted in field results presented as part of subsequent chapters (Chaps. 8 and 9).

Table 5.4 Reported laboratory measurements of saturated hydraulic conductivity of MSW

Method and reference	Hydraulic conductivity (cm s^{-1})
Constant head (Fungaroli and Steiner 1979)	10^{-4}–10^{-2}
Constant head (Korfiatis et al. 1984)	8×10^{-3}–1.3×10^{-2}
Constant head (Noble and Arnold 1991)	8.4×10^{-5}–6.6×10^{-4}
Falling head (Bleiker et al. 1995)	1×10^{-8}–3×10^{-7}
Falling head Zeiss and Major (1993)	1.35×10^{-3}–1.07×10^{-5}
Constant head (Chen and Chynoweth 1994)	4.7×10^{-5}–9.6×10^{-2}
Constant and falling head (Gabr and Valero 1995)	10^{-3}–10^{-5}
Constant and falling head (Zeiss and Uguccioni 1997)	1.98×10^{-6}–1.05×10^{-5}
Constant head (Landva et al. 1998)	2×10^{-6}–2×10^{-3} (vertical)
	4×10^{-5}–1×10^{-3} (horizontal)
Constant head (Powrie and Beaven 1999)	3.7×10^{-6}–1.5×10^{-2}
Constant head (Jang et al. 2002)	2.91×10^{-4}–2.95×10^{-3}
Constant head (Penmethsa 2007)	1.3×10^{-3}–8.8×10^{-3}
Permeameter (Buchanan et al. 2001)	7.1×10^{-4}–1.2×10^{-1}
Permeameter (Reddy et al. 2009a, b)	Shredded fresh: 2.8×10^{-3}–11.8×10^{-3}
	Shredded landfilled: 0.6×10^{-3}–3.0×10^{-3}
Constant and falling head permeameter (Reddy et al. 2011)	1.4×10^{-5}–8.3×10^{-9}
Constant and falling head permeameter (Hossain and Haque 2012)	2.6×10^{-3} (20 % cover soil)

Table 5.5 Reported field measurements of saturated hydraulic conductivity of MSW

Method and reference	Hydraulic conductivity (cm s^{-1})
Jacob pumping test method (Ettala 1987)	5.9×10^{-3}–0.25
Theis pumping test method (Oweis et al. 1990)	10^{-3}–2.5×10^{-3}
Slug test (Shank 1993)	6.7×10^{-5}–9.8×10^{-4} (horizontal)
Zaslavsky wetting front (Townsend 1995)	3×10^{-6}–4×10^{-6} (vertical)
Flow nets (Landva et al. 1998)	10^{-3}–3.9×10^{-2}
Slug and pumping tests (Jang et al. 2002)	9.6×10^{-4}–7.1×10^{-3}
Pumping test (Wysocki et al. 2003)	1.2×10^{-5}–6.3×10^{-4} (horizontal)
Pumping test (Cestaro et al. 2003)	1.1×10^{-2}–1.1×10^{-1}
Air injection test (Jain et al. 2005b)	2.5×10^{-4}–5.2×10^{-2} (horizontal)
Borehole permeameter test (Jain et al. 2006)	5.4×10^{-6}–6.1×10^{-5} (horizontal)
Seepage flux and pore water pressure (Fleming 2011)	3.0×10^{-7}–3.6×10^{-7}

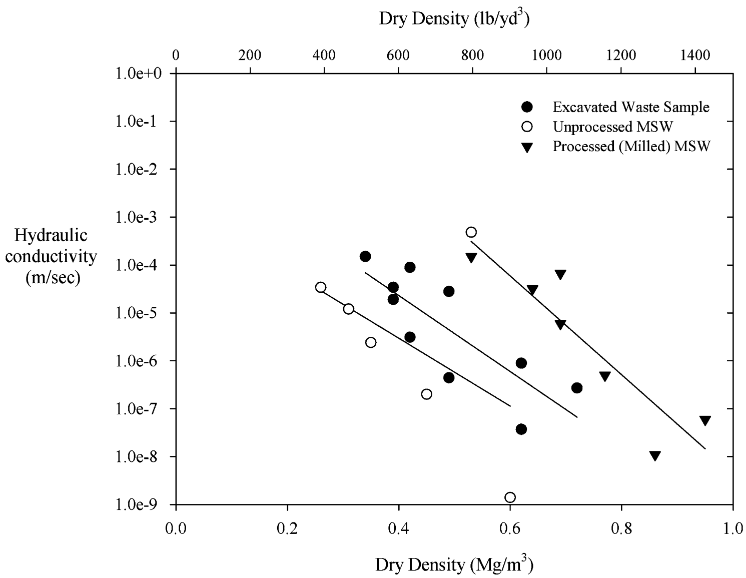

Fig. 5.8 Hydraulic conductivity measured as a function of dry density (Beaven 2000)

5.3.2 *Unsaturated Flow*

As indicated earlier, much of the moisture movement in a landfill will not be saturated, and thus tools and techniques that incorporate unsaturated flow principles must be discussed. First, a discussion of the differences between saturated and unsaturated flow is warranted. While the potentiometric head (h) in saturated flow includes both a liquid pressure (P) and elevation (z), liquid pressure will not be positive under unsaturated flow conditions. In fact, a suction head (ψ) resulting from capillary forces will serve along with the elevation head as the components of potentiometric head ($h = \psi + z$). Also, hydraulic conductivity under unsaturated conditions will not be constant. Thus, Darcy's law for unsaturated flow (in the z direction) can be written as:

$$q_z = -K(\theta)\frac{\partial(\psi + z)}{\partial z} \tag{5.16}$$

Inserting this into the governing equation for Darcy's law presented earlier, the equation can be written as:

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial \psi}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial \psi}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z \frac{\partial \psi}{\partial z}\right) + \frac{\partial K_z}{\partial z} = \frac{\partial \theta}{\partial t} \tag{5.17}$$

This is commonly referred to as the Richards equation. Both K and ψ vary as a function of the moisture present in the unsaturated media.

Several different relationships have been developed to describe ψ and K as a function of volumetric moisture content (θ). Two of the more common ones, the Brooks-Corey equation and the van Genuchten equation, are presented in Table 5.6. The retention of soil water and subsequently porous media water content in both equations is a function the of matric potential of the porous media. In the Brooks-Corey model, the relationship between these two variables plots as a straight line on a log–log plot, with the slope of the line represented by λ (the pore size distribution factor). In the van Genuchten model, the relationship between volumetric water content and the log of the matric potential yields a more complex plot that tends to work well for most soils. The van Genuchten equation is generally applicable to a larger range of environmental data, while the Brooks-Corey model tends to fit coarse soils within a narrow pore size distribution range (high λ values); however, the Brooks-Corey equation yields functions that are mathematically easier to manipulate (Stankovich and Lockington 1995); several authors have documented parameter equivalencies for moving from one framework to the other (Lehnard et al. 1989; Stankovich and Lockington 1995).

Unsaturated flow is a special case of simultaneous flow of two immiscible fluids (air and water), where the non-wetting phase (air) is assumed to be stagnant and its pressure is assumed to be zero everywhere in the porous media. More detailed discussion of the wetting phase, non-wetting phase and unsaturated flow can be found in other sources (Bear 1979; Stephens 1995) and is briefly described at the end of this chapter.

The Richards equation has been used in the past for predicting leachate generation from MSW landfills (Ahmed et al. 1992; Korfiatis et al. 1984; Schroeder et al. 1994; Straub and Lynch 1982). However, the Richards equation does not account for changes in fluid storage in the medium due to deformation of the medium and compressibility of the fluid that can result from high pore fluid pressure. The fluid pressure in conventional dry landfills is expected to be low, thus changes in fluid storage due to deformation of media and compressibility of fluid realistically can be neglected. The fluid pressure that would be encountered in landfills where liquids are actively added into the waste mass will likely be high, especially in the vicinity

Table 5.6 Comparison Brooks-Corey and van Genuchten parameter relationships

Hydraulic soil characteristic	Parameter
Brooks-Corey	
Soil water retention	λ = pore size index
$\frac{\theta-\theta_r}{\varphi-\theta_r}=\left(\frac{\boldsymbol{h_b}}{\boldsymbol{h}}\right)^{\lambda}$	h_b = bubbling capillary pressure
Hydraulic conductivity	θ_r = residual water content
$\frac{\boldsymbol{K}(\theta)}{\boldsymbol{K_S}}=\left(\frac{\theta-\theta_r}{\varphi-\theta_r}\right)^{n}=(\boldsymbol{S_e})^{n}$	φ = porosity
	K_S = fully saturated conductivity ($\theta=\varphi$)
	h = matric potential
	S_e = effective saturation
	$n=3+\frac{2}{\lambda}$
van Genuchten	
Soil water retention	φ = porosity
$\frac{\theta-\theta_r}{\varphi-\theta_r}=\left[\frac{1}{1+(\alpha \boldsymbol{h})^{n}}\right]^{m}$	θ_r = residual water content
Hydraulic conductivity	α = constant
$\frac{\boldsymbol{K}(\theta)}{\boldsymbol{K_S}}=\left(\frac{\theta-\theta_r}{\varphi-\theta_r}\right)^{\frac{1}{2}}\left\{1-\left[1-\left(\frac{\theta-\theta_r}{\varphi-\theta_r}\right)^{\frac{1}{m}}\right]^{m}\right\}^{2}$	n = constant m = constant h = absolute value of matric potential

of liquids introduction devices. The change in fluid storage due to media deformation and fluid compressibility, therefore, might be considerable at such facilities.

Stephens (1995) proposed a modified version of the Richards equation (5.22) that also accounts for liquids storage due to deformation of the media and compressibility of fluid. The modified equation is more appropriate for modeling the fluid flow as part of landfill facilities where sustainable practices such as liquids addition are implemented. McCreanor (1998) and Jain et al. (2005a, b) used (5.22) for simulating fluid flow from liquids introduction systems in bioreactor landfills:

$$\frac{\partial}{\partial x}\left(K_x\frac{\partial\psi}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y\frac{\partial\psi}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_z\frac{\partial\psi}{\partial z}\right)+\frac{\partial K_z}{\partial z}=\left(C+\beta S_s\right)\frac{\partial\psi}{\partial t} \tag{5.18}$$

where β is a constant equal to 1 when $p \geq 0$ and 0 when $p < 0$.

5.3.3 Predicting Moisture Movement

Once a governing equation for moisture flow has been established, it can be solved for the resultant moisture movement for specific scenarios of interest and associated boundary conditions. While analytical solutions to some problems may be available, in most cases, complex problems require the use of a numerical flow model. Table 5.7 summarizes several fluid flow modeling studies related to landfills and their application. The remainder of this section focuses on two specific, commonly used models: the Hydrologic Evaluation of Landfill Performance (HELP) and SEEP/W. SEEP/W is focused upon because much of the work presented elsewhere in this book was developed using this program; similar software packages are expected to yield comparable results.

SEEP/W, a commercial program from Geo-Slope International (Alberta, Canada), has been used to numerically simulate subsurface liquids addition. SEEP/W is a finite element model and numerically solves the Richards equation for saturated and unsaturated water flow. The model has been used to analyze groundwater seepage and excess pore-water pressure dissipation problems within porous media (Jain et al. 2010a, b). SEEP/W can model various material types and boundary conditions such as unsaturated soils, different injection pressures, groundwater seepage, and excess pore-water pressure dissipation problems within porous media (Hughes and Sanford 2004). The governing differential equation used in SEEP/W is as follows:

$$\frac{\partial}{\partial X}\left(K_x \frac{\partial H}{\partial X}\right) + \frac{\partial}{\partial Y}\left(K_y \frac{\partial H}{\partial Y}\right) + Q = \frac{\partial \theta}{\partial t} \tag{5.19}$$

Where H is the total head (L); K_x and K_y are the hydraulic conductivities in horizontal and vertical directions, respectively (L T^{-1}); Q is liquid flux (L^3 T^{-1}); θ is the volumetric water content; and t is time (T). The van Genuchten function for soil-water characteristic curves and the van Genuchten-Mualem function for the calculation of relative permeability are one option in SEEP/W and were used for the simulations presented in this book. Additional details on SEEP/W can be found in Krahn (2007).

The HELP model is a computerized water-budget program for landfills that the US Army Corps of Engineers developed for the United States Environmental Protection Agency (USEPA). The HELP model is the predominant tool used by engineers in North America to estimate the leachate production rate from lined landfills as a function of weather data (precipitation, evapotranspiration, wind, and temperature) and landfill design and operating parameters (daily cover, area etc.). HELP is a quasi-two-dimensional model that simulates one-dimensional flow in cover soil and waste layers and two-dimensional flow in the drainage layer (Schroeder et al. 1994). HELP serves as a tool for the rapid modeling a landfill's water balance and uses a mixture of empirical and numerical modeling to estimate moisture inputs, moisture retention, and moisture transport into, within, and out of a landfill. Most state landfill permitting agencies in the US require that the HELP model be performed as part of a landfill permit application.

Table 5.7 Moisture flow models used to simulate specific landfill scenarios

Study	Model	Application
McCreanor and Reinhart (1996, 2000)	SUTRA—USGS unsaturated and saturated flow model with capabilities for density variation as well as solute and energy transport modeling	SUTRA was used to model leachate distribution around vertical and horizontal leachate recirculation devices for a range of liquids addition rates, waste and cover permeability, waste anisotropy, waste heterogeneity, and dosing frequency
Beaven (2000)	MODFLOW—USGS, 3-D groundwater flow model, used for simulating steady state and transient flow	MODFLOW was used to model infiltration into landfill with hydraulic conductivity varied as a function of effective stress
Oldenburg (2001), Kling and Korkealaakso (2006)	TOUGH(2)—Transport of unsaturated groundwater and heat-landfill gas migration	TOUGH(2) incorporates gas/liquid partitioning and was applied to a bioreactor landfill with a module devoted to bioreactor option (T2LBM) which uses a Monod kinetic rate for biodegradation (acetic acid used as a proxy for degradable waste) either by aerobic or anaerobic means (Oldenburg 2001). Kling and Korkealaakso used the model to plan a bioreactor monitoring system (sensors and located in Finland)
Bachus et al. (2002)	VS2DI—a finite difference model that simulates liquid flow and solute or energy transport in saturated-unsaturated porous media	Bachus et al. (2002) used VS2DI to simulate the liquid flow from horizontal trenches in a homogenous and isotropic media to estimate lateral and vertical extents of the zone of impact as a function of injection pressure for intermittent system operation
Haydar and Khire (2007), Khire and Mukherjee (2007), Haydar and Khire (2007), Khire and Kaushik (2012)	HYDRUS—A finite element model for simulating the two-dimensional movement of water, heat, and multiple solutes in variably saturated media. The model includes a parameter optimization algorithm for inverse estimation of a variety of soil hydraulic and/or solute transport parameters	Khire and Haydar (2005) numerically modeled steady-state fluid flow from horizontal trenches as a function of injection pressures, trench geometry and size, hydraulic conductivity of the trench backfill, and horizontal and vertical trench spacing for isotropic waste. Khire and Mukherjee (2007) simulated the impact of the leachate injection rate on the steady-state injection pressure, lateral extent of moisture movement, and head on the bottom liner for isotropic waste. The impact of well radius, well depth, and screen length, and dosing frequency were also investigated
Jain et al. (2010a, b)	SEEP/W simulates liquid flow in saturated and unsaturated porous media using a combination of finite element and finite difference methods	Jain et al. (2010a, b) used SEEP/W for modeling liquids distribution around horizontal and vertical sources for a range of injection pressure, waste permeability and anisotropy, and source dimensions. The modeling results were used to develop generalized design charts to estimate flow rate, lateral and vertical extents of the zone of impact as a function of injection pressure and the added liquids volume

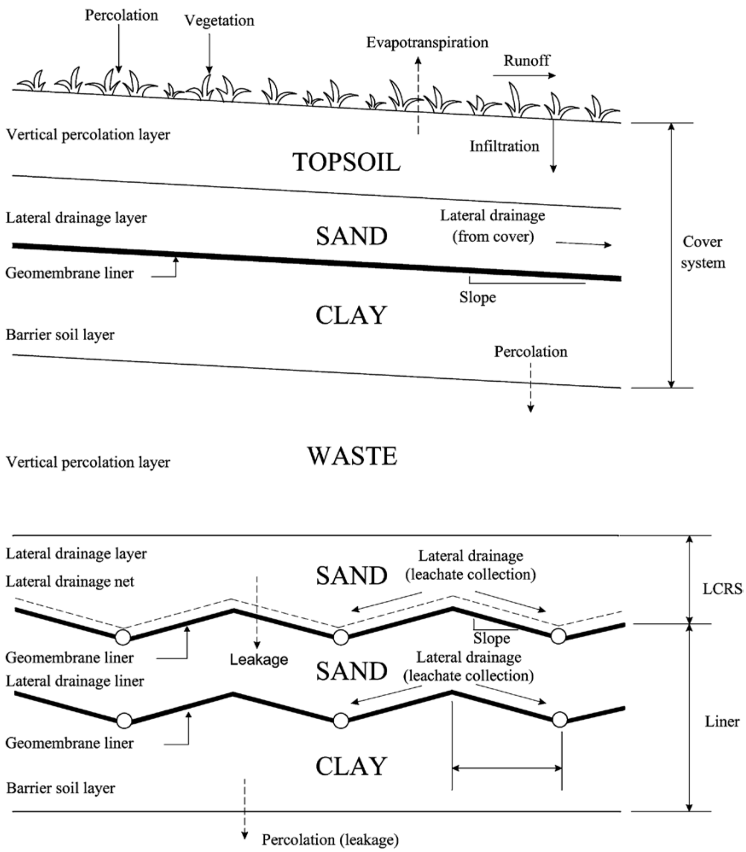

Fig. 5.9 Definition sketch of the HELP model

In HELP, the landfill's vertical cross section is defined in the soil properties input file as layers, classified in one of the four predefined types in the model (Fig. 5.9). The layer types identified by the model are vertical percolation, lateral drainage, barrier soil, and geomembranes. The user has the option to specify the initial moisture of different layers or use model default values for the initial moisture content for each layer based on the wilting point, field capacity, and total porosity for each layer of material. In the HELP model, surface water runoff is forecasted using the US Soil Conservation Service's curve number method, infiltration, evapotranspiration, and percolation are simulated using the Darcy equation adapted for unsaturated conditions. Lateral drainage is determined using the Boussinesq equation adapted for landfill conditions. Liner leakage is estimated using Darcy's equation for saturated conditions. Evapotranspiration is modeled by a plant growth and decay model for perennial and annual crops. Vertical flow is modeled in the vertical direction with the gravitational and hydrostatic potentials considered as driving forces. While nowhere near as powerful for simulating liquids flow in landfills as the numerical software packages described in Table 5.7, HELP does provide several opportunities for the designer to incorporate liquids addition (Xu et al. 2012), and these will be discussed in detail in Chap. 10.

5.3.4 Dominant Factors Controlling Leachate Flow

Future chapters illustrate the application and output of fluid flow models as part of the landfill design process. A number of operating conditions (added flow rates, pressures) and landfill properties (initial moisture content, hydraulic conductivity) must be defined as part of the specific application simulated. In this section, example results from several simulations of liquids addition into landfills (using SEEP/W model runs for horizontal trenches, vertical wells, and horizontal blankets) are presented to provide the reader with sense of the expected influence of several major inputs. Figure 5.10 depicts the saturated zone that may result under steady-state conditions to illustrate how moisture distribution progresses under steady-state conditions in a landfill, depending on the liquids addition devices. Transient zones are also depicted, displaying the manner in which moisture movement progresses to steady-state conditions.

Waste hydraulic conductivity has a significant impact on moisture distribution in a landfill. Figure 5.11 shows the results of simulations where liquids are added to waste with different hydraulic conductivities (1×10^{-4} cm s^{-1}, 1×10^{-5} cm s^{-1}, 1×10^{-6} cm s^{-1}) and compares the saturated zones formed. Liquids are added into waste through devices under a constant pressure and the waste is assumed to be isotropic (i.e., anisotropy is equal to 1). Under the same injection pressure, the higher the waste conductivity is, the larger the wetted zone will be. Due to the assumed isotropic property of waste, the saturated zone formed by a horizontal injection trench is initially a circle with the center at the location of the injection pipe. Once it reaches the steady state, its lateral spread will remain constant, and the wetted zone will only expand vertically downward by gravity. If a constant flow rate is used, as opposed to a constant injection pressure, the saturated zone formed by the liquid addition will be essentially the same because the total amount of added liquids is the same. However, to achieve the same flow rate, a higher injection pressure is required for the waste with low hydraulic conductivity.

Figure 5.12 illustrates the effect of waste anisotropy (K_x/K_z) moisture distribution under a constant injection pressure. The waste was simulated with the same vertical hydraulic conductivity, 1×10^{-5} cm s^{-1}, but with different anisotropy, ranging from 1 to 100. The waste with high anisotropy has a larger lateral expansion because of a higher lateral hydraulic conductivity (K_x). Under the same injection pressure, the saturated zone formed in highly anisotropic waste is larger than that

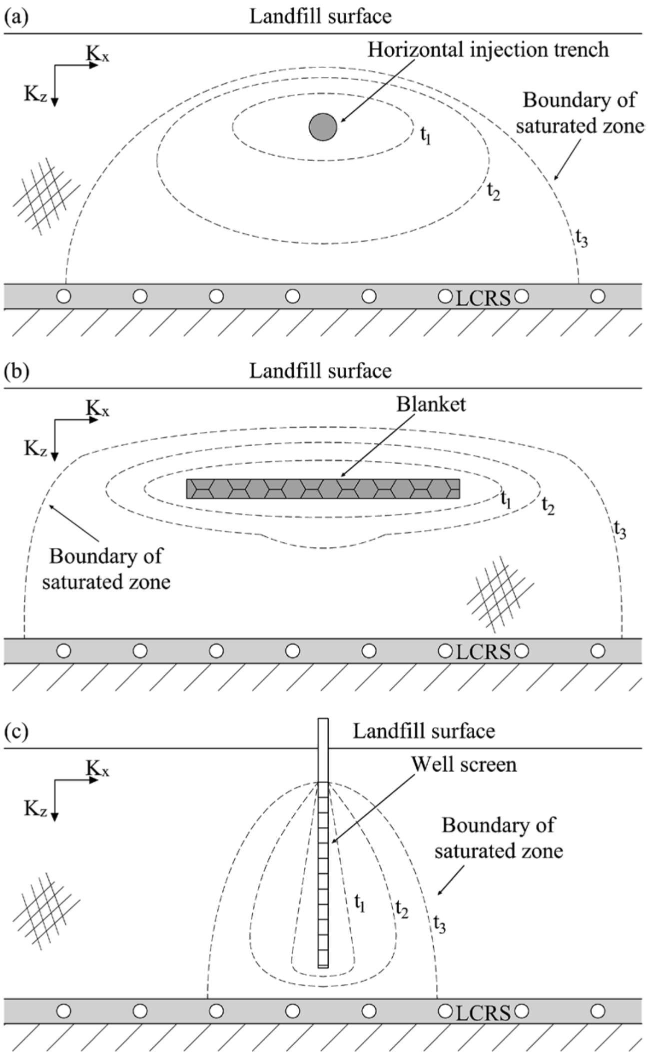

Fig. 5.10 Illustration of two transient zones as well as the saturated zone under steady state conditions for: (**a**) horizontal trench; (**b**) horizontal blanket; and (**c**) vertical well

for a waste with low anisotropy. With the same vertical hydraulic conductivity, higher anisotropy means higher lateral hydraulic conductivity, which results in larger lateral liquid distribution. When the vertical hydraulic conductivity is the same, the liquid has the same vertical distribution as horizontal.

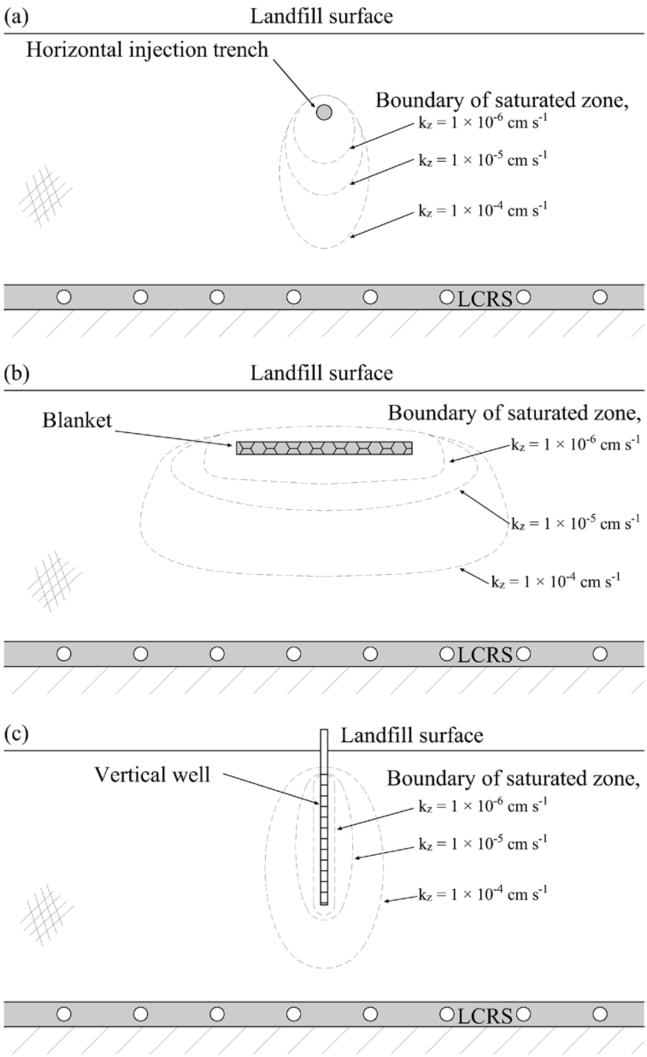

Fig. 5.11 The effect of hydraulic conductivity on liquids distribution: (**a**) vertical well; (**b**) horizontal trench; (**c**) infiltration gallery

The hydraulic conductivity of waste may change with depth. Waste deeper in the landfill has been further degraded and compacted than waste near the surface. Therefore, it is reasonable to assume that the hydraulic conductivity of waste decreases with depth, impacting the distribution of liquids in the subsurface. Figure 5.13 shows a vertical well, a horizontal trench, and a horizontal gallery in

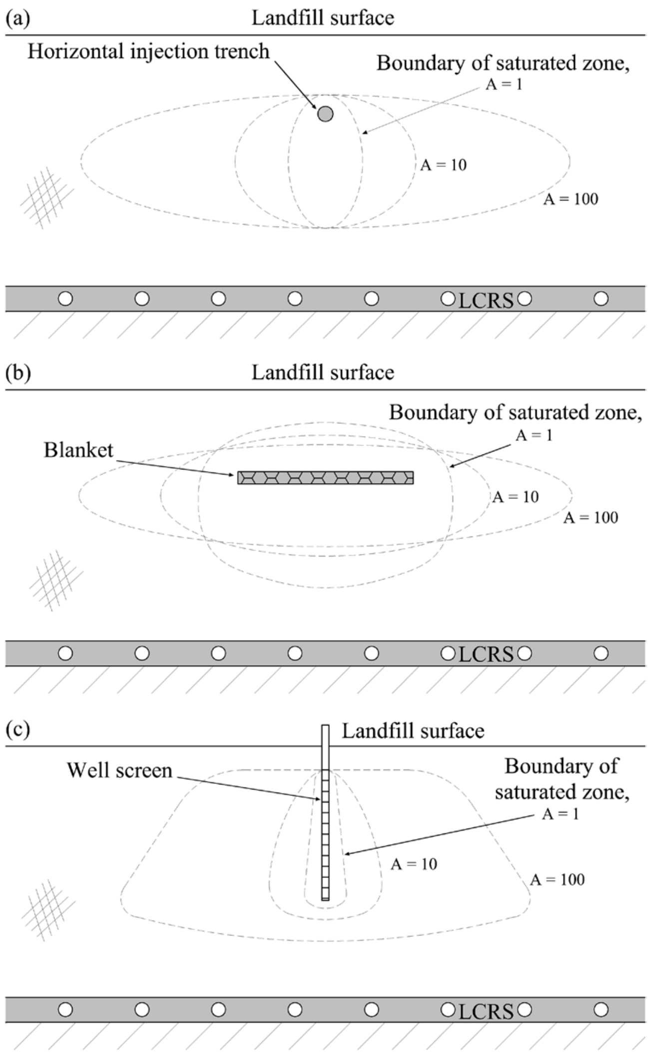

Fig. 5.12 The effect of waste anisotropy on liquids distribution: (**a**) vertical well; (**b**) horizontal trench; (**c**) infiltration gallery

two scenarios. The first shows the distribution of liquids assuming that hydraulic conductivity is constant. The second shows hydraulic conductivity decreasing from 10^{-5} to 10^{-6} cm s^{-1}. A decreasing hydraulic conductivity as a function of depth results in more lateral movement as the moisture moves deeper into the landfill.

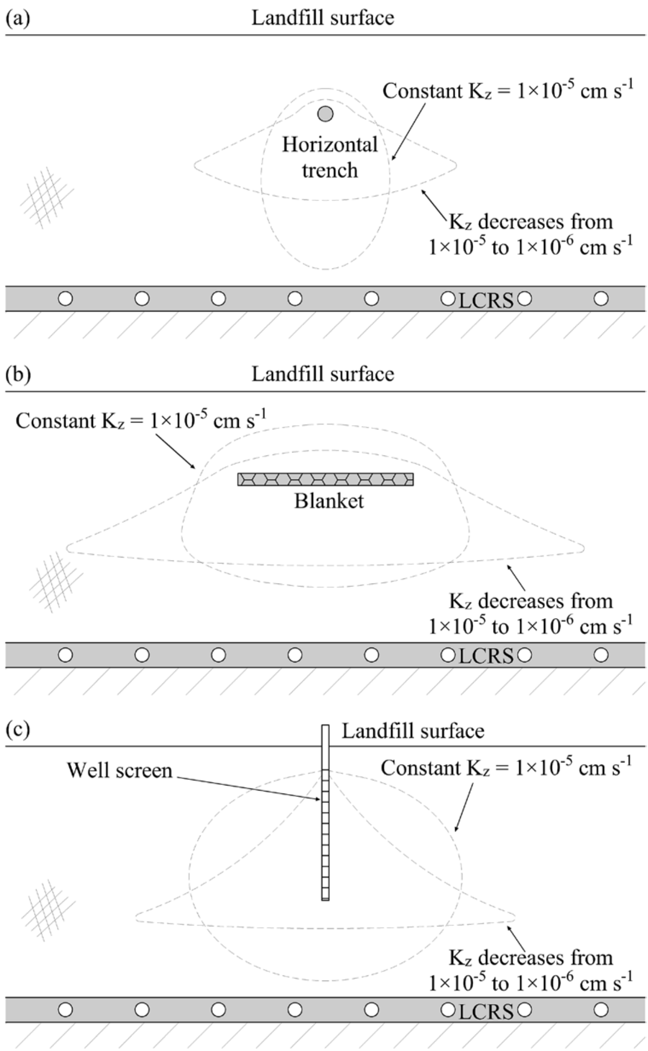

Fig. 5.13 The effect of hydraulic conductivity decreasing with depth on liquids distribution: (**a**) vertical well; (**b**) horizontal trench; (**c**) infiltration gallery

5.4 Gas and Air Movement

In Chap. 2, the fundamental biological reactions occurring in MSW landfills were reviewed, and the primary mass loss mechanisms—the conversion of solid organic matter to gases CH_4 and CO_2—were described. Design issues regarding landfill gas and its role in sustainable technologies for waste management will be discussed in detail in Chap. 13. Presented briefly here are some basic gas production and dynamic concepts.

5.4.1 Production of Landfill Gas

The typical practice of landfill gas production estimation assumes that average disposed mass of waste has some associated gas production potential. This production potential may be explained in terms of total gas produced (CH_4 and CO_2), or often simply in terms of CH_4. Thus, the total volume of CH_4 produced from a given mass of waste may be written as:

$$V_{CH_4} = L_o M_{waste} \tag{5.20}$$

Where V_{CH_4} is the volume of methane (m^3), M_{waste} is the mass of waste (Mg), and L_o is the CH_4 generation potential (m^3 CH_4 per Mg waste). As CH_4 is usually approximately 50 % of the volume of total landfill gas for the majority of a landfill's active and post-closure lifetime, a common expression for total potential gas production (V_{GAS}) is:

$$V_{GAS} = 2\,L_o M_{waste} \tag{5.21}$$

L_o can be measured using chemical assays or reactor testing, although the potential based on laboratory studies may be larger than that occurring under true landfill conditions, and even estimates based on large-scale operating facility data can result in poor estimation of L_o.

The realization of gas production depends on many factors, notably moisture content, hence the reliance on liquid addition for waste stabilization as described already. Most engineers predict gas production evolution over time by assuming basic reaction kinetics, with a first-order kinetic relationship being the most common approach. Thus, a common expression to predict landfill gas production rate over time is:

$$\bar{G} = 2\,L_o\,k\,M_{waste}\left(e^{-kt}\right) \tag{5.22}$$

where $\bar{G}$ is gas production rate (m^3/year) and k is the first-order decay rate coefficient ($year^{-1}$). The use of this relationship for design and prediction, especially as related to landfills practicing liquids addition to increase waste decomposition rates, will be discussed in Chap. 13.

5.4.2 Gas Movement in Landfill Waste

When gas is produced in the confined pore spaces of the landfilled waste mass, gas pressures increase. Similarly, when air is added to a landfill under pressure, gas pressure in the waste pore space increase. Gas will move in the landfill in response to the resulting pressure gradient (gas will migrate from high pressure zones within the landfill toward lower pressure zone such as a gas wells or the landfill surface), and a concentration gradient (high gas constituent concentration inside the landfill compared to low concentrations in the surrounding atmosphere). In a similar manner as previously discussed for moisture movement in the landfill, gas movement within the landfill can be simulated by using an appropriate governing equation.

Important to developing such a governing equation, however, is the fundamental relationship between gas pressure and flow through a porous media. In the earlier presentation of Darcy's law for moisture movement, hydraulic conductivity was used, but this relates to water movement through a porous media. Permeability is a property of the media itself and is independent of the fluid being transmitted. Equation (5.23) provides for the relationship between hydraulic conductivity and porous media permeability.

$$K = \frac{k\rho g}{\mu} \tag{5.23}$$

where: K is hydraulic conductivity (L T^{-1}), k is the media permeability (L^2), ρ is the fluid density (M L^{-3}), g is acceleration due to gravity (L T^{-2}), and μ is the dynamic liquid viscosity. Several researchers have presented MSW air permeability data measured from laboratory (Stoltz et al. 2010a, b; Druilhe et al. 2013) and field (Cestaro et al. 2003; Jain et al. 2005a, b; Wu et al. 2012) experiments; MSW air permeability has been reported to range from 10^{-10} to 10^{-13} m^2 in pump tests at full-scale landfills.

Using the fundamental relationship of Darcy's law with permeability instead of hydraulic conductivity, the law of conservation of mass can be used to derive an appropriate governing equation. As an example, Hashemi et al. (2002) developed the following governing equation for gas flow in a landfill:

$$\frac{\partial}{\partial x}\left(D_{e_{jm}}\frac{\partial \rho_j}{\partial x}\right)+\frac{\partial}{\partial y}\left(D_{e_{jm}}\frac{\partial \rho_j}{\partial y}\right)+\frac{\partial}{\partial z}\left(D_{e_{jm}}\frac{\partial \rho_j}{\partial z}\right)+\alpha_j(z)=\frac{\partial\left(V_x\rho_j\right)}{\partial x}+\frac{\partial\left(V_y\rho_j\right)}{\partial y}+\frac{\partial\left(V_z\rho_j\right)}{\partial z} \tag{5.24}$$

Where D_{ejm} is the effective diffusivity of gas j in the pore space (m^2/year), ρ_j is the mass concentration of the j^{th} component of the gas mixture (kg/m^3), α_j is the gas generation rate of the gaseous species j, V_x, V_y and V_z is the flow velocity in the x, y, and z direction, respectively. In this approach, the convective-diffusion governing equation was derived assuming no sudden changes in pumping rates, temperature and barometric pressure, and with the landfill as a rectangular cell.

A number of researchers have developed governing equations and developed solutions to address specific design or operational questions. For example, Tinet and Oxarango (2010) conducted an analysis examining LFG flow to a given collection device that accounted for waste settlement and resultant impacts to the hydraulic properties of the waste. Townsend et al. (2005) utilized the governing equation to develop an analytical solution for the distribution of pressures within a landfill as a function of pressures at the base (the LCRS) and the surface of the landfill as presented in (5.25).

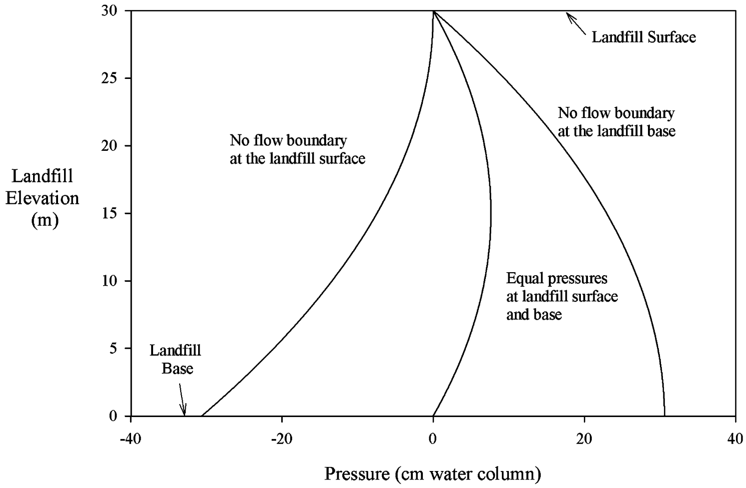

Fig. 5.14 Landfill gas pressure distribution within a landfill with different boundary conditions (Townsend et al. 2005)

$$\theta_g \frac{\partial}{\partial t}\left(\frac{p}{RT}\right) = \frac{\partial}{\partial z}\left(\frac{k_z}{\mu}\frac{p}{RT}\frac{\partial p}{\partial z}\right) + M \tag{5.25}$$

Where θ_g is the gas constant of the media (i.e., waste) (unitless, volume of gas per volume of bulk material), p is gas pressure ($ML^{-1}\,T^{-2}$), T is absolute temperature, R is the gas constant for landfill gas ($L^2T^{-2}\,K^{-1}$), k_z is the vertical intrinsic permeability of the waste (L^2), μ is the dynamic fluid viscosity ($ML^{-3}\,T^{-1}$), and M is the gas generation rate ($ML^{-3}\,T^{-1}$). The equation considers partial gas pressures as well as Darcy's law for the gas phase. Because the horizontal extents of waste layers within a landfill are much greater than the vertical extents, the vertical profile is the only considered direction for variation in pressure distribution. Figure 5.14 illustrates a potential outcome of the solution developed; the pressure profiles within the landfill are presented for conditions when all of the gas exits through the surface (no flow boundary at the base), all of the gas is collected through the LCRS (no flow boundary at the top) and when pressures are equal at the base and surface.

5.5 Solids Movement

5.5.1 Waste Settlement

The transformation of solid components in the waste to gaseous products through stabilization results in a net loss of mass from the landfill. This mass loss translates to a loss in landfill volume, and thus a decrease in the height of the landfill.

The observation of landfill settlement in traditional landfills is well documented (El-Fadel and Khoury 2000) and these settlement mechanisms are expected to be enhanced at landfill sites practicing sustainable landfill technologies. As described in Chaps. 1 and 2, promoting rapid waste settlement is a primary goal of sustainable operation either for reclaiming landfill space for additional filling or for returning the site to a more stable condition as quickly as possible.

Multiple processes contribute to landfill settlement. As waste is placed, it is at first subjected to mechanical pressures from compaction equipment, and then as more waste is placed, it is subject to the added pressure resulting from added overburden stress. Settlement results as an immediate response to added pressure, and long-term change of waste and soil configuration as materials bunch or unravel. Biological decomposition results in mass loss, but this may not immediately translate to volume loss. The degraded waste structure will settle with time as it responds to mechanized stress, and the liquid and gas occupying the pore space of the waste matrix will inhibit volume loss while pressure dissipates. Settlement analysis is particularly critical for sustainable landfills because of the greater and more rapid degree of waste decomposition expected. A typical approach to predict settlement of the waste itself involves using principles commonly employed in soil mechanics. Identifying appropriate parameters to use in waste settlement analyses is complicated by the heterogeneous nature of MSW and other factors such as compaction effort and waste composition (which are critical and site-specific). Typically, surface settlement is considered to be the sum of primary settlement (which occurs shortly after waste materials are placed) and secondary settlement (which occurs over the long term).

In primary settlement analysis, the total anticipated waste thickness (which is often based on the permitted design elevations) is broken up into multiple layers and the settlement of each layer is calculated and summed. Values used in the primary settlement calculation include site-specific dimensions (e.g., the selected waste layer thickness) and literature-reported values related to the compression of waste materials. In secondary settlement analysis, the designer likewise selects parameters specific to the waste material and literature-reported values associated with compression along with a time horizon of interest to examine the settlement behavior. Finally, the designer chooses two or more points on the landfill surface and calculates the waste settlement beneath each point—the settlement beneath each point is the sum of the primary and secondary settlement.

A variety of approaches or equations have been developed to predict waste settlement as presented in Table 5.8. Some rely on classic soil mechanics settlement estimation methods, while others attempt to incorporate the phases of the landfill environment where waste settles in response to mass loss from decomposition. Table 5.8 presents a summary of some of the analytical methods developed where a settlement estimate may be calculated using an equation.

Many of the recently developed settlement prediction methods apply analytical or numerical solutions to a governing equation based on conserving mass through the waste decomposition process (Liu et al. 2006; Durmusoglu et al. 2005; Chen et al. 2012; McDougall 2007). For example, Hettiarachchi et al. (2007) developed a method to determine bioreactor landfill settlement as a result of organic degradation and mechanical compression under the assumptions that waste remains at field

Table 5.8 Summary of landfill settlement models and associated equations and key parameters

Model description, application, and reference	Equation and parameters
One-dimensional Consolidation Model	
This model was developed for soils which undergo consolidation settlement (Terzaghi and Peck 1967)	$\delta_c = \frac{C_c}{1+e_0} H\log\left(\frac{\sigma'_z}{\sigma'_{z0}}\right)$
	H = initial refuse height
	C_c = Compression index
	e_0 = initial void ratio
	σ'_{zo} = Initial load
	σ'_z = load at time, t
	Assumptions:
	1. Void space is water saturated
	2. Solids are incompressible
	3. Darcy's law is valid
	4. Coefficient of permeability, k, is constant
	5. Consolidation time lag is due to low soil permeability
Log-time Extension Model	
This model accounts for factors other than consolidation which attribute to settlement, raveling, decomposition, and physico-chemical reactions. Given that these parameters tend to be time dependent, the settlement as a function of the log time was proposed. This model has been applied to various field studies and shown to have a significant correlation to long term settlement (Yen and Scanlon 1975; Sowers 1973)	$\Delta e = -\alpha \log\left(\frac{t_2}{t_1}\right)$
	α is analogous to Cc (compression index) and is a function of the void ratio and is dependent on degradation conditions within the waste
	α ranges from 0.03 (poor degradation conditions to 0.09 (favorable degradation conditions)
Gibson-Lo Model	
One-dimensional consolidation model which accounts for secondary settlement process (long-term) settlement as long-term mechanical stress. The settlement is modeled similar to the compression of a spring in two phases (initial and long-term). This model was initially applied to peat soils and shown to work satisfactorily for solid waste (Gibson and Lo 1961)	For large time values:
	$S(t) = q_o h\left[a + b\left(1 - e^{\frac{-\lambda}{b}}\right)\right]$
	S(t) = settlement at time, t
	q_o = initial stress
	h = initial refuse height
	a = primary compressibility
	b = Found via plot of time vs. log
	λ^{-1} = viscosity of the soil structure
Power Creep Model	
Settlement as a function of initial stress and time (Edil et al. 1990)	$S(t) = H\Delta\sigma m\left(\frac{t}{t_r}\right)^n$
	S(t) = settlement at time, t
	m = compressibility index
	t_r = reference time
	n = rate of compression

capacity and that settlement is due to the compression of void space from overlying waste. The governing equation formulated coupled settlement to landfill gas pressure as follows:

$$\frac{\partial p}{\partial t}+\left(P_{atm}+p\right)\frac{\partial}{\partial t}\left(\ln Z_g\right)=\left(\frac{Z}{Z_g}\right)\left(k_g\frac{\partial p}{\partial z}+D\frac{\partial^2 p}{\partial z^2}+\frac{RT}{m}G\right) \tag{5.26}$$

Where p is gauge pressure, P_{atm} is atmospheric pressure, R is the universal gas constant (J mol^{-1} K^{-1}), T is temperature (K), Z is waste height (m), k_g is the landfill unsaturated gas conductivity (m day^{-1}), D is the diffusion coefficient (m^3 day^{-1}), m is the molar mass of the landfill gas (kg mol^{-1}), G is the rate of generation of gas per unit volume of waste (kg m^{-3} day^{-1}), t is the time (day).

5.5.2 Landfill Movement

Shear strength properties of MSW are important in the landfill system as these properties play a key role in an engineering evaluation of the stability of the waste mass at the design stage (see Chap. 12 for a detailed discussion of the application of shear strength to slope stability analysis in sustainable landfill design). The shear strength properties of soils and MSW are evaluated since the landfill system includes components such as the final cover system, the waste itself, and the bottom liner system. In contrast to most soils, MSW is heterogeneous which can make the selection of a single set of key variables that impact shear strength difficult (e.g., cohesion (c) which is the non-frictional part of shear resistance and is independent of normal stress, and internal friction angle (φ), which is the angle on the Mohr's Circle of the shear stress and normal effective stress at which shear failure occurs). Not only does the heterogeneity of the waste itself complicate parameter selection, but other factors such as the amount and type of cover soil used in operations, moisture content of the waste, decomposition effects, and waste placement methods also create difficulties for the designer in selecting a defensible set of values to examine shear strength.

With both c and φ, the designer has the flexibility to choose parameter values based on engineering judgment—the design may incorporate the use of both values, although sometimes c is disregarded for a more conservative analysis (see discussion by Thiel (2009) for more information on interpreting direct shear testing data). MSW shear strength can be measured using standard measurement tests such as direct shear—in some cases, specialized equipment may be used for direct shear testing to accommodate the large particle size that will be encountered in MSW. Several investigators have conducted experiments and testing to estimate these factors, which could serve as a basis for parameter selection. In addition, several authors have reviewed literature pertaining to cohesion and friction angles for MSW (Dixon and Jones 2005; Zekkos 2005; Gabr et al. 2007). In general, MSW has a reported cohesion range from 0 to 50 kPa and a typical friction angle ranging from 20° to 35°. Table 5.9 summarizes reported values for c and φ from the technical literature. Figure 5.15 graphically presents the result of many of the shear tests conducted on MSW; the cohesion is presented as a function of the internal angle of friction.

Table 5.9 Reported values of MSW cohesion (c) and internal friction angle (φ)

Study summary and reference	Cohesion	Internal friction angle (φ)
Geotechnical testing on aged solid waste removed from a landfill which began accepting waste in 1940 in Pennsylvania (US). Strength parameters evaluated at 20 % strain level (Gabr and Valero 1995; Kavazanjian et al. 1995)	Under consolidated, undrained conditions	Under consolidated, undrained conditions
	Effective strength: 16.8 kPa	Effective strength: 34°
	Cohesion remained relatively constant with changing horizontal displacement	Increased with increasing displacement
	24 kPa	0–3°
Samples were collected from two landfill sites in the US (Kentucky and New York), shredded, and processed (Harris et al. 2006)	KY Landfill: 11.6 kPa	KY Landfill: 23.5°
	NY Landfill: 9.3 kPa	NY Landfill: 28°
Landfilled samples extracted via borehole every 1 m depth from a landfill closed in 1985 (Al-Yaqout et al. 2007)	Effective strength: 7.43–35 kPa	Effective strength: 26.7–50° (mean 33.4°)
Large scale direct shear testing (30 cm × 30 cm) of MSW collected from a San Francisco Landfill (US), 109 shear strength tests were performed (Zekkos et al. 2010a, b)	15 kPa (low moisture content MSW)	36° (at 1 atm normal stress, low moisture MSW)
Synthetic MSW was examined for geotechnical properties. Leachate recirculation, which causes enhanced waste degradation, was performed (Reddy et al. 2011)	1 kPa (fresh MSW)	35° (fresh MSW)
	16 kPa (anaerobic acid)	34°
	18 kPa (accelerated CH_4)	29°
	34 kPa (decelerated CH_4)	29°
	40 kPa (CH_4 stabilized)	28° (CH_4 stabilized)
	Under consolidated, undrained conditions	Under consolidated, undrained conditions:
	Total strength: 21–57 kPa	Total strength: 1–9°
	Effective strength: 18–56 kPa	Effective strength: 1–11°
Geotechnical testing on fresh and aged solid waste from a long-running bioreactor experiment was performed (Bareither et al. 2012b)	Waste extracted from a bioreactor experiment:	Waste extracted from a bioreactor experiment:
	22.3 kPa (Initial condition)	40.0° (Initial condition)
	21.7 kPa (aged 2.9 year)	42.6° (aged 2.9 year)
	Transfer station MSW: 8.9 kPa	Transfer station MSW: 31.5°

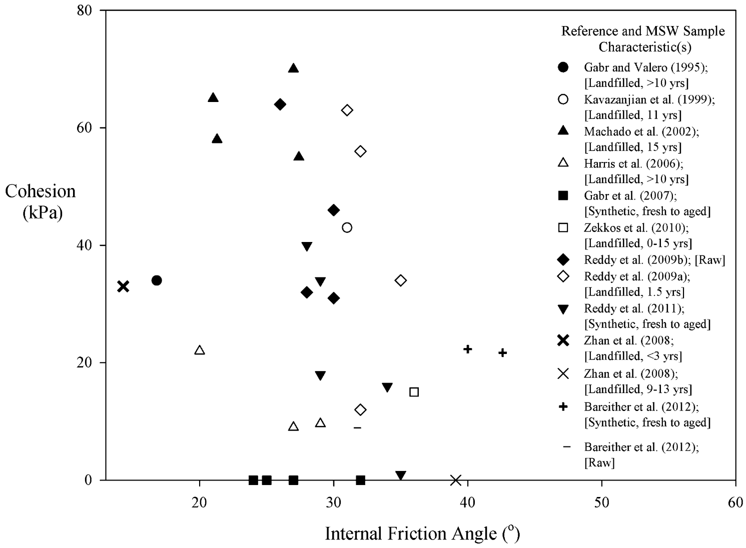

Fig. 5.15 Ranges of measured waste cohesion and internal friction angle reported from the literature

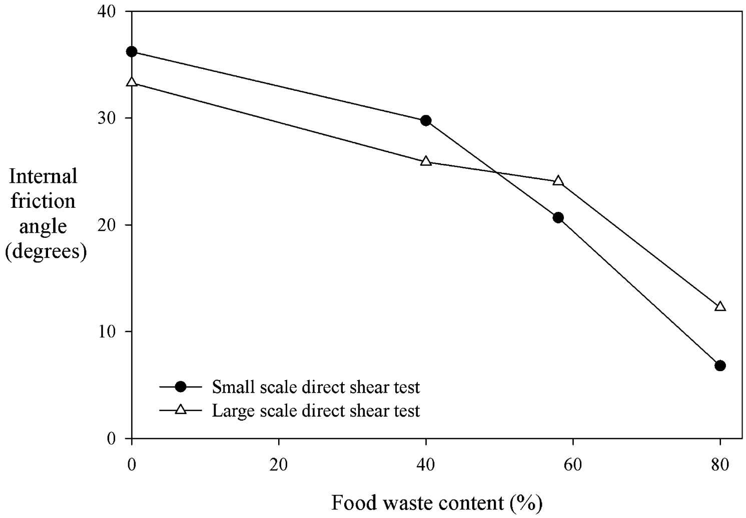

Fig. 5.16 Internal friction angle as a function of food waste content measured using a direct shear test (from Cho et al. 2011)

Food waste has been suspected of contributing to lower MSW friction angles, which is a critical design consideration in areas with comparatively less packaging wastes in the discard stream (e.g., developing countries, many Asian countries). Cho et al. (2011) examined this relationship in both a small- and large-scale direct shear apparatus. Figure 5.16 presents the results of this experiment. At lower food waste contents typical of MSW in the western part of the world, the friction angle was similar to those values presented in Table 5.9 (between 30° and 40°). However, at a food waste content of 40 % (by weight), more reflective of wet landfills of Asian countries and developing nations, the internal angle of friction was shown to decline markedly.

5.6 Multiphase Dynamics

In reality, fluid flow in a MSW landfill is a multiphase phenomenon, and the prediction of moisture and gas movement using the techniques described so far can be seen as approximations. One approach to better simulate the combined interaction of moisture and fluid with respect to the dynamics of these constituents is to develop separate governing equations for each phase, and to relate them with characteristics that scale existing properties (e.g., permeability) to the relative amount of each phase present. For example, the flow of moisture movement could be described by the following governing equation:

$$\frac{\partial}{\partial x}\left(\frac{k_x k_{rl}\rho_l}{\mu_l}\frac{\partial p_l}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{k_y k_{rl}\rho_l}{\mu_l}\frac{\partial p_l}{\partial y}\right)+\frac{\partial}{\partial z}\left(\frac{k_z k_{rl}\rho_l}{\mu_l}\frac{\partial \rho k}{\partial z}\right)+\frac{\partial}{\partial z}\left(k_z k_{rl}\rho_l\right)=\frac{\partial}{\partial t}\left(\rho_l S_l \eta\right) \tag{5.27}$$

While the flow of gas could be described by a separate and distinct governing equation:

$$\frac{1}{\mu_g}\left[\begin{array}{l} k_x k_{rg}\left(\frac{\partial p_g}{\partial x}\right)^2+p_g\frac{\partial}{\partial x}\left(k_x k_{rg}\frac{\partial p_g}{\partial x}\right)+k_y k_{rg}\left(\frac{\partial p_g}{\partial x}\right)^2+p_g\frac{\partial}{\partial y}\left(k_y k_{rg}\frac{\partial p_g}{\partial y}\right) \\ +k_z k_{rg}\left(\frac{\partial p_g}{\partial z}\right)^2+p_g\frac{\partial}{\partial z}\left(k_x k_{rg}\frac{\partial p_g}{\partial z}\right)+\frac{g w_g}{RT}p_g z k_{rg}\frac{\partial p_g}{\partial z}+\frac{g w_g}{RT}\frac{\partial}{\partial z}\left(k_{zg}p_g\right) \end{array}\right]$$
$$=\frac{M_g RT}{w_g}+\frac{w_g}{RT}\frac{\partial}{\partial t}\left(p_g S_g \eta\right) \tag{5.28}$$

Where k_{rl} is relative permeability, $k_{x, y, z}$ is permeability in the respective directions, p_l is liquid pressure, p_g is gas pressure, η is porosity, S_l is the degree of saturation for liquid phase, Sg is the degree of saturation in the gas phase, M_g is gas generation rate per unit waste volume (kg m^{-3} s^{-1}), w_g is the molecular weight of the gas, μ_l is liquid viscosity, μ_g is gas viscosity. Equations (5.27) and (5.28), along with (5.29)–(5.33) (Corey 1994), using appropriate boundary conditions, should be solved simultaneously to simulate gas and liquid flow in solid waste:

$$S_l + S_g = 1 \tag{5.29}$$

$$P_c = P_g - P_l \tag{5.30}$$

$$S_l = f_1\left(P_c\right) \tag{5.31}$$

$$k_{rl} = f_2\left(P_c\right) \tag{5.32}$$

$$k_{rg} = f_3\left(P_c\right) \tag{5.33}$$

This approach has been attempted for MSW landfill systems by several researchers (Berglund 1998; Nastev et al. 2001) to meet specific design or research objectives. Future research should continue such efforts with respect to better understanding and developing tools for sustainable landfill practices.

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Chapter 6
Moisture Supply and Conveyance

Abstract The most commonly-deployed aspect of sustainable landfilling technologies is the deliberate addition of moisture to the waste mass to promote rapid stabilization. There are numerous potential liquid sources available to the operator, so this chapter presents a variety of options that could be used as a stand-alone option or in combination. In addition to liquid sources, moisture addition targets—a critical design and planning decision for every site that is using or wants to use sustainable landfilling technologies—are also discussed. The chapter ends with a discussion of different liquid conveyance systems and the addition of wet wastes to achieve moisture addition goals.

Keywords Landfill • Leachate • Bioreactor • Recirculation • Moisture Addition • Field Capacity • Biosolids

6.1 Designing for Moisture Addition

As conveyed in earlier chapters, one of the primary methodologies employed to operate a landfill more sustainably is promotion of rapid waste stabilization by increasing landfill moisture content. The designer and operator of landfills implementing this practice can utilize several different techniques to introduce and distribute additional moisture into the landfill. Presented in future chapters are detailed construction and operation considerations, along with design methodologies, for surface systems (Chap. 7), buried vertical systems (Chap. 8), and buried horizontal systems (Chap. 9). Pertaining to these detailed operation and design considerations, however, are several planning and engineering steps that must be completed to address fundamental issues of how the addition of liquids and wet wastes will be managed. Considerations include: what sources of moisture should be used, how much moisture addition to target, both in total and the rate of addition (i.e., over what time will addition occur), how to convey the liquids or wet wastes to the landfill, and how to control the addition process to meet desired objectives for moisture distribution and liquids containment within the landfill unit. This chapter discusses fundamental issues including the sources of supplemental moisture, target moisture addition volumes, and methods for conveying liquids or wet wastes to the landfill.

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6.2 Moisture Sources

6.2.1 Options for Moisture Sources

Moisture levels can be enhanced through the addition of either liquids or wet wastes (e.g., sludges). The most common source of supplemental moisture deliberately added to landfilled waste is leachate collected from the same (or perhaps adjacent) landfill unit. Leachate recirculation has been practiced as a means of enhanced waste stabilization and for basic liquids management. However, in some cases, the target moisture addition requirements specified by the engineer as well as the available leachate volumes for recirculation necessitate other sources of moisture to achieve project objectives. These additional moisture sources may be storm water purposefully retained after rain events or surface water or groundwater extracted from outside the landfill. In other cases, the moisture sources are waste products themselves (e.g., industrial wastewater, septage, wastewater sludges), and in this case the landfill operator is presented with an opportunity to collect revenue for the disposal of the waste liquids or wet wastes in addition to providing a needed source of moisture to the landfill itself.

The choice of an additional moisture source will depend on several factors: availability; difficulty and cost associated with capturing, extracting, or obtaining the source; and limitations imposed by applicable regulations. With regard to regulatory requirements, planners and engineers must consult the appropriate regulations and regulatory agencies. In the U.S., for example, federal MSW landfill regulations permit the addition of leachate and landfill gas condensate back to the landfilled waste (US government 2012). As described in Chap. 3, however, the addition of bulk liquid wastes is prohibited unless special permission is granted. A solid waste that fails the paint filter test is considered a bulk liquid waste. In the case of domestic wastewater sludge (e.g., municipal biosolids), for example, the moisture content must be less than approximately 80–85 % (by weight) to pass the paint filter test. The subsequent sections provide more detailed discussion on the following potential supplemental moisture sources: leachate, water, wastewater, spent aqueous products, and wet wastes.

6.2.2 Leachate

Much of the early work on the subject of wet landfills involved examining the effects of leachate recirculation on leachate quality (Pohland 1980). Today, leachate recirculation is commonly practiced both by landfill operators targeting enhanced waste stabilization and when a lower cost method of managing leachate is sought. Most leachate recirculation systems involve constructing a pumping system to convey leachate from storage units (tanks, ponds) to the liquids addition devices within the landfill. Another option sometimes practiced is to utilize the landfill's existing

Fig. 6.1 Leachate storage and aeration pond equipped with a pump for recirculating leachate to the landfill

pumping system (as part of the LCRS) to convey leachate back to the landfill. Liquids conveyance strategies are discussed in further detail later in this chapter.

Depending on site-specific design and operation features, the chemical quality of the leachate recirculated may differ from that emanating at the base of the landfill. Storage ponds and tanks may be equipped with aeration systems to help control odors and achieve some rudimentary treatment (Fig. 6.1). The leachate recirculated in this case may be somewhat lower in organic content (BOD), ammonia, and metals that precipitate under oxidation (e.g., iron). Leachate at uncovered ponds or tanks may also become diluted as a result of large rain events, or concentrated in areas where evaporation is greater than rainfall.

Leachate treated in a more rigorous manner—as part of a treatment plant, for example—may in some cases also be recirculated to the landfill, although a benefit of leachate recirculation is reduction of some of the landfill constituents to minimize external treatment requirements (e.g., BOD). As will be described in greater depth in Chap. 11, landfill operators may opt to deliberately treat leachate prior to recirculation to meet specific facility objectives. For example, leachate nitrification transforms much of the ammonia-nitrogen (NH_3/NH_4^+) to nitrate-nitrogen (NO_3^-), which, when recirculated back to the landfill, may undergo denitrification to nitrogen gas (N_2) (Berge et al. 2005). Advanced oxidation processes have the potential to convert organic matter otherwise recalcitrant to decomposition to a more biodegradable form (Batarseh et al. 2010). Treatment techniques such as reverse osmosis, ultrafiltration, and evaporation can be used to dewater leachate (i.e., concentrate the leachate by removing relatively clean water) prior to return to the landfill.

6.2.3 Stormwater and Groundwater

As will be illustrated in the next section, designers often target the addition of sufficient liquids to the landfill to reach the waste's field capacity. Even in wet climates, the amount of leachate generated (especially when good stormwater management practices are employed) is often insufficient to reach this target. Thus, outside water sources are sometimes added, such as stormwater, surface water, or groundwater. Regulatory allowance of water addition will be a major controlling factor in the implementation of this procedure, as some regulatory agencies do not permit the addition of water. As stated earlier, US regulations allow leachate recirculation, but prohibit the addition of bulk liquid wastes (US government 2012). The allowance of water addition, however, has been interpreted differently among US states. Since clean water is not a liquid waste, some regulators allow water addition, while others argue that the intent of the bulk liquids waste prohibition is to minimize moisture entry into the landfill and thus this practice is not permitted.

Groundwater and surface water addition has been practiced at several sites in the US (Yazdani et al. 2010; Ko et al. 2013) to meet target moisture content. These operators normally utilize separate pumping systems to deliver water to a leachate storage tank or pond where it is mixed with leachate prior to addition to the landfill (Fig. 6.2). Landfill operators have the ability to retain rainfall depending on stormwater management practices; this is described in more detail in Chap. 11. Regulatory operating requirements for landfills, however, typically limit the

Fig. 6.2 Groundwater well used for extracting fresh water to mix with leachate before recirculating to a landfill

presence of standing water on the landfill surface, so purposefully retained stormwater must be managed in a manner that does not compromise site operating requirements or permit conditions.

6.2.4 Wastewater and Spent Aqueous Products

Some landfill operators have pursued the disposal of industrial wastewaters or other spent aqueous products. At the Outer Loop landfill (see Chap. 4), for example, operators disposed of beverage waste, oily wastewater, paint waste, ink water, and other industrial wastewaters (US EPA 2006). Such liquid wastes would otherwise require treatment and disposal at a domestic or industrial wastewater treatment facility, often at considerable expense. By accepting such wastes for disposal, landfill operators can provide supplemental moisture while adding a revenue source. As stated previously the operator may need to obtain special regulatory permission, as this practice could be restricted under normal circumstances.

Industrial wastewater or spent aqueous products would typically be hauled directly to the landfill in a tanker truck and discharged to a designated disposal area. Surface application techniques such as those described in Chap. 7 would be most common. Concerns discussed in this chapter and others regarding proper leachate containment will be magnified when outside liquids are disposed. While subsurface techniques such as those described in Chaps. 8 and 9 might be feasible if appropriate liquids unloading and conveyance infrastructure is available, the operator should be cautious when adding liquids with high solids content that might clog or otherwise limit future liquids addition.

Tolaymat et al. (2004) reviewed the factors that should be considered prior to addition of industrial wastewater or similar liquid wastes. For example, liquid pH and its impact on microbial activity should be assessed. Extremes in pH, particularly low pH, might require neutralization prior to disposal. Tolaymat et al. (2004) suggested conducting limited field tests to determine the ability of the waste to buffer added liquid and to distribute the liquids over large areas to limit possible harmful effects.

Elevated concentrations of chemical constituents (salts, heavy metals, organic pollutants) have the potential to be toxic to the landfill biota responsible for carrying out the waste stabilization process. While MSW has an ability to attenuate and transform many trace pollutants (Reinhart and Pohland 1991; Pohland et al. 1992), the operator should carefully consider the chemical composition of a new liquid waste prior to disposal. Some useful toxicity information might be available from the existing literature, but specific anaerobic toxicity testing may also be warranted. The BMP assay, for example, was developed in part as an anaerobic toxicity test (Owen et al. 1979); this methodology is discussed in greater detail in Chap. 16.

Industrial wastewater and similar supplemental liquids with high organic matter content may provide a potential substrate for the production of methane as a result of anaerobic decomposition, but as described in Chap. 2, anaerobic biological systems consist of multiple biotic groups and are subject to upset if the system becomes unbalanced. If a liquid waste has a large concentration of rapidly fermentable organic compounds, this may result in rapid acid buildup, which in turn, suppresses methanogenic activity. Similar to concerns with trace chemicals or salts, specific tests such as the BMP should be considered as a screening technique, at least for the first time a candidate liquid waste is proposed. Ko et al. (2012) used the BMP assay to assess the potential effect (toxicity and methane yield) of three industrial liquids (fishery, dairy, and brewery wastewaters) when added to landfills.

6.2.5 Wet Wastes and Biosolids

Several solid waste streams have inherently high moisture contents. Examples include wastewater sludge and food processing waste. While some operators are reluctant to accept such sources (because of operational and nuisance issues described below), in a similar manner as industrial liquids, receipt of wet wastes offers a source of supplemental moisture and potential revenue. In some cases, certain wet wastes such as biosolids may be accepted as a service to a local utility department, and sometimes may be part of a negotiated deal to accept some or all of the landfill's leachate at the utility's wastewater treatment plant. Similar to the other moisture sources discussed already, special regulatory permission may be required if the waste falls outside the bounds of allowable wastes for disposal.

Domestic wastewater sludge (biosolids) is perhaps the most commonly proposed wet waste added to landfills; it is a waste stream generated in relatively large magnitudes in most developed nations. While biosolids are commonly applied to agriculture, forest, mined land, or disposed offshore in the ocean, these practices are facing growing opposition and restrictions. When disposed in landfills, biosolids present a source of moisture, methane potential, and nutrients. Many of the early studies exploring potential sustainable landfill technologies (see Chap. 4) examined the addition of wastewater sludge as a means of enhancing waste stabilization and increasing gas production (EMCON Associates 1975; Pohland 1980; Buivid et al. 1981). In a sludge digester at a wastewater treatment facility, the solids content of biosolids will be on the order of 0.5–2 % (98–99.5 % moisture). Dewatering will often be practiced prior to disposal to reduce transportation and disposal costs. As previously described, to pass the paint filter test, domestic biosolids need to be dewatered to 15–20 % solids content (80–85 % moisture).

The reluctance of many landfill operators to accept biosolids for routine disposal stems from operational difficulties, odors, and health and safety concerns. Biosolids possess a strong and often offensive odor, which coupled with the propensity of this waste stream to attract flies and other disease vectors, and the possible health risks resulting from pathogenic organisms, demand that disposed biosolids be covered relatively quickly to minimize concerns to landfill personnel, customers, and the surrounding community. When disposed at a landfill, biosolids will normally be transported using a dump truck or similar vehicle (Fig. 6.3). Since this waste stream

Fig. 6.3 A truck load of biosolids unloaded at the working face of a landfill

is so wet and has little or no strength in this form, biosolids cannot be moved and compacted in the same manner as MSW. Biosolids adhere to the tracks of dozers and the cleats of compactors, and the equipment may become stuck or sink into the working surface, thus making waste compaction a laborious process. Unless mixed with other waste, the presence of biosolids may hinder compaction efforts and result in lower compaction densities. Wet biosolids create an extremely slick working surface, making it very hard for waste spotters and other landfill personnel to walk on it. Longer-term operational issues derive from the differential settlement or soft spots that might occur when biosolids are buried without mixing with other wastes, and possible slope stability concerns if the biosolids are placed in continuous layers near the side slopes of the landfill. Methods that operators have successfully used for disposing of biosolids are reviewed in a later part of this chapter.

6.3 Moisture Addition Targets

6.3.1 Establishing Moisture Addition Requirements

Once an objective of increasing the MSW moisture content has been established and available moisture sources have been identified, the designer can proceed with estimating the targeted amount of moisture to add to the landfill. As described in Chap. 4, multiple laboratory, pilot-scale, and full-scale studies have confirmed that elevating the moisture content of MSW from the original relatively dry conditions enhances the rate of waste stabilization. Additionally, the movement of moisture through the landfilled waste serves to transport micro-organisms, substrates, nutrients, and waste products throughout the landfill. Although some researchers recommend a specific moisture content desirable to optimize waste stabilization (e.g., Guijara and Suflita (1993) reported that at least 50 % moisture content would result in optimal methanogenesis), selection of a target moisture content for a full-scale operation based on optimized smaller-scale studies is generally not practical. First, the achievable moisture content of waste is very much related to the specific weight of the waste (see Chap. 5). Second, waste stabilization will likely be optimal under saturated or near-saturated conditions where liquids are moving relatively rapidly, a condition that is not feasible (and questionably safe) for full-scale landfill operations.

In lieu of selecting a target moisture content needed to achieve optimal waste stabilization, a common practice in the design of bioreactor or similar landfills is to target the introduction of at least enough moisture to reach landfilled waste field capacity. The field capacity concept was described in Chap. 5; in theory, all liquids added to increase the moisture content to field capacity would be absorbed by the waste, rather than leaving the landfill as leachate. In reality, because of the fundamental processes governing fluid flow in porous media, there is no way to bring all waste to field capacity without first bringing some of the waste to moisture levels greater than field capacity (including some at saturation), and then letting the liquids drain by gravity. Thus targeting field capacity as the desired moisture content is not a necessary outcome for success of the system, but rather a means to provide a realistic target for moisture addition for design purposes.

Chapter 5 provided measured data from several studies reporting the initial moisture content of landfill disposed waste; the reported moisture content depends upon composition and local climate, and the designer should gather information specific to the site being planned. Similarly, previous measured data for field capacity were presented; a very notable observation from these data is the strong relationship between field capacity and waste specific weight. Tolaymat et al. (2013) present a recommended approach for determining a target liquid addition volume to achieve field capacity (or other desired target moisture content) for a given waste. For waste with an initial moisture content of MC_i (% wet weight) and a target moisture content of MC_t (% wet weight), the volume of moisture required to bring per a unit mass of waste to the target value (V_r) may be determined from (6.1):

$$V_r = \frac{MC_t - MC_i}{100 - MC_t} C \tag{6.1}$$

Where C is a conversion factor for which C = 1,000 L/Mg for metric units and 239.8 gal/ton for customary units. Figure 6.4 presents a plot of V_r as a function of MC_i and MC_t.

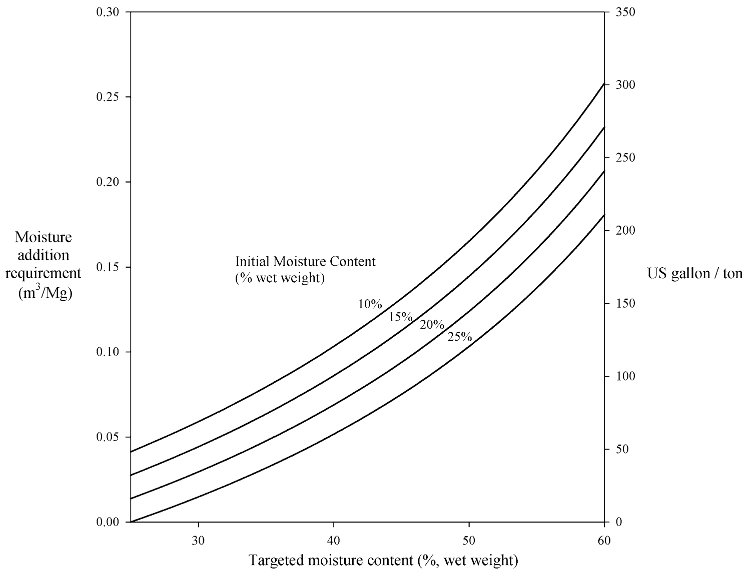

Fig. 6.4 Graphic representation of V_r as a function of MC_i and MCr

The addition of wet waste (e.g., biosolids) would also increase the overall moisture content of the landfill. The mass of wet waste ($M_{wet\ waste}$) required per mass of MSW (M_{msw}) required to reach a target moisture content (MC_{target}) may be determined using (6.2):

$$\frac{M_{wet\ waste}}{M_{msw}} = \frac{MC_{target} - MC_{msw}}{MC_{wet\ waste} - MC_{target}} \tag{6.2}$$

Where MC_{msw} is the moisture content (% wet weight) of the MSW and $MC_{wet\ waste}$ is the moisture content (% wet weight) of the wet waste.

6.3.2 Determining Moisture Addition Rates

In the case of liquids addition, when a target moisture addition volume has been determined and an estimate of the total mass of waste to be wetted is known, the total target liquid volume to be added to the landfill can be calculated. In this section, moisture addition rates are discussed on a longer scale (e.g., monthly, yearly) and for the entire landfill. In the following three chapters, liquid addition rates achievable for individual liquids addition devices are discussed. Prior to the detailed design, however, the engineer must develop a target liquid addition rate.

A specification of flow rate (volume that should be added over a given duration) is necessary for the detailed design of a liquids introduction system and for developing an operation plan for the system. Several factors affect the rate at which liquids should be or can be added, including available liquids volumes, the ability of the waste to accept the liquids, the desired time to operate the system, impacts on the leachate collection system, and operational and safety considerations (e.g., slope stability, seepage).

The time available for system operation has a direct impact on the liquids introduction rate. The liquids addition system is generally operated during the working hours of the landfill staff. The system will also be shut down occasionally for maintenance and may be prevented from operating during heavy rainfall events or other inclement weather. The total system operation time also depends on the manner in which a system is constructed. A liquids addition system constructed as the waste is placed (often referred to as an as-built system) has a greater potential window of operation compared to a landfill where the liquids addition system is not constructed until after waste placement is complete (often referred to as a retrofit system).

The impact of added liquids on the LCRS and the liner also play a major role with respect to establishing the liquids addition rate. As discussed in Chap. 2, regulatory design requirements often limit the depth of leachate ponded on top of the bottom liner. Chapter 10 provides guidance on how to integrate liquids addition rate into the LCRS design and performance. While as-built operations with a LCRS designed to handle liquids addition may not be limited by LCRS performance, retrofit sites where the LCRS was not designed with liquids addition design in mind may require wetting to be conducted over a longer period of time (i.e., at a lower rate) to reach desired addition targets.

Even though an engineer may select a desired liquids addition rate, such a rate might not be achievable within the constraints placed as a result of other considerations (e.g., construction techniques, costs). As described in Chap. 5, compacted solid waste has a relatively low permeability, especially deep in the landfill. The distribution of desired moisture volumes into the landfill over a specified time interval may thus require a large number of devices or operational pressures. Both of these factors have an impact on system cost and operational complexity. In addition, other concerns with regard to leachate seepage (Chap. 11), slope stability (Chap. 12), and impact on gas system performance (Chap. 13) may limit an operator's ability to achieve target addition rates.

6.4 Conveyance Systems for Liquids Addition

An important component of the design of a liquids addition system is the infrastructure (pumps, pipes, valves, controls) to convey leachate (and other liquids) from the liquids storage units to the targeted landfill areas or addition devices. Some landfill operators utilize tanker trucks to haul liquids to the landfill, although this is most common with surface application systems (Chap. 7). Operations of greater complexity that involve multiple wells or buried conduits require design and construction of a mechanical pumping system. The design of a pumped conveyance system will in general be similar to pumping systems for the conveyance of water and wastewater. The rest of this section addresses several design- and operational-related issues specific to landfill liquids addition, including pumping system options, necessary valves and controls, considerations for gravity-controlled systems, and incorporating expected performance of buried devices into pressurized system design.

Most bioreactor landfill operators pump liquids directly from existing leachate storage devices such as tanks and ponds. In some cases the pumping system will be the same as the one used for discharging leachate off-site (or to other leachate management options), while some sites utilize dedicated pumping stations for liquids addition. Another approach may include storing leachate temporarily in portable storage devices (referred to as backer frac tanks) and pumping from these storage containers. Using a tank as the source of added liquids ensures that sufficient liquid volume will be available for addition during desired operational periods (e.g., operation hours of the landfill). The pumping system can be designed to meet the specific operating conditions of the liquids addition system. The leachate storage units also provide a good place to consolidate and mix other moisture sources prior to addition. One drawback to this approach is that because additional pumps and controls are required, the storage system may be a some distance (relative to pumping from a leachate sump corresponding to the cell that added liquids) from the landfill, necessitating additional piping and energy is required to deliver the liquids back to the landfill from which they originated.

An alternative approach is to utilize the landfill's existing pumping system for removing leachate (part of the LCRS) as the means to introduce liquids back to the landfill. In this case, as leachate is pumped from the landfill, the leachate (or some fraction of it) will be diverted back into the landfill as opposed to the storage system. Benefits of this approach may include reducing pumping energy demand and infrastructure costs. In this approach, the pumping system may not be optimal for the flow rate or pressures desired for liquids addition. This approach may offer less control than pumping from a large storage unit, as the storage volume associated with the LCRS will in most cases is much smaller than the external leachate storage system. Thus, the rate of liquids addition will be dictated by leachate generation and the operation of the LCRS; pumping may occur intermittently operation throughout the day, including non-operational hours.

Another consideration is whether the pumping system will be gravity or pressure controlled. These two systems are conceptually illustrated in Fig. 6.5. Addition systems that are pressure controlled use the pressure of the pumping system as the driving force for introducing liquids into the landfill. This would be case where liquids are pumped directly into horizontal trenches (Townsend and Miller 1998) or blankets (Khire and Haydar 2005). In the case of vertical wells, liquids are most commonly discharged into the well openings at atmospheric pressure, although

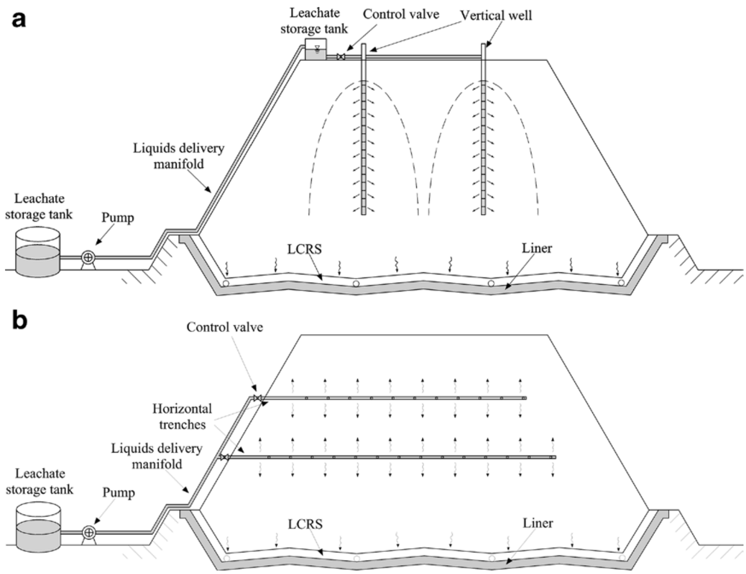

Fig. 6.5 Schematic of two different pumping systems in bioreactor landfills (**a**) gravity feed system, and (**b**) pressurized pumping system

pressurized injection into vertical wells has been attempted (Kadambala et al. 2014). In the case of a pressure-controlled approach, the pumping system provides not only the pressure to deliver the liquids to the source, but also enough to achieve the desired design injection pressure.

In a gravity-controlled system, liquids are delivered to a target source and discharged to an open atmosphere at the surface of or within the landfill. Examples include surface application (such as spray irrigation), ponds, or a vertical well where a free water surface exists (no pressure beyond the depth of water column is applied). The main goal of a gravity-controlled system is to deliver sufficient volume of liquids either directly to the landfill surface or to a secondary storage system. Controlling the flow rate is a common issue in gravity-controlled systems and may require manual labor to control or add a sufficient flow rate while avoiding a condition where the liquid surface rises above the waste surface. Certain mechanical and/or electrical controls can be installed to reduce manual labor associated with operating the system. For example, a water level sensor can trigger a control valve once the water level is below or above a desired level. Another approach that has proven successful is placing a storage tank on top of a landfill, as shown in Fig. 6.6. With this approach, liquids are first delivered to the storage tank by a pump system and then discharged into the waste by control valves; in this case, lower flow rates are easier to regulate.

Fig. 6.6 Tank container chassis used for the storage and gravity discharge of leachate to a liquids distribution system on top of a landfill

The type of pump system selected will be dictated in part by the degree of control and automation desired. Centrifugal wastewater pumps, such as those commonly used as part of most LCRS can be specified, but their control may be limited relative to other pump types less commonly used for leachate, such as positive displacement pumps. In addition to specifying on-off conditions (which can be accomplished for any pump type), some designers may wish to control injection pressures, and for landfills where pressurized liquids are added at different elevations, such control might be more easily accomplished with positive displacement or similar pumps. Smooth-walled plastic pipe is commonly used for pressurized leachate force mains at landfills, although some regulatory jurisdictions may require double-walled pipe when placed outside the lined landfill unit. Depending on the degree of control desired (Chaps. 8 and 9) and the specific data to be monitored and recorded (Chap. 16), the piping system can be equipped with meters or sensors for measuring flow rate, cumulative fluid flow, and pressure. Figure 6.7 shows a hydrant system used to distribute pressurized liquids to individual horizontal liquids addition trenches at a North American site; pressure measurements in the force main were integrated into the pumping system's control logic so valves could be actuated shut when target pressures were reached.

Chapters 7, 8, and 9 provide more information on the individual liquids addition devices that might be employed. The devices will be connected to the liquids conveyance system by either direct pipe connection or with a flexible hose. Flexible hoses have the advantage of accommodating differential settlement if this is a concern. Figure 6.8 shows the point where liquids are conveyed from a pressurized

Fig. 6.7 Hydrant system for delivering liquids to specific addition devices in a landfill

Fig. 6.8 Connection of liquids addition manifold to surface trench

force main to a shallow surface trench (described further in Chap. 6). In this example, the trench was also connected to the landfill's GCCS, and appropriate valves (and pressure monitoring devices) were provided to isolate liquids addition from gas extraction. The opportunities and challenges associated with combining liquids addition and gas extraction from trenches, wells and similar devices are discussed in Chap. 13.

The pumping system design for the liquids conveyance system will follow standard procedures used for water and wastewater. A system curve that plots the system pressure as a function of flow rate from the entrance to the exit of the conveyance system will be developed and compared to candidate pump curves. The following equation portrays a typical system curve:

$$P_h = (Z_2 - Z_1) + (P_2 - P_1) + \frac{V_2^2 - V_1^2}{2g} + h_{L,minor} + h_{L,friction} \tag{6.3}$$

$$\frac{V_2^2 - V_1^2}{2g} \tag{6.4}$$

where, V = velocity head (L); Z = elevation head (L); *Pi* = pressure head (L); $h_{L,friction}$ = head loss due to friction (L); $h_{L,minor}$ = head loss due to local disturbances of flow (e.g., valves, bends, and couplings) (L). The friction loss term ($h_{L,friction}$), which accounts for the pressure loss as liquids flow through the pipe, can be estimated using several approaches, such as the Darcy-Weisbach Equation, which is presented as (6.5):

$$h_{L,friction} = \frac{8fLQ^2}{\pi^2 g D^2} \tag{6.5}$$

where L = the length of the pipe section (L); D = the pipe diameter (L); g = the gravity constant (L T^{-2}); Q = the flow rate (L^3 T^{-1}); and f = the dimensionless friction factor and is a function of the Reynolds number (Re) and relative roughness (e/D). The minor loss, $h_{L,minor}$, results from in-line fittings, changes in direction, and changes in flow area. It is usually calculated using the method of loss coefficients. Each fitting has a loss coefficient, K_{minor}, associated with it. The minor loss is obtained by multiplying the loss coefficient by velocity head:

$$h_{L,minor} = \sum K_{minor} \cdot \frac{V^2}{2g} \tag{6.6}$$

A system curve can be created using (6.3), and then used to select an appropriate pump. The operation point is determined by plotting the system curve and a manufacturer's pump curve.

In the case of gravity-controlled liquids addition systems, the starting point of the system curve would be the liquid elevation in the storage unit, and the ending point would be the point where pressurized liquids are discharged at atmospheric pressure at the liquid addition device (e.g., the point where liquids are discharged into a pond or a vertical well). In the case of pressure-controlled liquids addition systems, the ending point is the pressurized device itself. This can be accomplished by treating the elevation of the liquids addition device entrance as Z_2, and including a term Q/κ, such that:

$$P_h = \Delta Z + \frac{Q}{\kappa} + \frac{V_2^2}{2g} + h_{L,minor} + h_{L,\text{friction}} \tag{6.7}$$

where κ is the fluid conductance of the device. The fluid conductance relates flow rate to pressure; this concept will be discussed with respect to vertical and horizontal liquids addition devices in Chaps. 8 and 9, respectively.

6.5 Addition of Wet Wastes

Many operators are reluctant to accept biosolids for disposal because of the issues described earlier (workability, operational issues, odors, and health and safety concerns). Since operators cannot move or compact wet wastes in the same manner as MSW, a variety of techniques may be utilized to bury these wastes. Some procedures involve burying the biosolids in depressions excavated on or near the working face. This practice, however, can result in soft spots or differential settlement. Other techniques therefore focus on mixing the biosolids with the waste or other materials. Reinhart et al. (2007) evaluated biosolids disposal techniques at MSW landfills, and a summary of typical operational techniques is presented in Table 6.1. In most cases, these practices would be applicable for similar wet wastes.

When increasing the moisture content of the solid waste is a primary objective, mixing the biosolids (or other wet waste) with the MSW is the preferred option. Figure 6.9 displays mixing of biosolids with MSW by pushing a load of MSW on to of a layer of biosolids; this would be followed by making several passes over the waste with a compactor, with an end result being the mixing of the two materials. Mixing wet and dry waste with available landfill equipment also can also be used achieve this outcome. Operators can also mix wet waste with other materials, such as mulch or soil, to improve workability; this may limit some moisture distribution to MSW, however.

Table 6.1 Techniques for biosolids disposal at MSW landfills (from Reinhart et al. 2007)

Method	Description
Direct unloading and mixing with waste loads	The landfill operator practicing co-disposal of biosolids with MSW would direct the biosolids truck directly to the landfill's working face, where biosolids are unloaded and disposed of with loads of MSW. This method requires more coordination of landfilling operations to ensure that there are a couple of new loads of MSW set aside for the incoming loads of biosolids. Spreading biosolids in thin layers on the working face and covering with MSW is another option. This method is similar to the MSW co-disposal method discussed before in that biosolids are disposed of directly on the landfill's working face. However, the biosolids are handled separately with the blade of the bulldozer by spreading them in a thin layer over the surface of the landfill and then covering this layer with regular MSW before compacting
Pit or trench burial of biosolids	Pit (trench) burial of biosolids involves more site preparation and equipment requirements than others because of the need to dig the pit or trench into the waste before the biosolids are unloaded into the landfill. Some landfill operators might prefer this method since it minimizes the need for handling the biosolids. One of the disadvantages of this method is the potential creation of soft spots on the surface of the landfill where the biosolids have been placed
Mixing biosolids with other materials prior to disposal or use as cover material	The mixing with additives technique includes mixing biosolids with MSW, yard waste, mulch or mulch fines, or soil. One of the main advantages of this disposal method is that it provides a more workable material than biosolids alone. However, this method requires a separate area of the landfill to be cleared and designated for the mixing process
	Another method is to mix biosolids with additives using a predetermined ratio, as discussed in the previous method, and used as daily cover It should be noted that the use of materials other than site soils dirt for daily cover may require regulatory approval

Fig. 6.9 MSW pushed on top of biosolids at the working face of landfill

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Chapter 7
Systems for Surface Addition of Liquids

Abstract One of the earliest forms of liquids addition practiced by landfill operators was surface addition. Techniques include: direct wetting of the waste, spray or drip irrigation, and ponding. In contract to subsurface liquid addition systems, construction requirements for surface systems are minimal. Care must be taken to ensure that liquids do not migrate outside of the controlled landfill area. The different configurations of surface systems are presented and discussed, along with design approaches that can be used to identify liquids addition amounts in light of the site's moisture addition goals.

Keywords Landfill • Leachate • Surface • Irrigation • Pond • Trench • Recirculation • Bioreactor

7.1 Surface System Fundamentals

Surface systems involve adding liquids to the surface of the landfill, either directly to uncovered waste or to a layer of high-permeability drainage media on top of the waste. The liquids migrate downward into the landfilled waste under the influence of gravity and capillary (suction) forces, although some liquids may be lost as a result of evaporation (and possibly transpiration). Surface systems are often selected because of their relative simplicity with respect to construction and operation. Unlike subsurface systems, surface systems can normally be constructed with existing or readily available equipment and supplies. Surface systems have been widely utilized at landfill sites where the primary goal was leachate management via recirculation as opposed to control of biological reactions (Barber and Maris 1984), and were often an early method employed at landfill sites that later evolved to using more elaborate subsurface techniques (Watson 1987; Townsend et al. 1995; Mehta et al. 2002).

While surface systems provide a cost-effective and relatively easy-to-construct methodology for introducing liquids, this approach presents several potential concerns and limitations. From an environmental, human health, and aesthetic perspective, these systems often result in an increased potential for leachate exposure. Exposure of workers to airborne leachate, odor from leachate, and increased opportunities for contamination of stormwater are all issues that must be assessed as part

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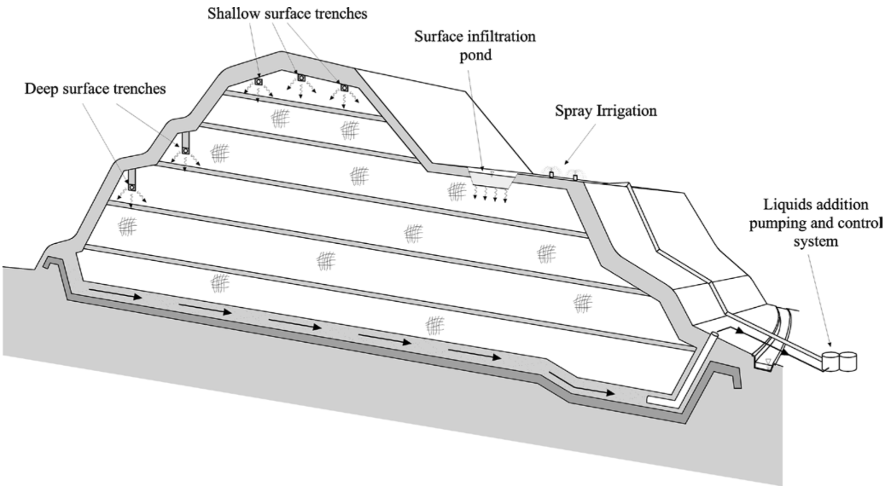

Fig. 7.1 Illustration of surface liquids addition techniques

of planning, design, permitting, construction, and operation. From a performance perspective, adding liquids to the surface with gravity as the primary driving force poses significant limitations with respect to introduction of moisture to deeper areas of the landfill within a reasonable timeframe, and such systems add greatly to the challenge of gas collection and control especially when the gas control system infrastructure consists of vertical wells. While many of these concerns have led landfill operators pursuing sustainable operation to move toward subsurface systems, surface application remains a commonly-employed technology for many facilities.

Methods for surface application at open, operating landfills include direct wetting of the working face, spray or drip irrigation, infiltration ponds, and infiltration trenches (conceptually illustrated in Fig. 7.1). Surface application techniques are most often employed at landfills that are open (i.e., an engineering cap has yet to be constructed), but in some cases liquids have been introduced to the surface of the waste using trenches, leach fields, or drip lines underneath the cap. The remainder of this chapter provides a discussion of the common surface application techniques and their design.

7.2 Surface System Configuration

7.2.1 Tanker Truck Application

Direct application at the working face typically involves a water tanker truck that carries leachate to the working face and then discharges the leachate by a hose, rear-mounted spray bar, or spray nozzle to the waste before the application of daily/intermediate cover. Since many landfills are already equipped with water trucks for

Fig. 7.2 Spray application of leachate at the landfill surface using a tanker truck (Photo courtesy of John Schert)

dust control, this method of surface application is often the most familiar and direct method for a landfill operator to implement. Figure 7.2 shows the process of liquids application on the landfill's active face via tanker truck application using a front-mounted spray nozzle.

As with many surface liquid addition techniques, when the primary objective is to increase moisture content of the waste, tanker truck application is typically limited to recently-deposited waste that has not yet been covered with soil. While some evaporation will occur, addition directly to the waste promotes retention of moisture within the landfill and limits potential for leachate runoff from the desired application area. Some operators construct temporary berms of soil around the application area to minimize leachate run-off to side slopes and other areas that are not targeted for leachate recirculation. Liquids distribution from the truck using the rear spray bar may be feasible, but only if the truck has access to the application area; if newly-deposited waste is the target, access by the water truck may be limited. Thus, although use of the truck's spray nozzle is often more practicable, this method requires more operator control, but allows for better liquids distribution. An alternative is to introduce the liquids using a hose connected from the truck to the waste, but since this does not provide as efficient distribution, controls to prevent migration from the application area are important (e.g., soil berms).

Direct application of liquids to the waste using a water truck can result in effective moisture distribution in the areas where it is applied, and may aid in waste compaction. As with many of the surface techniques, application is limited to periods of dry weather to minimize potential mixing with stormwater and off-site migration. Possible concerns to landfill operators include exposure to aerosols from leachate that is sprayed, additional odors that may result from the leachate, and the wet conditions of the working area.

7.2.2 Spray Application

The spray irrigation of vegetated land as a means of managing both raw and treated leachate has been practiced at landfills around the world (Gordaon et al. 1988; McBride et al. 1989a, b). This practice has been extended to leachate application on the landfill surface, both on closed areas where soil and grass cover the waste, and directly on the waste prior to placement of cover soil. Spray application was one of the first reported methods for leachate recirculation at landfills. For many operators utilizing spray irrigation, a primary objective is reduction of leachate volume through evaporation and transpiration.

Spray irrigation systems for large grassed areas at landfills utilize standard irrigation equipment; issues with reduced spray head performance due to biological or mineral clogging may necessitate frequent maintenance and repair. The primary concern for application to covered landfilled areas is limiting the application rate so that leachate mitigation outside the landfill area does not occur. This typically limits application during dry weather conditions to rates that do not exceed the liquids removal through evapotranspiration and infiltration into the landfill. Application during wet weather will normally be prohibited concerns over potential stormwater impacts often pose a regulatory hurdle.

Landfill operators also use spray irrigation to introduce liquids to uncovered waste prior to placement of the cover soil. This is accomplished using portable spray heads that can be moved around the landfill as the disposal area progresses. Figure 7.3 shows a spray irrigation system for leachate on the working face of an

Fig. 7.3 Spray irrigation at the landfill surface prior to cover soil placement using portable spray heads

active landfill; standard irrigation equipment was used. Similar to issues faced with direct wetting using tanker trucks, control of liquids migration from the waste must be considered, and may require the use of soil berms at strategic locations around the active disposal area.

Potential worker and customer exposure to airborne leachate represents a commonly-voiced concern with leachate spray irrigation systems. Gray et al. (2005) modeled potential exposure of landfill workers from spray irrigation of leachate. Based on results from conservative worst-case exposures, they concluded that the risk posed to landfill workers exposed to several trace organic chemicals was minimal. Given the variable nature of leachate quality from one landfill to another, however, a site-specific assessment may be advisable if this technique is to be employed.

7.2.3 Drip Irrigation

Similar to spray application, drip irrigation, if properly designed, can provide relatively uniform liquids distribution at the surface of the landfill. Drip irrigation does not pose the same problems with aerosol dispersion as spray application. Two general drip irrigation configurations include fixed and portable systems. Fixed systems utilize a permanent or semi-permanent pipe or tubing configuration that is placed on the surface of a covered landfill, or more commonly, embedded within soil above the waste. Orifices in the pipe or tubing are sized and spaced to optimize liquids distribution when liquids are added under pressure; the drip lines are at times placed within a bed or trench of gravel or similar permeable medium to optimize distribution.

Portable systems are used for drip irrigation directly to waste after deposition but prior to placement of cover material. Perforated pipes, hoses or tubing are dragged into place by hand or using landfill equipment and connected either to a force main or to a tanker truck. Liquids are added to the waste and the system is moved within the targeted waste area as necessary to provide needed distribution and capacity. Figure 7.4 shows a surface drip system consisting of perforated HDPE pipe on top of the landfill surface. Periodic monitoring and controls to prevent migration from the application area, such as soil berms, are important.

Although leachate aerosol concerns are not present with drip irrigation systems, migration of leachate outside the landfill area and subsequent impacts to stormwater must be evaluated. Selecting an appropriate rate of application is important, as the rate of liquids infiltration into compacted waste will be less than infiltration rates associated with most soils. From an operational perspective, drip irrigation orifices may require periodic cleaning and maintenance because of clogging from the leachate.

Fig. 7.4 Drip irrigation piping for liquids distribution at the landfill surface (Photo Courtesy of Waste Management Inc.)

7.2.4 Surface Ponding

Surface ponding involves the use of infiltration ponds, lagoons, or pits at the surface of the landfill. Liquids are hauled by truck or pumped directly to the ponds, where liquids added at an amount that standing liquids levels develop. Because of the simplicity in construction and operation, surface ponding was one of the first methods of leachate recirculation used at many landfills. Ponds provide storage capacity for liquids that permit moisture infiltration into the landfill even when liquids are not actively added. The standing liquids also provide additional driving force to enhance the rate of liquids addition into the landfill.

Surface ponds have been constructed in several different manners. In some cases, a surface layer of waste is excavated and re-compacted to construct perimeter berms around the excavated area to provide for greater storage capacity (Townsend et al. 1995). Alternatively, a perimeter berm of low permeability soil can be constructed on the existing landfill surface to form the pond (Warith 2002), or incoming waste can be compacted in place to form the pond perimeter. Ponds that are excavated into the waste must be lined with a permeable media (e.g., rock, sand) to prevent waste from floating (which over periods of prolonged operation can still be a problem even if the pond bottoms are covered). If berms are used, they should consist of low-permeability soils to keep leachate from seeping through the walls. To optimize liquids distribution, pond locations should be staggered and moved.

Fig. 7.5 Leachate infiltration pond at the landfill surface

Townsend et al. (1995) reported on the operation and hydraulic performance of an infiltration pond system constructed on the surface of a MSW landfill in Florida over a period of 28 months (see Fig. 7.5). In this study, a total of 36,470 m^3 (9.6 million gallons) of leachate was recirculated using a system of four infiltration ponds. The rate of application was found to be limited by the permeability of compacted waste, and although some permeability reduction of the soils lining the pond occurred, the reduced soil permeability was still greater than the compacted waste. This system was found to provide an effective method for increasing moisture in the waste underneath the ponds (Townsend et al. 1996), ultimately leading to enhanced waste stabilization (Kim and Townsend 2012). Among the lessons learned from this site were that caution must be taken during the rainy season as large storms may result in pond overflowing and that prolonged periods of operation can lead to floating waste (an issue because of aesthetic and regulatory compliance concerns).

Some operators have used surface ponding methods that were either covered (e.g., by an inverted waste container such as a roll-off box) or where the pond was filled with a permeable media material (such as a leach bed used for wastewater discharge to the environment). For example, Mehta et al. (2002) used a system of shallow excavations filled with tire chips to recirculate leachate into a landfill in California. An analogous surface ponding system where a leach bed was placed under a landfill cap or cover system would have the same issues as those described for covered surface trenches (see below). Leach beds covered with additional waste are characterized as a sub-surface system and are thus described in Chap. 9 (horizontal blankets or galleries).

7.2.5 Surface Trenches

Surface trenches represent a liquids introduction technique which relies on the use of excavated trenches on the surface of the landfill to distribute liquids into the upper layers of the waste mass. A liquids distribution pipe would typically be placed in the trench and the trench would be backfilled with a permeable protective media (e.g., stone, shredded tires). Unlike ponds, the trenches are normally covered with soil so that the liquid surface is not visible at the surface of the landfill. To prevent soil from migrating into the trench and filling in voids of the permeable media, a geotextile will normally be placed above the bedding material prior to placement of soil. Liquids are added to trenches using a pipe manifold or tanker truck through vertical access pipes that connect the surface of the landfill to the buried pipe or bedding media.

Reported trench depths used at landfills range in depth from 1 to 4.5 m (3–15 ft) into the waste, depending on the excavator's reach. The width of the trench is often the same as that of the excavator bucket, with 1–1.7 m (3–5 ft) being a typical range. Two approaches used for surface trench liquids addition are distinguished here as shallow trenches and deep trenches. Shallow trenches are excavated into the top layer (approximately 1 m) of the waste and covered with soil. This approach offers the advantage of a relatively simple construction procedure. The rate of liquids application will be limited by the maximum depth of liquids that can be safely ponded without exiting the trench and causing leachate migration issues. Figure 7.6 shows a shallow surface trench system under construction. In this system, perforated HDPE pipe surrounded by whole tires was covered by a geotextile and then by compacted soil. Trenches excavated then ultimately buried within the waste (e.g., subsurface horizontal systems; see Chap. 9) are most often constructed as shallow trenches.

Fig. 7.6 Installation of liquids addition trench at the surface of a landfill

Fig. 7.7 Deep surface trench for recirculation of liquids (Photo courtesy of Waste Management Inc.)

Deep trenches are still excavated at the surface of the landfill, but they can extend into the landfill to depths of 4–5 m or more. Bedding media and pipe are placed in the bottom of the trench, but the remaining trench volume is backfilled with compacted waste (a geotextile might be used to separate the bedding media from the waste, but this is less common in deep systems). Each completed trench is covered with soil and an appropriate inlet pipe for liquids addition provided. Figure 7.7 illustrates the construction of a deep trench used for surface application of liquids. The use of deeper trenches allows a greater volume of liquids to be stored in the trench, and the greater depth (as well as the backfilled waste) offers the operator the potential to add liquids under some degree of pressure. Depending on the depth of the trench from the surface, short-circuiting of leachate back to the surface may be a problem if enough waste is not added on top of the trench. With respect to design, deeper surface trenches operated under pressure are more appropriately designed following the subsurface techniques described in Chap. 9.

7.3 Design Methodology

The primary design variables associated with the sizing of a surface liquids application system include the target liquid addition volume, the application time, and the application rate. Considerations for selecting the target addition volume were discussed in Chap. 6. The duration of application will be dictated by the target volume and addition rate, as well as other site-specific constraints such as waste filling rates, precipitation amounts and frequency, and stormwater control methods. Given that the primary driver for liquids infiltration into the landfill will be gravity, the rate of surface liquids addition is largely controlled by the hydraulic conductivity of the waste, the area of the application, and the depth of liquids ponded on the surface of the waste. Other design elements (e.g., pumping and storage systems, stormwater control infrastructure) are described elsewhere in the book.

7.3.1 Direct Wetting, Spray and Drip Irrigation

When designing a system to apply liquids directly to the waste surface by spraying (or similar application techniques), the application rate should not result in any excessive ponding or migration from the application zone. The designer could use software that models unsaturated flow (see Chap. 5); the surface application of liquids where the liquids are not ponded above the waste would likely be an unsaturated flow case. A simple approach, however, is to specify an application rate, q, equal to the vertical saturated hydraulic conductivity (K_Z) at the surface of the landfill. At a unit gradient ($i = 1$), the liquid infiltration rate per unit landfill surface area into the landfill (L/T or L^3/L^2 T) would be equal to K_Z as shown in (7.1).

$$q = K_Z i = K_Z \tag{7.1}$$

Table 7.1 presents a range of unit gradient infiltration rates for various K_Z values representative of what is typically reported in the literature. As described in Chap. 5, vertical hydraulic conductivity of compacted waste is greatest at the surface of the landfill where it is exposed to the least overburden pressure.

Table 7.1 Unit gradient infiltration rates at different vertical hydraulic conductivities

Hydraulic conductivity	Infiltration rate at unit gradient		
$\left(\frac{\text{cm}}{\text{s}}\right)$	$\left(\frac{\text{m}}{\text{day}}\right)$	$\left(\frac{\text{m}^3}{\text{hectare} - \text{day}}\right)$	$\left(\frac{\text{gal}}{\text{acre} - \text{day}}\right)$
5×10^{-4}	0.432	4,320	469,000
1×10^{-4}	0.0864	864	93,900
5×10^{-5}	0.0432	432	46,900
1×10^{-5}	0.00864	86.4	9,390
5×10^{-6}	0.00432	43.2	4,690
1×10^{-6}	0.000864	8.64	939

The design engineer may wish to factor in evaporative losses when calculating an expected achievable application rate for a spray irrigation system. As spray irrigation of wastewater effluent is a common practice, design manuals for these systems can provide guidance for spray field configuration and application rates that include evaporation and transpiration (US Environmental Protection Agency 2006). Evaporative losses from spray irrigation systems are a function of water droplet size, air temperature, humidity, and air velocity (Kincaid and Longley 1989; Tarjuelo et al. 1999). As small droplet size will lead to substantial evaporative losses due to greater amounts of surface area, specification of efficient spray nozzles (as well as practicing maintenance) is important for maximizing evaporation (if this is an objective). Estimating evaporation of water from ponded systems (such as surface ponds described in the next section) can be estimated by applying appropriate pan evaporation data and a corresponding pan coefficient.

7.3.2 Surface Ponding

The difference between surface ponding and surface application through spray and drip irrigation is that a larger amount of liquids are added with ponding such that infiltration of liquids into the waste occurs continually. The pressure head build-up associated with the ponding technique has the benefit of providing a greater driving force for liquids movement into the landfill. Figure 7.8 provides a conceptual illustration of a surface infiltration pond at a landfill.

The infiltration rate of a surface pond can be simply expressed using Darcy's Equation:

$$q = K_z \frac{h + d}{d} \tag{7.2}$$

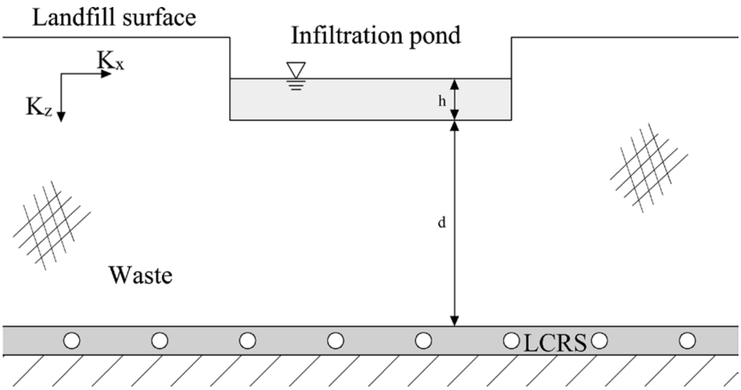

Fig. 7.8 Definition sketch for calculation of liquid infiltration rate into landfill from surface pond

Where, q = the vertical infiltration rate per area (L^3 L^{-2} T^{-1}); K_z = the vertical hydraulic conductivity (L T^{-1}); h = the depth of the surface pond (L); and d = the depth of the saturated waste under the pond (L) (see Fig. 7.8 for a definition sketch of the system). Soon after ponding begins, when the depth of liquids is lowest relative to the depth of the saturated waste, the infiltration rate of liquids into the landfill is at its greatest. As the saturated zone moves downward into the landfill, the driving gradient approaches 1, and q_Z approaches K_Z. Although the vertical hydraulic conductivity is considered a constant, in practice, it decreases with the depth due to overburden pressure. In this approach, seepage from the pond walls is neglected. An approach for including liquids migration from the pond walls is provided in the subsequent section on surface trenches. Depending on local climatic conditions, the effects of evaporation and precipitation should be considered in sizing the ponds.

Townsend et al. (1996) measured the performance of surface infiltration ponds at a landfill in Florida. Infiltration was measured by conducting a daily water balance on four separate ponds and estimating evaporation. The observed surface infiltration rates (q_z) ranged from 0.005 to 0.02 m/day (5,500–17,000 gal/acre-day). These infiltration estimates were used to assess the waste hydraulic conductivity (see Chap. 5).

7.3.3 Surface Trenches

The description and modeling of surface ponds in the previous section was such that only flow from the bottom of the ponds was considered. In large pond areas, the exposed infiltration area on the sides of the ponds will be small relative to the bottom area. This will not be the case for surface trenches, however, and given the anisotropic nature of landfilled MSW, accounting for flow from the trench sides is important.

Singh (2010) tested surface trenches containing waste tires as a bedding material and measured infiltration rates. The trenches were 1 m wide and 1.2 m deep. After 16 days of operation, flow rates in each trench (Q) normalized to a unit trench length (L) ranged from 0.69 to 0.95 m^2/day (56–77 gal/ft-day). For comparison purposes, when these measurements are normalized to only the bottom area of a trench (sides excluded), the values are considerably larger than infiltration rates measured by Townsend et al. (1995) for surface ponds; this illustrates the role that flow through the more permeable trench walls can play.

Jain et al. (2010) developed a method for predicting flow through a horizontal source. This technique and its utility are presented in greater detail in Chap. 9, but the technique can be applied to surface trenches and ponds. Figure 7.9 presents a design chart, which includes a definition sketch. Based on dimensions of the trench (length and width) and properties of the waste (anisotropy, $a = K_X/K_Z$), a dimensionless value, η, can be obtained. From this, a dimensionless flow rate may be estimated, and using the value of trench width (l) and K_Z, the steady-state flow into the trench can be predicted.

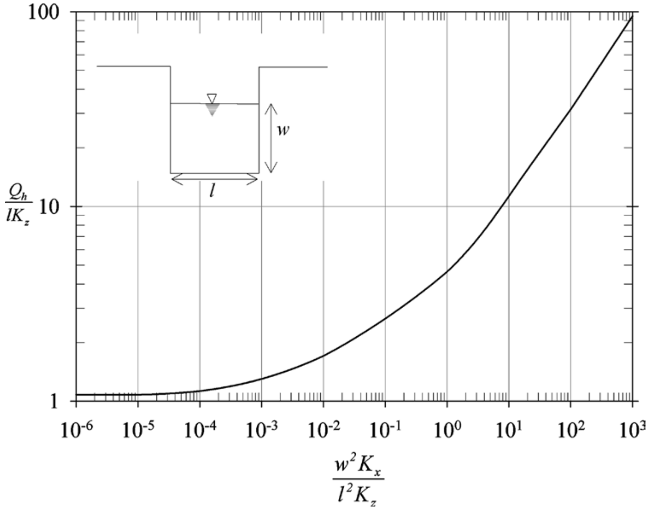

Fig. 7.9 Design chart for estimating steady state flow into horizontal source (trench or pond) at the landfill surface (from Jain et al. 2010)

As the trench width (l) becomes greater than the depth of liquids in the trench (w), the value for q_s (the dimensionless flow rate) approaches a minimum value close to 1. This condition represents an infiltration pond and q_Z would approach K_Z (as described in the previous section). As the degree of anisotropy gets larger, or as the trench depth increases, the values for η increases, illustrating the greater impact of liquid infiltration through the sides of the trench.

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Chapter 8
Buried Vertical Systems for Liquids Addition

Abstract Chapter 8 presents the second of three chapters that explore major liquid additions systems types, with the focus of this chapter being buried vertical systems. Configuration options, construction options, and materials of construction are discussed, including small-diameter and large-diameter systems. Design approaches with vertical wells are presented along with operational experience to inform the designer of potential opportunities and drawbacks. Coupled with the design discussion is a presentation of several design charts and tools to identify and justify the selected spacing of liquids addition devices. The chapter finishes with a discussion of operations, monitoring, and closure consideration related to vertical systems.

Keywords Landfill • Leachate • Bioreactor • Recirculation • Vertical • Well • Subsurface

8.1 Vertical Well Fundamentals

The two general configurations for subsurface (buried) liquids addition systems are vertical wells and horizontal trenches or galleries. This chapter describes the design, construction, and use of vertical wells for the addition of liquids into landfills. The concept of these devices, as illustrated in Fig. 8.1, is that a vertical borehole is constructed within landfilled waste, allowing liquids to be added to a range of depths within the waste mass. As a subsurface system, vertical wells avoid many of the issues associated with the surface systems reviewed in the previous chapter (odors, aerosols, disrupting surface conditions, and impacts from inclement weather). From a performance perspective, vertical wells can have an advantage over surface systems in that the potentially large hydrostatic head of water within the well can provide a comparatively larger driving force (pressure) to encourage liquids distribution within the landfill.

Vertical wells are commonly used in active GCCS, thus many landfill operators have familiarity with vertical well construction techniques. One advantage of vertical wells is that they can be installed after large depths of waste have been placed (as we will see in the next chapter, buried horizontal systems are limited to construction at relatively shallow depths). This approach is thus well-suited to sites where liquids addition operations are conceived or initiated after most of the planned landfill operation or filling has been completed. It may also be a preferred option for

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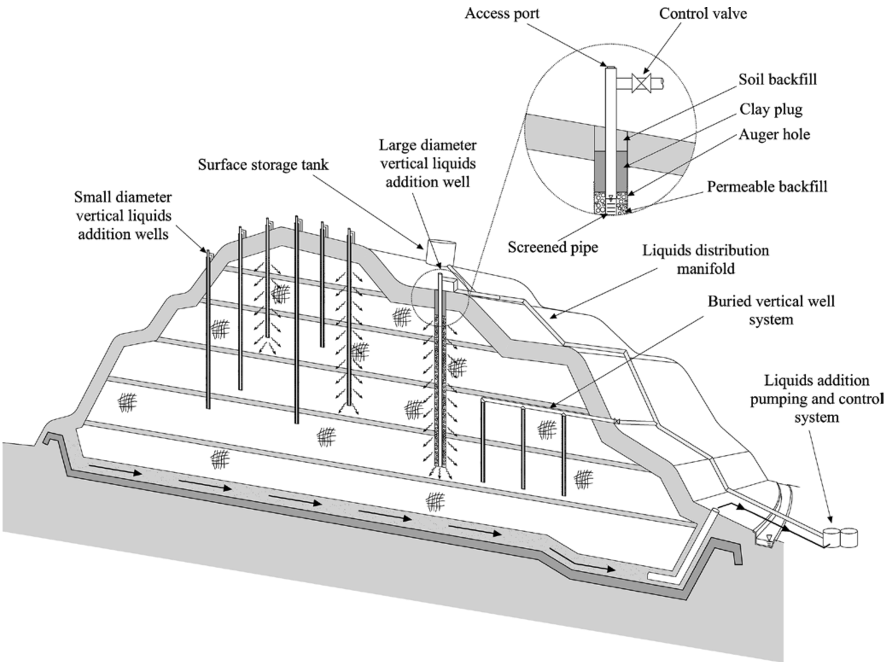

Fig. 8.1 Features of a vertical liquids addition well at a landfill

those operators wishing to avoid the necessity of frequent installation of horizontal devices as waste placement and compaction occurs.

The use of vertical wells may present several disadvantages relative to horizontal systems. For one, given that landfills are often much larger in the horizontal dimension relative to the vertical dimension, the cumulative length of a vertical liquids addition device is much less than a typical horizontal device. Thus, as can be assessed using the design approaches described later in this chapter and discussed further in Chap. 9, many more vertical wells may be needed to add an equivalent liquids volume relative to a horizontal device. Horizontal devices also have the potential to increase the moisture content of the landfill mass to a greater extent as a result of the larger device dimensions that are possible compared to vertical systems.

8.2 Configuration, Construction and Materials

8.2.1 Construction Techniques

A variety of construction techniques have been attempted for vertical liquids addition systems. Most techniques involve installing the well after the waste has been placed and compacted, and thus require specialized equipment for drilling a hole into the landfill. An alternative, however, is to construct the well as waste is being

Fig. 8.2 Bucket auger rig for drilling vertical wells in landfill waste

placed; this well construction method is discussed in greater detail in Chap. 13 on landfill gas. Construction of a vertical liquids addition well during waste filling was reported for a landfill operated by the Delaware Solid Waste Authority (Watson 1987; Morris et al. 2003, see more discussion in Chap. 4).

A variety of different well construction techniques (primarily derived from methods and equipment typically used for soils augering) have been utilized for augering into landfills. Bucket augers are large in diameter (0.5–1 m) and commonly used for the construction of landfill gas wells. These devices consist of large hollow buckets with tools designed for cutting into soil and waste on the bottom edge of the bucket. As the auger bucket turns, the waste is cut in a rotary fashion; a tool on the bucket can be engaged to allow frequent removal of cuttings. Figure 8.2 shows the construction of a vertical landfill well at a landfill using a bucket auger. In addition to constructing gas wells, these devices are commonly used to collect waste samples for characterization (e.g., Kelly et al. 2006; see Chap. 16).

Hollow stem augers are typically smaller in diameter compared to a bucket auger and can be utilized with most standard rotary drilling rigs used for geotechnical soil sampling and testing. Segments of hollow drill shaft are employed to auger into the landfill; a cutting tool is placed on the end of the bottom-most length of drill stem, which can be fitted with a plug to keep cuttings (waste and soil) from entering the hole. The cuttings are removed from around the top of the hole as augering occurs (Fig. 8.3). Undisturbed soil or waste is accessed through the hollow drill stem. Hollow stem augers have also been used at landfills to install moisture sensors as part of sustainable landfill operations (Jonnalagadda et al. 2010).

Solid-shaft open-flight augers come in a range of sizes; smaller diameter devices have been frequently used for collecting waste samples (Kim and Townsend 2012) and for constructing vertical air and liquid addition wells (Jain et al. 2005a, 2006). Solid-shaft augers (Fig. 8.4) are commonly equipped with rotary drilling equipment used for

Fig. 8.3 Hollow stem auger equipment for drilling vertical wells in landfill waste

Fig. 8.4 Solid shaft open flight auger for drilling vertical wells in landfilled waste

Fig. 8.5 Direct push rig installing vertical wells at the surface of a landfill

geotechnical sampling and water well drilling. The use of these devices for small-diameter liquid addition well installation is discussed in more detail in Sect. 8.2.3.

Another device commonly used for installing small diameter wells in soil is a direct push rig or direct push technology (DPT), which involves hammering the well pipe into place. A DPT rig was tested at a Florida landfill as part of small-diameter (5-cm) liquids addition well installation (Fig. 8.5), but the maximum reachable depth was 6 m (20 ft). The maximum depth that could be achieved would be a function of the waste characteristics (the presence of rigid debris that would cause drill refusal) and those of the rig itself.

8.2.2 Large Diameter Surface Wells

In the context presented here, large-diameter wells are differentiated from small-diameter wells in several ways. First, large-diameter wells are in most respects the same as wells commonly installed for landfill gas collection, with diameters ranging from 0.6 to 1 m. Second, a major fraction of the volume of the borehole is filled with a permeable media, typically rounded stone. A perforated pipe (either HDPE or PVC) is placed in the center of the rock, with sufficient distance between the landfill surface and the beginning of pipe perforations to avoid losing liquids to the surface. While large-diameter wells can be constructed during the progression of waste filling by continuously adding new segments, the use of specialized drilling equipment to construct a well after waste has been placed is more common. Large-diameter bucket augers are most frequently employed, but large diameter open flight augers may also be used. With a bucket auger, the bucket is typically removed from the hole every 0.15 m to remove the cuttings. When open flight augers are used, drill cuttings emerge from the borehole as the auger stem is rotated. In both cases, the cuttings must be removed and appropriately disposed of.

Once the boring is completed to the target depth, the well pipe is lowered into the hole, with an effort made to keep the pipe in the center of the hole. Permeable media (e.g., non-calcareous rock) is backfilled between the waste mass and the pipe. A seal of concrete and/or bentonite (clay) is placed as part of the surface completion step above the top of the rock and below the landfill surface to minimize possible entry and exit of liquids or gases around the well pipe.

8.2.3 Small Diameter Surface Wells

In contrast to large diameter wells, small diameter wells as presented here are those that involve augering a hole in the landfilled waste using mechanized equipment and inserting a perforated pipe within the hole without the presence of surrounding drainage media. In this case, the pipe is in direct contact with the surrounding waste mass. Both solid shaft and hollow stem augers can be used, but the most commonly-reported application has been the use of a solid shaft open flight auger and PVC pipe. The bottom sections of the pipe are slotted or perforated and the top part is solid to minimize the potential of surface seeps during liquids addition operation.

Figure 8.6 conceptually illustrates the method through which vertical wells were installed at the New River Regional Landfill in Florida (see Chap. 4). Each solid shaft drill stem was 1.6 m long, and the first stem was equipped with a tool for cutting into the landfill. As needed, additional lengths of drill stem were added (Fig. 8.7). Periodically, the drill shaft was rotated in place without advancing the depth; this action resulted in drill cuttings being brought to the landfill surface and assisted in enlarging the hole.

When the target well depth was reached, the drill shaft was again rotated without advancing for an extended period to clean the hole of as many cuttings as possible. At this point, the drill stem was removed from the hole without rotating; this helped keep any remaining cuttings on the stem, thus removing them from the hole. As soon as the final piece of stem was removed, the lowest portion of the well pipe was inserted into the boring (Fig. 8.8). The pipes were connected as they were lowered into place in the hole. Threaded or glued connections can be used, although threaded connections have shown to be more quickly deployed during construction. When drilling small-diameter wells in landfills, the borehole tends to close back on itself relatively quickly, requiring mechanical force to push the pipe to the desired depth in some cases.

One of the critical requirements during vertical well installation of any kind is close monitoring of the length of drill stem in the augered borehole (Fig. 8.9). Targeted well depths are typically designed to provide at least 3 m (10 ft) of buffer

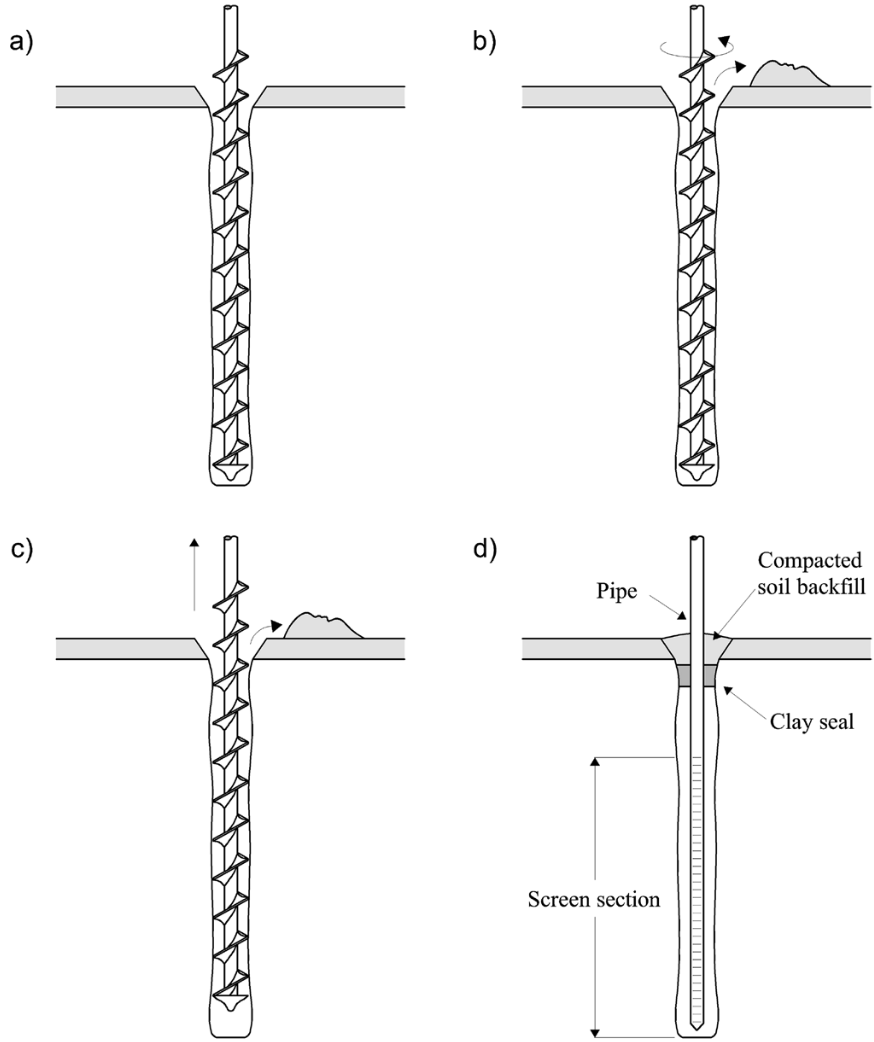

Fig. 8.6 Illustration of small diameter liquids addition wells as installed at the New River regional landfill. (**a**) Auger into landfill (**b**) spin auger in place to remove waste and clear hole (**c**) pull auger from hole without spinning (**d**) place pipe immediately in hole and add clay seal

between the bottom of the well and the top of the LCRS. This is needed to both avoid short-circuiting of the liquids to the LCRS and to avoid damage to the liner from the drill stem. It is thus critical that the engineer provide specific instructions for the depth for each specific well location based on accurate landfill surface elevation measurements and record drawings of the liner system and LCRS.

A common practice when constructing vertical wells is to place a low permeability seal or collar in the annulus between the pipe and waste somewhere above the well screen and up to the landfill surface (Fig. 8.10). This helps avoid

Fig. 8.7 Drilling small diameter liquid addition wells in a landfill

Fig. 8.8 Construction of small diameter liquids addition wells

Fig. 8.9 Careful recording of auger depth into the landfill is critical to avoid damage to the bottom liner system

Fig. 8.10 A collar of bentonite (clay) being added to the annulus at the surface of a recently constructed liquids addition well

undesirable liquid entry into the hole (e.g., stormwater intrusion) and liquid or gas escape from the landfill. Under most designs where vertical liquids addition wells are used, the depth of liquid is maintained below the surface of the landfill. In some cases the engineer or operator may want to operate at hydrostatic pressures above the surface elevation of the landfill. Experience of how these well seals perform to prevent surface seepage of added liquids is discussed in more detail later in this chapter.

8.3 Design Methodology

The design process for vertical wells begins with an assessment of the target volume of liquids to be added to the landfill and an evaluation of the timeframe and rate at which that volume is to be added to the landfill. Chapter 6 provides more information on these design steps. Once the target liquids addition volume and overall design flow rate have been established, the engineer proceeds with the design of an individual well. The design of a single well includes the specification of the well diameter (both the auger boring and the pipe), construction materials, screen length, and well depth. The design of a vertical well system involves locating (at proper spacing) a sufficient number of vertical wells across the landfill and providing a delivery system to convey liquids to each of the wells. A primary objective in assigning the number of wells and their location is to provide a system that allows the operator to efficiently distribute liquids throughout the areas of landfill targeted for liquids addition. Two major design parameters that must be identified for a given landfill include the flow rate that can be added to a given well and the shape of the saturated zone that results from adding that flow rate to that well. It is important for the designer to understand that the fluid flow patterns predicted with methods outlined are idealized, and systems as heterogeneous as landfill should be expected to be much more variable, both spatially and with time. The engineer should use these techniques to develop an understanding of likely performance ranges, and couple this with good engineering judgment and system-specific objectives.

Both the flow and dimension of the saturated zone can be predicted by the engineer using fluid flow modeling as described in Chap. 5. Several authors have presented examples of such modeling for vertical liquid addition wells in landfills. McCreanor and Reinhart (1996) used the saturated-unsaturated flow and transport model (SUTRA) to simulate the saturation profiles that would occur around a vertical well in homogenous and isotropic waste at several constant flow rates. Using SUTRA, Jain et al. (2005b) modeled moisture flow through a vertical well installed in unsaturated waste. He reported pressure at the bottom of the well and the lateral extent of the zone of impact as a function of waste properties, well dimensions, flow rate, and time. Khire and Mukherjee (2007) simulated the impact of leachate injection rate on the steady-state injection pressure, the lateral extent of moisture movement, and head on the bottom liner for an isotropic waste. The impact of well diameter, well depth, and screen length was also investigated.

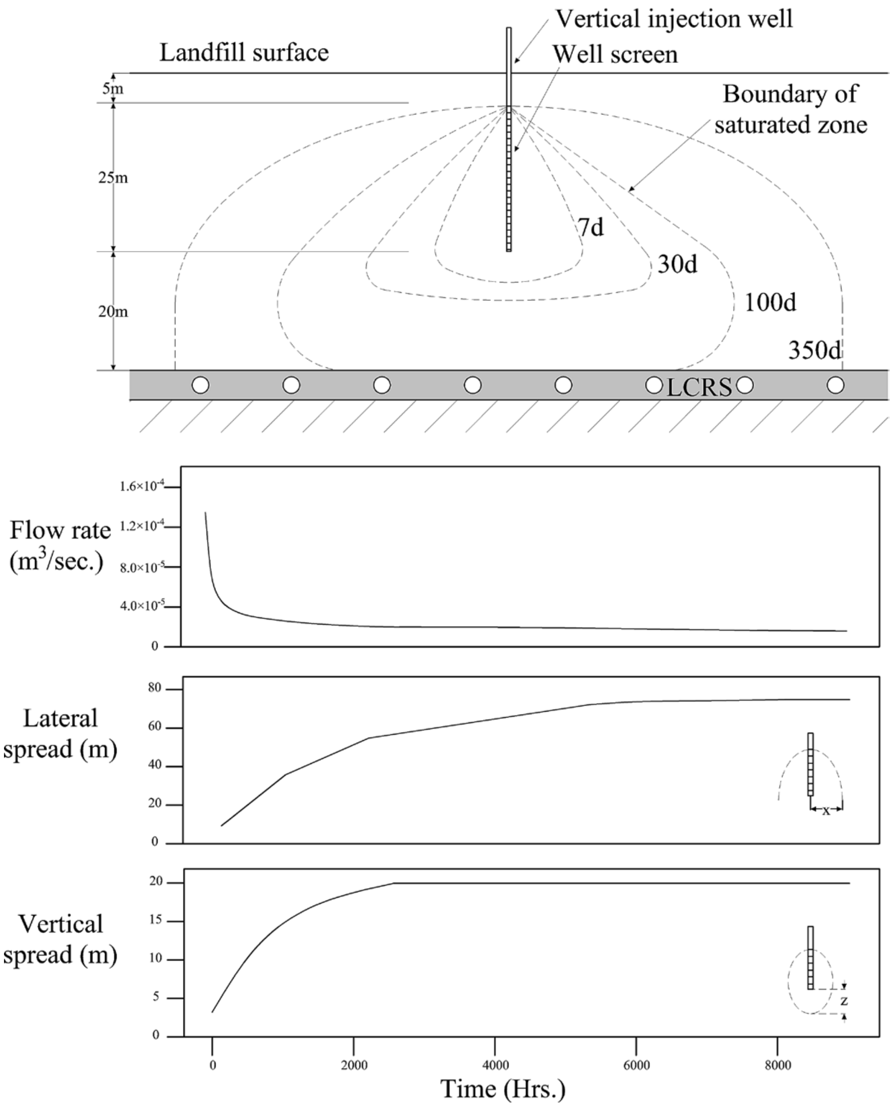

Fig. 8.11 Example output of a seepage model simulation (SEEP/W) of pressurized liquids addition into a vertical well

Figure 8.11 presents the output of a seepage modeling simulation of liquids added to a vertical well at a constant liquid depth. It is presented only to illustrate an example output, and that the displayed numerical results are only applicable to the defined simulation conditions. The results show that flow rates are greatest in the beginning as the pressure gradient is large. As the wetted zone around the well expands, the flow decreases to a steady state.

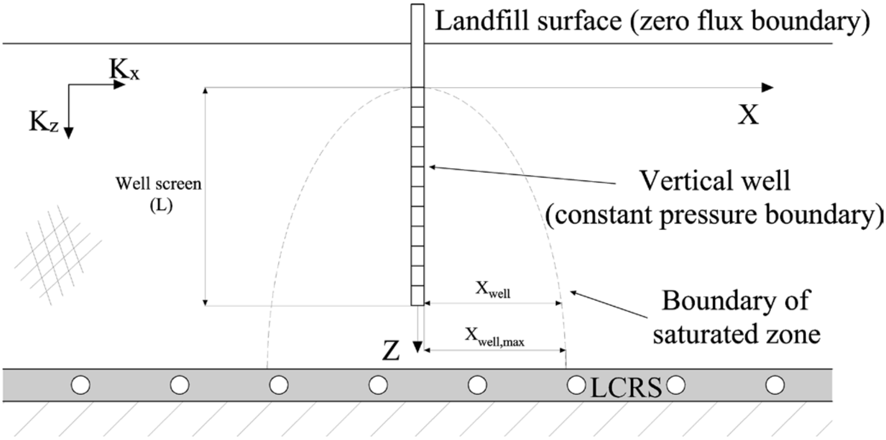

Fig. 8.12 Definition sketch for major dimensions associated with estimate of liquids into a vertical well in a landfill

The following sections discuss historic data measured at landfill sites using vertical wells for liquids addition and a design method that can be used to predict achievable flow rates and saturated zone dimensions for vertical liquids addition wells. The design methods presented allow the engineer to estimate these parameters without performing computer simulations. Figure 8.12 defines the system along with appropriate dimensions.

8.4 Flow Rates

8.4.1 Operational Experience

Several researchers have reported on the operational performance of vertical wells at landfills, and in some cases have provided total liquid volume addition data. For example, Read et al. (2001) described the recirculation of leachate in a 1-ha (2.5-ac) test cell in Georgia, US using a vertical system consisting of 27 wells spaced at 18.25 m (60 ft) and installed at depths ranging from 1.5 to 4.6 m (5–15 ft) with screen lengths ranging from 0.6 to 1.5 m long (2–5 ft). Approximately 3,400 m^3 (0.9 million gal) of leachate was recirculated over a duration of 9 months. Morris et al. (2003) described the recirculation of leachate into 1.2-m diameter wells at a Delaware, US landfill at rates of 0.008–0.75 m^3/min.

An extensive set of data on performance of a vertical well liquid addition was developed at the New River Regional Landfill in Florida (NRRL; see Chap. 4), where a system of small-diameter vertical wells was used for the introduction of leachate and groundwater to a 2.5-ha (10-ac) landfill area at the site (Jain et al.

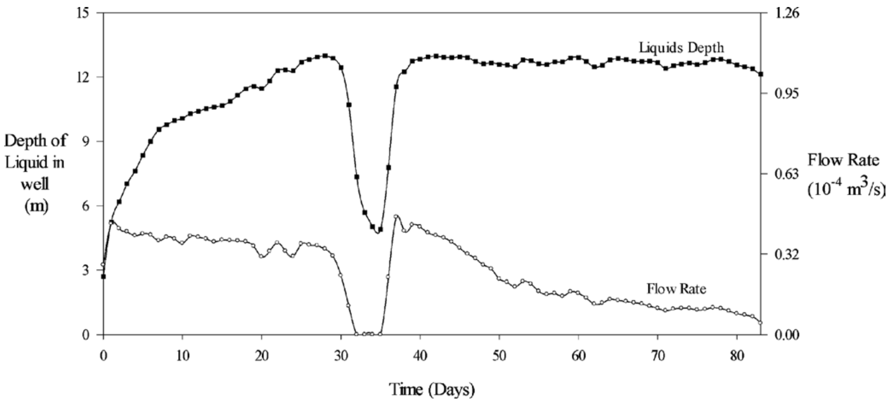

Fig. 8.13 Example data from the operation of a vertical liquids addition well at NRRL; liquid depth and flow rate as a function of time

2005b). Clusters of wells were installed, with each cluster containing three wells installed at 6, 12 and 18 m (20, 40, and 60 ft) depth. Reported flow rates ranged from 0.0019 to 0.011 m^3/min (0.5–2.91 gal per minute); Fig. 8.13 illustrates typical well performance for a single well over several days of operation. As part of initial site operations, Jain et al. (2006) observed that achievable flow rates decreased with depth in the landfill (hydraulic conductivity was lower at greater waste depths).

Longer-term performance of the NRRL liquids addition well field was reported in Jain et al. (2014a). More than 25,000 m^3 (6,600,000 gal) were added over a 5-year period. The performance was evaluated based on fluid conductance, defined as flow rate per unit well screen length per unit liquid head at the well bottom (units = L/T). Figure 8.14 presents variation in fluid conductance with the liquids volume added. The median fluid conductance was found to range from 5.6×10^{-8} to 3.6×10^{-6} m s^{-1} for all wells.

8.4.2 Estimation Methods

The achievable flow rate into a vertical well can be predicted by the engineer using a fluid flow simulation technique as described in Chap. 5. Figure 8.11 provided the result of an example of such a simulation under a defined set of conditions. The flow rate decreases during the first part of operation as the wetting zone progresses, ultimately reaching steady state.

Several researchers have developed approaches that allow estimation of flow rates into a vertical well without the need to conduct model simulations. Xu et al. (2014) conducted a series of SEEP/W simulations for a range of potential operating conditions and developed a best-fit relationship of the simulation results to produce a simple equation capable of estimating flow-rate (and several other parameters as

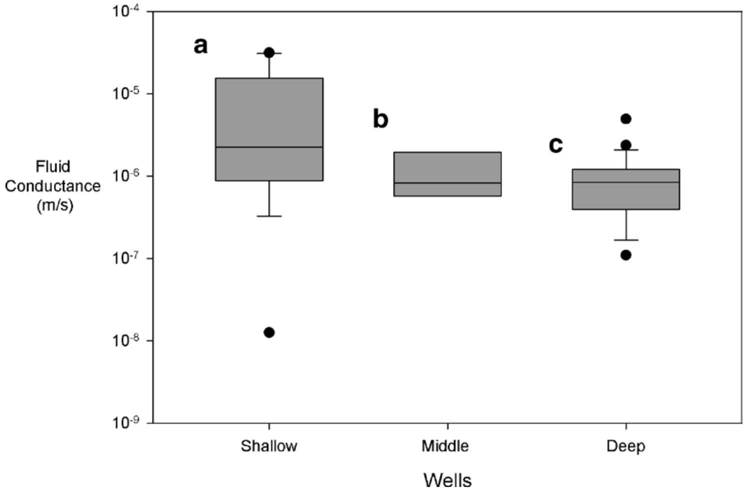

Fig. 8.14 Fluid conductance as a function of liquids volume added for (**a**) deep wells, (**b**) middle wells, and (**c**) shallow wells

discussed later in this chapter). The Xu et al. (2014) assessment simulated the vertical well as a line-source under axisymmetric flow conditions. Using this approach, the entire length of well screen is assumed to be saturated, with no liquid level above the well screen. The following relationship for steady state flow into a vertical well was developed.

$$Q = 0.61 \cdot \left(A \cdot K_z \cdot L^2 \right) \tag{8.1}$$

Where, Q = the flow rate of leachate ($L^3\ T^{-1}$); A = waste anisotropy ratio (K_x/K_z;) K_z = vertical hydraulic conductivity ($L\ T^{-1}$); and L = well screen length (L).

Jain et al. (2010) developed an approach to estimate steady-state flow rate into a vertical well as a function of well dimensions, injection pressure, and waste hydraulic conductivity and anisotropy using dimensionless parameters and design charts. SEEP/W model simulations were conducted over a range of operational conditions for vertical well systems. In addition to the parameters assessed by Xu et al. (2014), Jain et al. (2010) included the radius of the well and conditions where liquids were added at pressures greater than the screen length of the well. A dimensionless variable analysis was conducted to broaden the scope of applications for the results beyond the range of individual parameter values used for modeling. Use of the design process proposed by Jain et al. (2010) is described below.

First, the dimensionless variable η is calculated using information on well dimensions and landfill anisotropy:

$$\eta = \frac{L_V{}^2}{r_w^2} A \tag{8.2}$$

Where L_V = the screen length of the vertical well, r_w = the radius of the vertical well, and A = the anisotropy ratio (K_X/K_Z). The dimensionless variable η indicates the dominant flow direction, vertical or horizontal; a low η value signifies a flow that is dominant in the vertical direction, whereas a high η value indicates a flow that is dominant in the horizontal direction.

The designer identifies a target liquid level in the vertical well (h_v, measured from the bottom of the well), which allows for the depth of liquids to be greater than the screen length. Using the targeted liquid level, h_v, and the well screen length, L_V, a dimensionless injection pressure head, p_{Id}, is calculated as follows:

$$p_{Id} = \frac{h_V}{L_V} \tag{8.3}$$

Once the values of p_{Id} and η have been determined, the steady-state dimensionless flow rate, q_s, for a vertical well can be estimated using the chart presented in Fig. 8.15.

With a value of q_s in hand, the steady state flow rate into the vertical well (Q_S) can be calculated as:

$$Q_s = q_s \pi r_w^2 K_Z \tag{8.4}$$

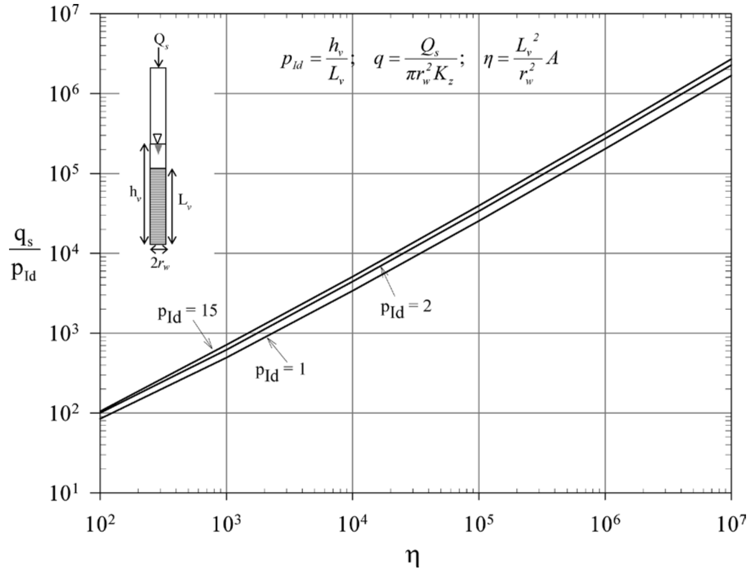

Fig. 8.15 Design chart for estimating steady state flow (Q_S) into a vertical source under buried conditions (from Jain et al. 2010)

Jain et al. (2014b) also presented a design chart to estimate average flow rate for conditions where the system does not reach steady state. The design chart provides an estimate of the error that might result from the use of steady-state flow rate in the design process decreases with an increase in the fraction of liquids volume needed to achieve steady state. The use of the steady-state flow rate for estimation of operating duration to add designed liquid volume may result in slight overestimation of the operating time.

8.5 Saturated Zone Profiles

The ability to estimate the size and shape of the saturated zone surrounding a vertical well can be of great value when determining the appropriate placement or spacing of liquids addition devices. The engineer and operator must consider numerous factors that may result in non-idealized flow conditions (e.g., cover soil layers, waste heterogeneity) and incorporate such conditions into design and operation. Both Xu et al. (2014) and Jain et al. (2010) used the output of vertical well simulations to develop a method for predicting the wetted zone around a vertical well at steady state. Refer to Fig. 8.12 for the definition sketch of pertinent dimensions in this approach.

Xu et al. (2014) examined the lateral spread of liquid away from a vertical well as a function of the maximum steady-state moisture distribution (X_{max}). At steady state, the maximum lateral spread is reached and the added liquids will only migrate downward in the vertical direction. According to Darcy's Law, the maximum lateral spread for a vertical well (X_{max}) injection can be expressed as:

$$X_{\max} = \sqrt{\frac{Q}{\pi K_z}} \tag{8.5}$$

A correction factor was developed that allowed for the estimation of lateral spread at a distance, D, from the top of the well, such that:

$$X = X_{\max} \cdot \left(1 - e^{-1.6 \frac{D}{L_V}} \right) \tag{8.6}$$

Where, D = the depth measured from the top well screen (L) and L_V = the length of well (L). The lateral distance at the base of the well (where D = L) would thus be:

$$X_{well} = 0.8\, X_{\max} \tag{8.7}$$

This equation allows the user to estimate the shape of the saturated zone profile, from the water surface to the depths below the bottom of the well, but only applies to cases where the water level is within the screened interval. Using the dimensionless analysis approach simplified by Jain et al. (2010), the relationship for X_{well} was found to be:

$$X_{well} = \sqrt{\frac{Q_s}{\pi K_Z}} \tag{8.8}$$

8.6 Liquids Addition Device Spacing

The engineer must specify the number of vertical wells for installation and their locations. While some measured data are available regarding the success of vertical wells for distributing moisture (see below), the engineer will need to decide upon an appropriate well spacing based on site-specific conditions and project objectives coupled with estimates of likely expected moisture movement within the landfill. The information presented in Sect. 8.4 allows the engineer to estimate the flow rate that can be added to a given vertical well. This, coupled with the liquid addition targets discussed in Chap. 6, can be used to provide a preliminary estimate of the number of wells needed. The engineer can specify spacing based on previous operational experience or using methods that allow prediction of the saturated zone surrounding the well.

Several projects have used 17-m (50-ft) spacing for small-diameter vertical wells (Read et al. 2001; Jain et al. 2005b). Only limited data are available from field measurements, however, regarding the distribution of moisture surrounding vertical wells. Based on the responses of moisture sensors (Kumar et al. 2009) installed around the NRRL vertical well clusters (50-ft spacing), the lateral extent of moisture movement was reported to range from 8 to 10 m. Jain et al. (2014a, b) reported that this system was effective in wetting the waste as the average gravimetric moisture contents of 272 samples collected in 2007 was 45 % (wet weight basis) compared to the initial average moisture content of 23 % (wet weight basis) (for 51 samples) collected in 2001.

Engineers often specify device spacing based on the distance needed to provide adequate moisture distribution within the landfill. The methods in Sect. 8.5 allow estimation of steady state zones of impact, and thus can be used for device spacing. For example, assigning a spacing based on X_{well} or X_{max}, or some desired overlap, would be a typical approach. However, the engineer may also wish to factor time into the design. The time needed to reach steady state may be large, and thus in cases where more rapid coverage is desired, closer spacing may be necessary.

The dimensionless design chart approach described earlier can be extended to determine the lateral extent of liquid movement at the base of the well (X_{well}) at times prior to reaching steady state. First, η is calculated in the same manner as presented in Sect. 8.4. Then using Fig. 8.16, the number of pore volumes needed to

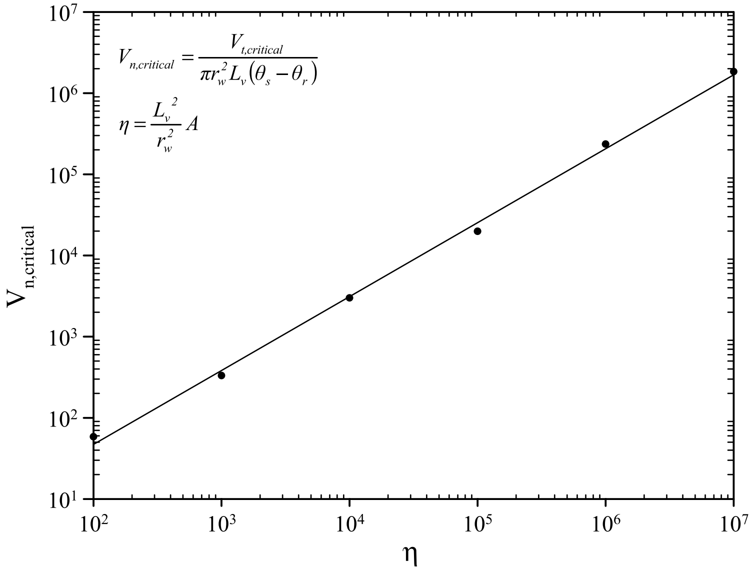

Fig. 8.16 Design chart to determine the cumulative volume of added liquids needed to reach steady state (from Jain et al. 2010)

reach steady state ($V_{n,critical}$) can be determined for different p_{ID} values. The cumulative volume of liquids to reach steady state ($V_{t,critical}$) can be calculated as follows:

$$V_{t,critical} = V_{n,critical} \left(\pi\, r_w^2\, w \left(\theta_s - \theta_d \right) \right) \tag{8.9}$$

Where r_w and L_v are as previously defined θ_s is the porosity and θ_r is the residual moisture content.

Figure 8.16 presents fractions of the steady-state lateral extent (ratio of transient lateral extent (X_{well}) to the steady-state lateral extent ($X_{well,s}$)) achieved as a function of the fraction of steady-state liquids volume (i.e., ratio of the design transient volume (V_t) to the volume needed to achieve the steady-state condition ($V_{t,critical}$) for vertical well) as published by Jain et al. (2014b). A ratio of 1 represents the steady-state condition whereas ratios less than 1 represent transient conditions. As can be seen in Fig. 8.17, coverage of approximately 70–90 % of the lateral extents of the zone of impact is achieved by addition of only 40 % of the liquids volume needed to achieve steady state for a vertical well.

With a value of $V_{t,critical}$ in hand, the value of X_{well} can be estimated as a function of added volume (V_t) using Fig. 8.17. First, the ratio of V_t to $V_{t,critical}$ is calculated. Then a value of X_{well} / $X_{well,s}$ is estimated using Fig. 8.16. As the SEEP/W simulation results did not converge on a simple relationship, a range is presented and the designer would need to select an appropriate value of $X_{well}/X_{well,s}$.

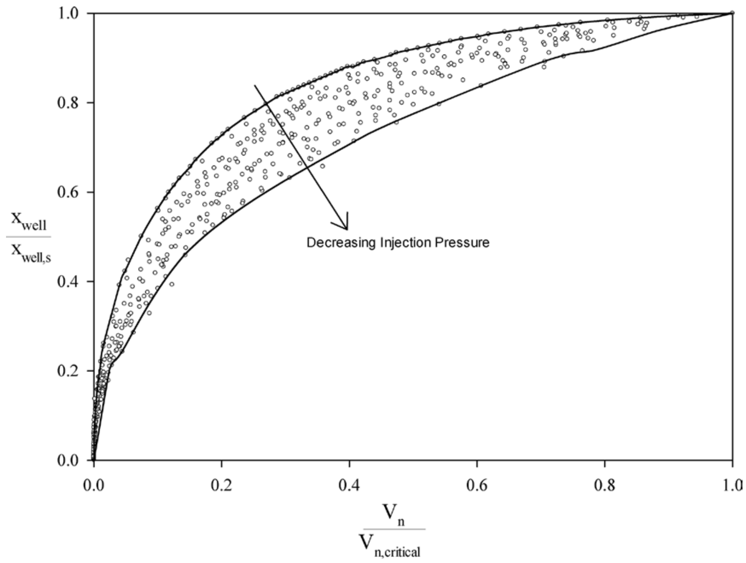

Fig. 8.17 Design chart to determine the fraction of the radial extent of flow from a vertical well as a function of the cumulative volume added

These design approaches reflect the technical aspects of design required for vertical wells. The design engineer and site operator must also consider other factors such as cost and compatibility with current and future operations when finalizing the number and configuration of vertical wells. Economics are addressed further in Chap. 18.

8.7 Operation, Monitoring and Closure

While horizontal systems can be operated under pressure, vertical systems normally require that liquid levels be maintained below the surface of the landfill and thus pressure is limited to the depth of the well below the landfill surface. As described earlier, construction of a vertical well will normally include placement of a low permeability seal (clay, concrete) to prevent the short-circuiting of leachate (liquid and gas) in the annulus of the well to the surface of the landfill. At the NRRL project, this was found insufficient to prevent liquids migration when the liquid surface in the well was above the landfill surface. Further attempts at the NRRL to examine pressurized addition at vertical wells explored the placement of a concrete collar around the vertical wells (Fig. 8.18). While this was more effective than a simple clay seal around the well, surface seepage still occurred. Jain et al. (2014a, b) reported that the liquid depths within the well had to be maintained below the landfill surface to avoid seeps at the base of the wellheads; therefore, system operation was labor intensive, especially for wells installed at shallow depths.

Fig. 8.18 Installation of a concrete collar around a nest of vertical injection wells

A challenge of operating vertical well systems, especially those with many wells, is maintaining sufficient addition rates to achieve liquid levels efficient for driving moisture distribution, but not large enough to result in surface seeps. This requires relatively frequent operator monitoring and adjustment. Routine liquid level measurements are necessary (see Chap. 6 for a discussion of monitoring techniques).

Settlement is also an issue that requires ongoing monitoring and maintenance. The settlement of waste beneath and surrounding a vertical well can result in "extending" the well to a point above the landfill surface that makes operations and monitoring difficult. The degree of settlement at any point depends on the underlying waste thickness. Since the waste thickness below the bottom of the well is less than the total waste thickness at the well location, the vertical wells settle less than the surrounding landfill surface. The designer and operator should expect vertical liquids addition wells to continue extending above the landfill surface in a similar manner, and at even more pronounced magnitude as a result of enhanced waste stabilization and consolidation. At NRRL, clusters of wells of different depths settled at different rates because of different depths of waste beneath them. The engineer must provide a flexible design that allows the operator to routinely adjust the connection between the well and the liquids distribution or gas collection manifold.

Vertical liquids addition wells also present an operational challenge in that waste will preferentially settle around the well as this is where most of the liquids are added. Greater liquids addition volumes result in greater weight which increases the stresses causing settlement and also results in more waste decomposition and more volume loss. Depressions may form around vertical wells which, if not addressed, will result in low spots for water to pond, thus making operator access difficult. This

Fig. 8.19 Differential settlement around a cluster of vertical liquids addition wells that resulted in ponding of stormwater

presented a problem at NRRL, where a geomembrane covering the landfill surface did not permit easy placement of soil or fill around the wells to eliminate ponding (see Fig. 8.19).

An alternative vertical well system was employed at the NRRL that reduced some of the aforementioned issues with surface seep occurrence and differential settlement (Kadambala et al. 2014). The objective of this system was to install multiple vertical wells and to tie groups of these together, and then to place another layer of waste above the top of the wells. The configuration included installation of nine wells installed in a grid spaced at 50-ft intervals. Each well was connected to a horizontally-oriented manifold and the entire well system was covered with a lift of waste (Fig. 8.20). To avoid damage to the wells by the placement of the overlying lift, the wells were installed in horizontal trenches constructed at the surface of the landfill (Fig. 8.21); the wells and their connecting manifold pipes were covered with the excavated waste to protect them from damage when the next lift of waste was placed. This allowed operation of the wells in a manner similar to horizontal wells (e.g., under pressure), but permitted addition to deeper areas of the waste compared to vertical wells that terminate above the landfill surface. This buried vertical well system showed that liquids addition using vertical wells was feasible, but this system takes away the ability to independently control individual liquids addition devices. Furthermore, given the critical need to avoid damage to the manifold system—which could preclude the ability to add liquids into any of the wells—the designer and constructor of buried vertical well systems must carefully select installation materials, locations, and procedures to avoid such damage.

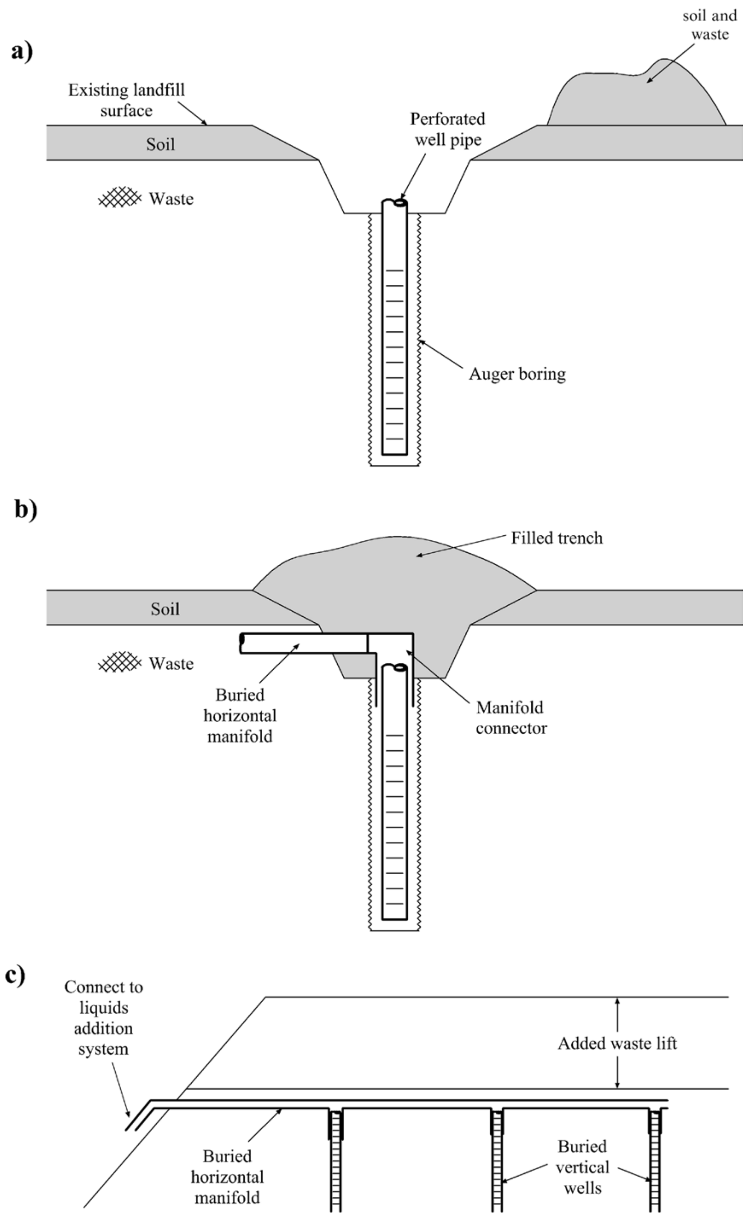

Fig. 8.20 Illustration of the construction of a buried vertical well system employed at the New River landfill in Florida. (**a**) Initial installation of the vertical well. (**b**) Connection of the vertical well to a horizontal manifold. (**c**) Placement of a lift of waste on top of the vertical wells and day-lighting of the manifold on the side slope of the landfill

Fig. 8.21 Installation of a vertical liquids addition well into an excavated trench as part of the construction of a buried vertical well system at the New River Regional Landfill

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Chapter 9
Buried Horizontal Systems for Liquids Addition

Abstract Chapter 9 is the third and final chapter on liquids addition system types, with a focus on horizontal systems. Buried trenches, blankets, and combination systems are discussed as the most common horizontal system types, with a companion evaluation of potential benefits and drawbacks of each. The latter portion of the chapter focuses on design techniques and approaches for horizontal systems, including tools to help identify and design horizontal systems over a variety of operating conditions and site constrains. Considerations for operation, monitoring and closure are presented at the end of the chapter.

Keywords Landfill • Leachate • Bioreactor • Recirculation • Horizontal • Trench • Blanket • Subsurface

9.1 Subsurface Horizontal System Fundamentals

The advantages that subsurface methods of liquids addition have over surface addition (e.g., ability to add liquids during inclement weather, greater capacity for providing adequate liquids to the bulk of the waste mass) were described in the previous chapter's presentation of vertical liquid addition wells, and these advantages are shared by horizontal subsurface systems. The subsurface liquids addition methodology discussed here utilizes buried pipes, trenches, or beds of permeable media constructed horizontally in the landfill during the waste filling process. The installation of these devices differs from vertical wells (which are installed only after a substantial amount of waste has been placed) and thus provides the operator the ability to add liquids much earlier in the operational life of the landfill.

The placement and use of horizontal liquids addition devices are among the most common of practices used at large-scale facilities implementing liquids addition. While this practice requires relatively frequent construction of devices throughout the life of the landfill, the types of equipment needed for construction are those often already part of the site's equipment fleet (e.g., excavators, loaders), and thus installation may be performed by the landfill staff themselves without the necessity of an outside contractor with specialized equipment (such as a drilling rig).

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Several configurations of buried horizontal systems have been utilized for liquids addition. For the purposes of discussions herein, these are grouped as horizontal trench (buried trench) systems and horizontal blanket (buried infiltration gallery or horizontal gallery) systems. Both types have been utilized to distribute liquids within the landfill mass. Horizontal systems can expand lengths to of hundreds of feet (or meters) and are vertically offset with spacing that depends on the dimensions of the horizontal trench or blanket among other factors (i.e., flow rates, pressures, and operational objectives). Similar to the previous chapter on vertical systems, this chapter examines the fundamentals of horizontal system construction and materials, along with design considerations; existing data from practicing facilities and methods for predicting achievable flow rates and moisture distribution profiles are both discussed.

9.2 Configuration, Construction and Materials

9.2.1 Buried Trenches

The installation of perforated pipes buried within the waste in a horizontal fashion has been described as horizontal injection lines (HILs), horizontal injection trenches (HITs), or simply horizontal trenches. Common to all systems is a conduit capable of distributing liquids placed on top of a lift of waste, with the inlet of that conduit configured to allow the introduction of liquids when desired (illustrated in Fig. 9.1).

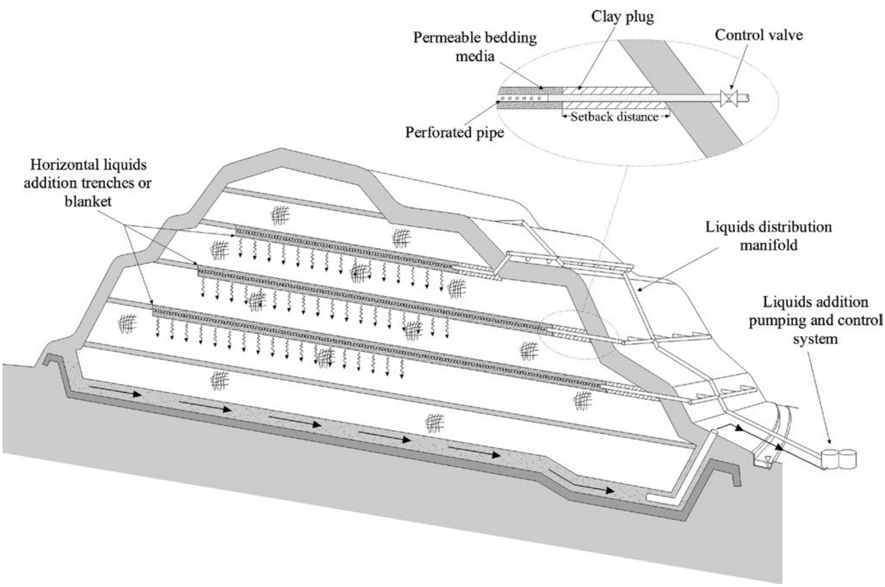

Fig. 9.1 Illustration of a subsurface horizontal liquids addition system at a landfill

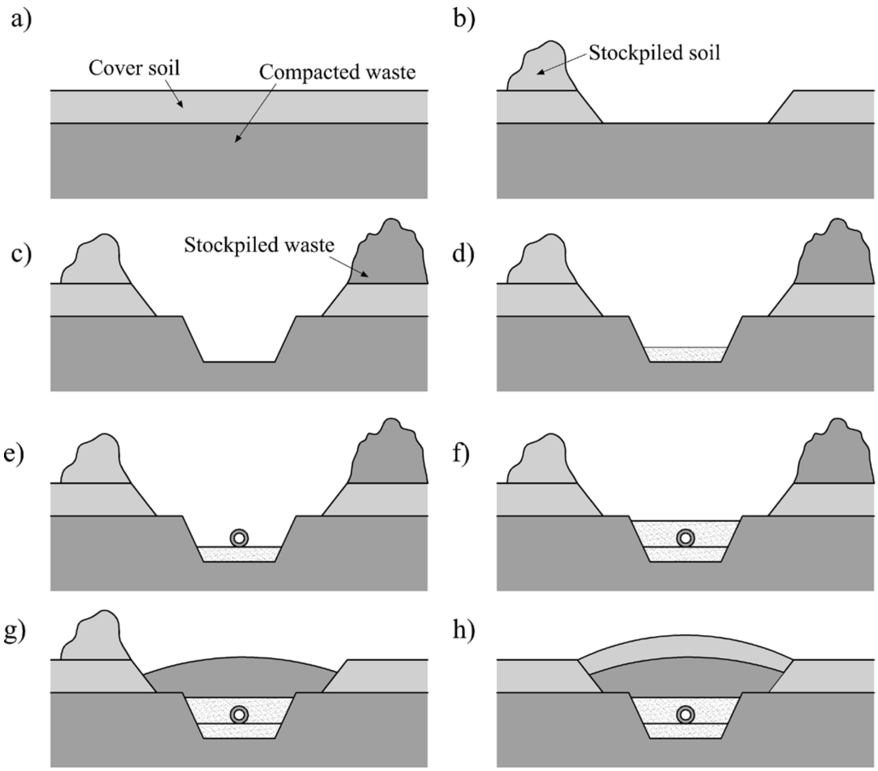

Fig. 9.2 Illustration of the process of constructing a horizontal liquids addition trench. (**a**) Initial conditions (**b**) scrape away cover soil (**c**) excavate trench (**d**) install first layer of bedding (**e**) install pipe (**f**) install additional bedding (**g**) compacted waste over trench (**h**) place soil over excavation area

In most cases, this approach utilizes perforated pipes embedded in a high-permeability drainage material placed in an excavated trench (some horizontal systems have been placed directly on top of the waste surface without excavation). Bedding media (e.g., gravel or shredded tire) is typically placed around the perforated pipe prior to placement and compaction of additional waste. Multiple conduits are typically constructed per lift, and additional conduits are placed on other lifts within the landfill in an effort to maximize moisture distribution in the landfill.

As illustrated in Fig. 9.2, the construction process begins with an existing landfill lift where compacted waste is overlain by a layer of cover soil. As these devices are normally intended for use only after the next lift of waste has been placed, a careful plan for coordinating installation with landfill waste filling and compaction is necessary. In some cases, new lines are continuously added as the landfill is filled. In other cases, if the filling sequence permits, many lines will be installed at once. Depending on the waste filling sequence at the landfill, the trench area will have to be covered with soil after installation, thus some operators choose to scrape away the cover soil layer prior to excavation of the trench. Additionally, since a major concern at many

Fig. 9.3 Excavation of horizontal injection trench using a track excavator

sites during the installation of horizontal devices is the potential interference of cover soil layers during future operation (see Chap. 11 for a description of how soil layers can contribute to preferential channeling and leachate seeps), scraping soil from the immediate trench area minimizes the amount of direct connection between the cover soil and the pressurized liquids addition device.

An excavator is the most common equipment used for the construction of an injection trench (Fig. 9.3). Trench dimensions vary, but a common size is 1 m by 1 m (as discussed in Chap. 7 on surface systems, deeper trenches are sometimes constructed). Some operators install square trenches with defined edges, while others excavate a more rounded trench. The designer and operator must plan for the staging and potential removal and management of the excavated waste. For large trench excavations, a considerable amount of waste is removed, and under most regulatory and permit requirements, this waste will have to be covered within a short period of time, often by the end of the working day. Some operators provide a truck for transport of excavated waste, followed by hauling the waste to the working face of the landfill for disposal. Another approach is to mound the waste to the side, complete trench construction within the needed time frame, and then push and compact the waste over the completed trench before covering with soil.

Most commonly, the liquids addition device specified for placement in the trench is a perforated pipe (high-density polyethylene (HDPE) or polyvinyl chloride (PVC)) surrounded by a permeable bedding material. The purpose of the bedding material is twofold. First, it provides a conduit for liquids distribution through the trench as the bedding material will be more permeable than the surrounding compacted waste. If a pipe breaks at some point in the future, liquids can still be transmitted through the trench. Second, the bedding material provides a cushioning

Fig. 9.4 HDPE liquids distribution pipe in the process of being placed on top of a bottom bedding layer of shredded tires in a horizontal trench

Fig. 9.5 Placement of shredded tires on top of HDPE liquids distribution pipe in horizontal trench

layer to provide some protection to the pipe against stresses from waste and equipment overburden and settling beneath the trench. Most designers and operators install bedding material on the bottom of the trench followed by the perforated pipe, followed by more bedding material (Figs. 9.4 and 9.5). Depending on availability of construction and bedding materials, as well as other site-specific construction constraints, some operators may place the pipe at the bottom of the trench

Fig. 9.6 HDPE liquids distribution pipe in the process of being placed on top of a bottom bedding layer of crushed glass in a horizontal trench

or the top of the trench. Similarly, the designer will specify the perforation scheme used in the recirculation pipes, and care must be taken to ensure that pipe perforations are placed appropriately during installation (e.g., construction specifications may call for the perforations to be placed vertically downward to avoid soil entrance into the pipe).

Bedding media can include standard materials used in civil engineering drainage systems, such as naturally rounded or crushed rock. Given the expense of these materials, alternative bedding media originating from waste materials have been used at many landfill sites, including chipped vehicle tires; mulch; crushed concrete, brick and other masonry; and crushed glass (Figs. 9.6 and 9.7). Since the limiting factors to liquids movement into the landfill is most likely the compacted waste, the bedding media must simply possess a permeability greater than the waste.

Because of its strength and flexibility, HDPE is the most commonly used pipe material with diameters of 3 or 4 in. being most common. Segments of HDPE pipe can be thermally welded inside or adjacent to the trench and the welding device moved as needed (Fig. 9.8). Many operators prefer to weld a long length of pipe at a central location and to drag the pipe into place (Fig. 9.9). PVC pipe has been successfully used for horizontal injection trenches at some sites (Fig. 9.10; Townsend and Miller 1998), and since it can be solvent welded (glued) with readily available supplies, it does not require the thermal welding equipment necessary for HDPE installation. Given the possible stresses the pipe will be exposed to, however, HDPE is most common in current installations. An alternative to gluing or welding pipe includes leaving some sections of pipe unconnected and having a segment of larger

Fig. 9.7 Placement of crushed glass on top of HDPE liquids distribution pipe in horizontal trench

Fig. 9.8 Welding HDPE pipe in trench during construction

diameter pipe sheathed around two adjacent smaller diameter pipe ends to allow for future expansion and contraction.

Liquids addition pipes are perforated to allow for liquids distribution into the waste. At the flow rates commonly used, the size and spacing of perforations may differ based on site conditions to prevent preferential discharge into certain areas of

Fig. 9.9 Pulling welded HDPE pipe with tractor to proximity of excavated trench

Fig. 9.10 Placement of shredded tires in liquids addition trench on top of PVC pipe

the trench. For example, engineers have employed specific, more complex patterns of smaller and varying hole sizes along with different spacing to achieve uniform flow distribution along the length of the pipe; the design procedures for this are common in manifold design for liquid outfalls. Given the experience that the limitation to liquids addition into the trench will be the waste itself, for larger flow rates,

Fig. 9.11 Drilling orifices in HDPE liquids injection pipe

the trench will fill regardless of the perforation scheme, and thus most engineers opt to provide more and larger perforations rather than incorporate a detailed manifold distribution design. Only in cases where lower flow rates are added (in a manner where liquid depths are not expected to build up) are more complicated designs warranted. Typical orifice spacing is every 0.6–2 m (2–6 ft) with diameters of 0.5–1.0 cm (0.25–0.375 in.). Pipes can be purchased pre-perforated, although some operators choose to drill orifices with landfill personnel using standard drilling tools (Fig. 9.11).

An important consideration in the construction of a liquids addition system is the recording of trench and pipe locations. Surveying pipe locations as they are installed is a recommended practice (Fig. 9.12). Many modern landfills are equipped with equipment that allows ready measurement of vertical and horizontal coordinates, and these devices can be used to routinely measure device location and elevation, with the results incorporated into the site's record drawings. Detailed record keeping with regard to device location may be required as part of the facility's operating permit. Regardless of whether recording locational details is required, this information is critical to evaluation of system performance and facilitates future construction activities and operation of other systems such as those for gas collection.

As described above, the placement of perforated pipes and permeable bedding material into trenches excavated into the surface of the landfill is the most common construction technique. Distribution pipes have been placed in trenches without bedding material (Townsend and Miller 1998), and devices constructed in this fashion can provide liquids addition capability (though not initial liquids storage); the downside to this approach is potential damage to the pipe greatly limiting liquids distribution because of the absence of permeable bedding for liquids to flow through

Fig. 9.12 Surveying specific location of injection pipe during construction

the compromised pipe section. An installation technique with similar limitations was employed at a site using a trenching machine that directly installed perforated pipes on the top of a lift of waste (Figs. 9.13 and 9.14); however, this approach did provide for rapid pipe installation. Although horizontal or directional drilling have been discussed, no large-scale attempts at this technique for liquids addition have been reported. After installation of the pipe and bedding material, the excavated waste can be compacted back in place over the trench and possibly followed by a soil cover.

The horizontal liquids addition pipes are either constructed to individually exit from the side of the landfill where they can be connected to the manifold system, or bundled/connected together in groups within the landfill and exiting at common points. As discussed in Chap. 11, while individual pipe penetrations provide for a greater level of control, this results in increased maintenance and a greater potential for side slope seepage. Regardless of configuration, a setback distance of non-perforated pipe coupled with no permeable bedding material must be included in the design and construction to minimize seepage and possible slope instability issues. A collar or plug of low permeability soil placed at the location where the perforations and bedding material stop and where the solid pipe exits the landfill is a common approach to minimize channeling of liquids along the pipe to the side of the landfill (Fig. 9.15).

Fig. 9.13 Trenching machine used for installing horizontal injection pipe into the surface of a landfill lift

Fig. 9.14 Perforated HDPE injection pipe installed using a trenching device

Fig. 9.15 Clay seepage collar construction at the end of a horizontal injection trench where pipe perforations start

9.2.2 Blankets

Horizontal blankets, also referred to as buried infiltration beds or galleries, consist of a pipe embedded in a highly permeable media laid over a much larger area of landfilled waste than a buried trench. Like horizontal trenches, this system is also installed as landfilling progresses (Fig. 9.16) and in some respects can be regarded as a buried infiltration pond. While the area demands are much larger than a trench, this larger area minimizes the need for pressurized injection to distribute liquids.

Effective blanket construction requires placement directly on the waste to avoid channeling concerns, so cover soil should be scraped from the waste surface prior to installation. Similar drainage materials as those described for injection trenches can be utilized, such as shredded tires (Fig. 9.17) and crushed glass. Another material proposed for use in permeable blankets is geonet, a geosynthetic material commonly used for leachate drainage in modern leachate collection and removal systems (see Chap. 2). Khire and Haydar (2005) used a 34 m by 12 m permeable blanket constructed with a 5-mm geonet sandwiched between a non-woven geotextile on top and a woven geotextile at the bottom. To facilitate moisture distribution and to minimize channeling, the next waste lift should be installed directly on the blanket if the operation permit allows. Geotextile installation over the drainage layer merits consideration to prevent overlying sediment migration into the drainage media. Like the horizontal trench systems, basic survey information about the extent and constructed elevation of blanket systems should be recorded to assess system

Fig. 9.16 A horizontal drainage blanket of crushed glass installed on a landfill lift

Fig. 9.17 A horizontal drainage blanket of shredded tires installed on a landfill lift

performance and to facilitate the construction of gas collection infrastructure and similar engineered landfill components in the future. It is important that the liquid feed pipe be properly designed, constructed, and protected during landfill operation to avoid pipe damage, because significant damage would result in the loss of liquids addition capacity to that blanket. Redundant liquid feed pipes may provide a factor of safety against pipe crushing compared to using a single pipe.

9.2.3 Combined Systems

Seeps can be problematic with pressurized horizontal liquids addition systems (see Chap. 11), and a common route for leachate to channel to the landfill side slope is the pathway created by the trench and the pipe. Some designers and operators thus opt to connect multiple horizontal trenches and blankets together within the landfill, which results in fewer penetrations to the side of the landfill. Horizontal systems also have the potential to be utilized in conjunction with vertical systems. One example of this approach would be the construction of horizontal trenches or blankets throughout the progression of the landfill, but without the connection to exit lines leaving the landfill. At a later time, vertical wells could be drilled into the landfill with the purposeful intention of intercepting the buried horizontal devices (Fig. 9.18). This would require careful surveying of device locations, especially trenches, so a hydraulic connection can be made. Liquid would be added to the vertical entry points on the surface of the landfill, but the liquids addition capacity would be much larger than a typical vertical well.

9.3 Design Methodology

The design process begins with determination of the target volume of liquids to be added to the landfill and the determination of the rate at which that volume will be added to the landfill. Chapter 6 provides information for completing these design steps. Once the target liquids addition volume and flow rate have been determined for the landfill as a whole, the design must include the individual horizontal devices and their operating conditions, with ultimate integration into a design of multiple devices comprising the complete system. The design of an individual horizontal device includes specification of the trench configuration and materials, the length of perforated pipe, and the flow and/or pressure at which the device should be operated.

Similar to the design of a vertical system, horizontal system design entails locating a sufficient number of horizontal trenches (or blankets) throughout the landfill and designing a delivery system to convey liquids to each of the liquids addition devices. The design engineer should aim to efficiently distribute liquids throughout the landfill by systematically locating trenches within a set of established boundaries. These boundaries might include the anticipated saturated zone of adjacent trenches, slopes, the landfill surface, and the landfill bottom.

To design within these constraints, two major design parameters must be identified for a given landfill: (i) the flow rate that can be added to a given horizontal device and (ii) the shape of the saturated zone that results from adding that flow rate to the horizontal device. Both the flow and dimensions of a saturated zone can be predicted by the engineer for a given design configuration, landfill properties, and operation conditions using a combination of historic performance from similar facilities and predictive tools resulting from fluid flow modeling techniques; both are discussed in the remainder of this chapter.

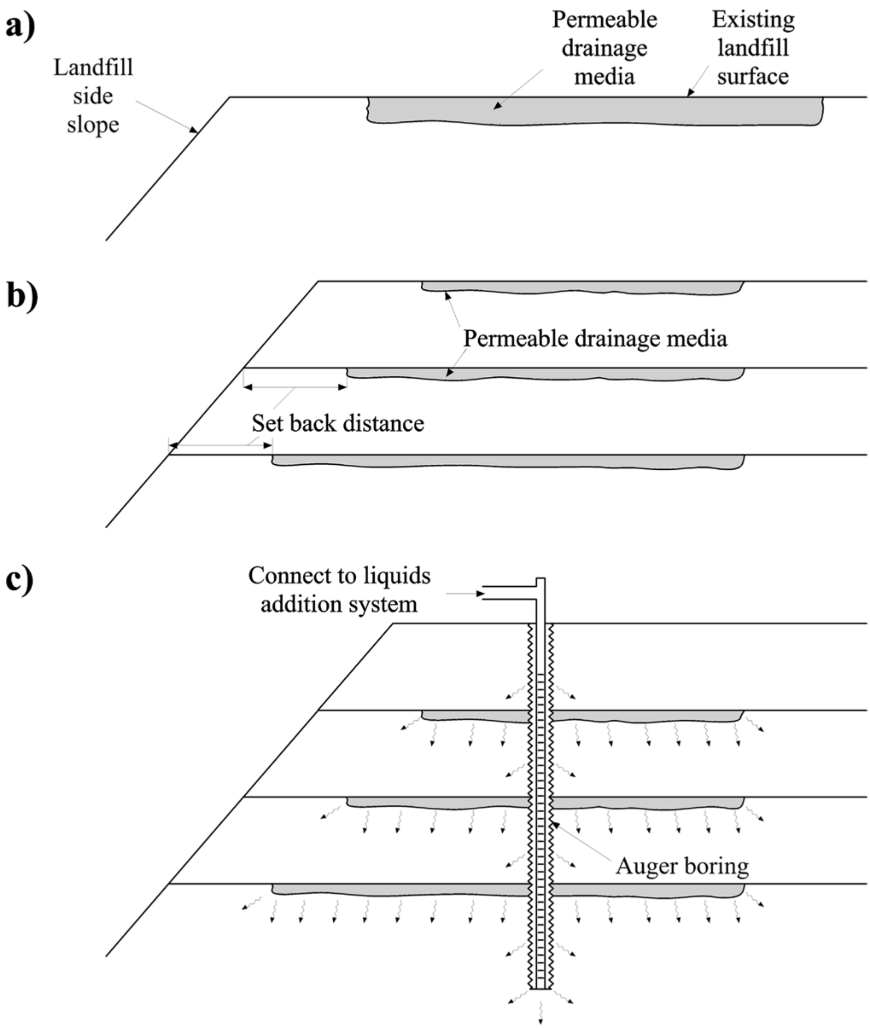

Fig. 9.18 Illustration of combining vertical and horizontal liquids addition (**a**) The selected area is backfilled with permeable media (**b**) Successive waste lifts have an area backfilled with permeable media in a fashion similar to that shown in (a) (**c**) A vertical well is drilled through the horizontally-constructed permeable media beds and the screened section intersects with each permeable layer

Figure 9.19 illustrates the typical performance of a pressurized horizontal liquids addition system at the beginning of operation (data from Alachua County Southwest Landfill; see Chap. 4). When liquids are first added, resulting back pressures are low; as the pipe and trench fill with liquid, followed by saturation of void space in the surrounding waste, the back pressure increases. The linear flow rate (flow rate per length of pipe or trench) decreases as a function of the characteristics of the pump (results from a centrifugal pump are shown). The relationship between linear flow rate and pressure is described as fluid conductance (κ); Fig. 9.19 shows a rapid decrease in fluid conductance after the initial start of operation, followed by relatively steady conditions.

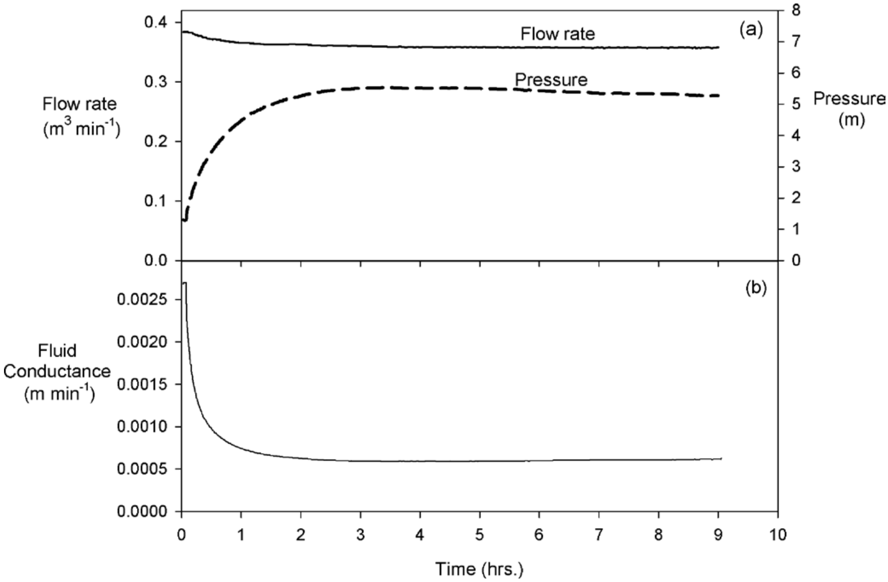

Fig. 9.19 Performance for a pressurized horizontal liquids addition device (**a**) linear flow rate and pressure, (**b**) fluid conductance

While liquids addition may be practiced in a continuous fashion, operators more commonly operate such systems intermittently as a result of landfill operation time limitations, availability of liquids, and necessity for inspection. Figure 9.20a provides an example of typical fluid conductance results for intermittent pressurized liquids addition (data from Polk County North Central Landfill; see Chap. 4). At the beginning of each liquids addition cycle, fluid conductance starts high and quickly drops to a steady value. When presented as a function of cumulative time (Fig 9.20b), the fluid conductance is observed to return to the previous steady conditions relatively soon, although over time the fluid conductance slowly decreases.

Figure 9.21a illustrates the change in pressure in response to stepped changes in liquids addition rate to a horizontal trench. The fluid conductance displays a relatively consistent pattern, with an initial drop as the available void space in the pipe, trench, and spacing and surrounding the waste are filled, followed by a steadily decreasing flow rate as more pressure is required to distribute the liquids into the waste through an expanding saturated zone. Horizontal lines that have not been operated for extended periods often encounter an initial period of resistance (higher pressure) at the start of liquids addition as a result of the gas pressure built up in the pipe (Townsend et al. 1994).

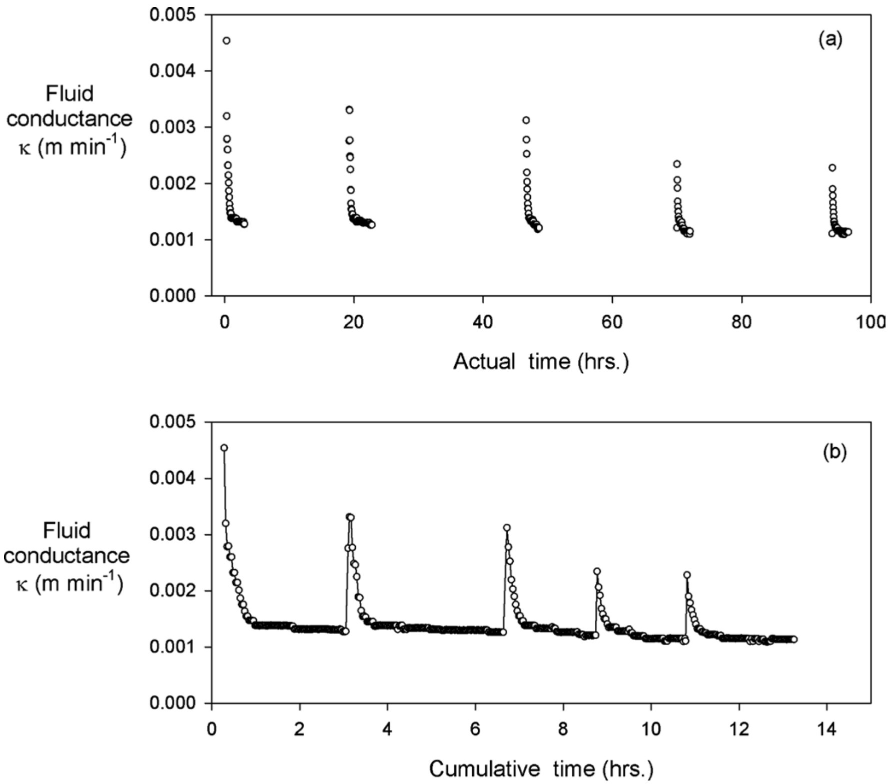

Fig. 9.20 Comparing fluid conductance change with time for a pressurized horizontal liquids addition (**a**) actual time (intermittent liquids addition), (**b**) cumulative operating time

The fluid flow modeling techniques discussed in Chap. 5 can be used to examine the distribution of liquids into the waste surrounding a horizontal liquids addition device as a function of operating conditions and landfill properties. Several authors have presented examples of the use of such modeling for horizontal trenches and blankets in landfills. In an effort to estimate the zone of influence of horizontal trench, Townsend (1995) developed an equation describing flow through a horizontal line source in a porous medium based on saturated and steady-state conditions. McCreanor and Reinhart (2000) numerically simulated fluid flow from horizontal injection trenches using SUTRA; the impacts of waste heterogeneity and anisotropy were investigated, but operating conditions such as injection pressure, and flow rate at the trench, which is an important operation variable, was not examined. Haydar and Khire (2005) numerically modeled fluid flow from horizontal trenches using HYDRUS-2D and examined the steady-state flow rate as a function of injection pressures, trench geometry and size, hydraulic conductivity of the trench backfill, and horizontal and vertical trench spacing. Jain et al. (2010a, b, 2013) modeled

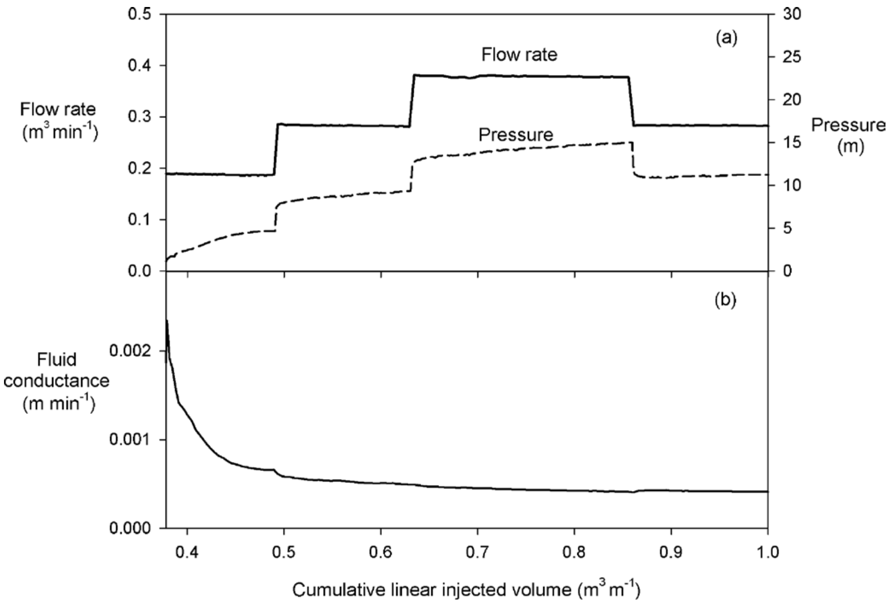

Fig. 9.21 Pressurized horizontal liquids addition performance in response to changing operating conditions (**a**) flow rate and pressure, (**b**) fluid conductance

liquids flow from horizontal trenches as a function of media properties (e.g., waste hydraulic conductivity, porosity), trench dimensions, and operating pressure and developed design charts to estimate both steady-state and transient flow rates and lateral and vertical zone of impact; this approach will be presented in greater detail in the following sections.

As an illustration of what the typical output results from a simulation of fluid flow into a horizontal liquids addition devices, Fig. 9.22 and 9.23 present the output of SEEP/W simulations for a horizontal trench and a horizontal blanket operated continuously under constant pressure. The data presented in these figures (flow rate, extent of lateral and vertical wetted front movement with time) illustrate typical outcomes for such a simulation, and the magnitudes are only reflective of the specific scenario and conditions modeled. As liquids are added, the flow rate drops notably in the first part of operation, followed by a relatively steady flow that decreases slowly with time. The decrease in flow rate corresponds to the expanding wetted zone around the device.

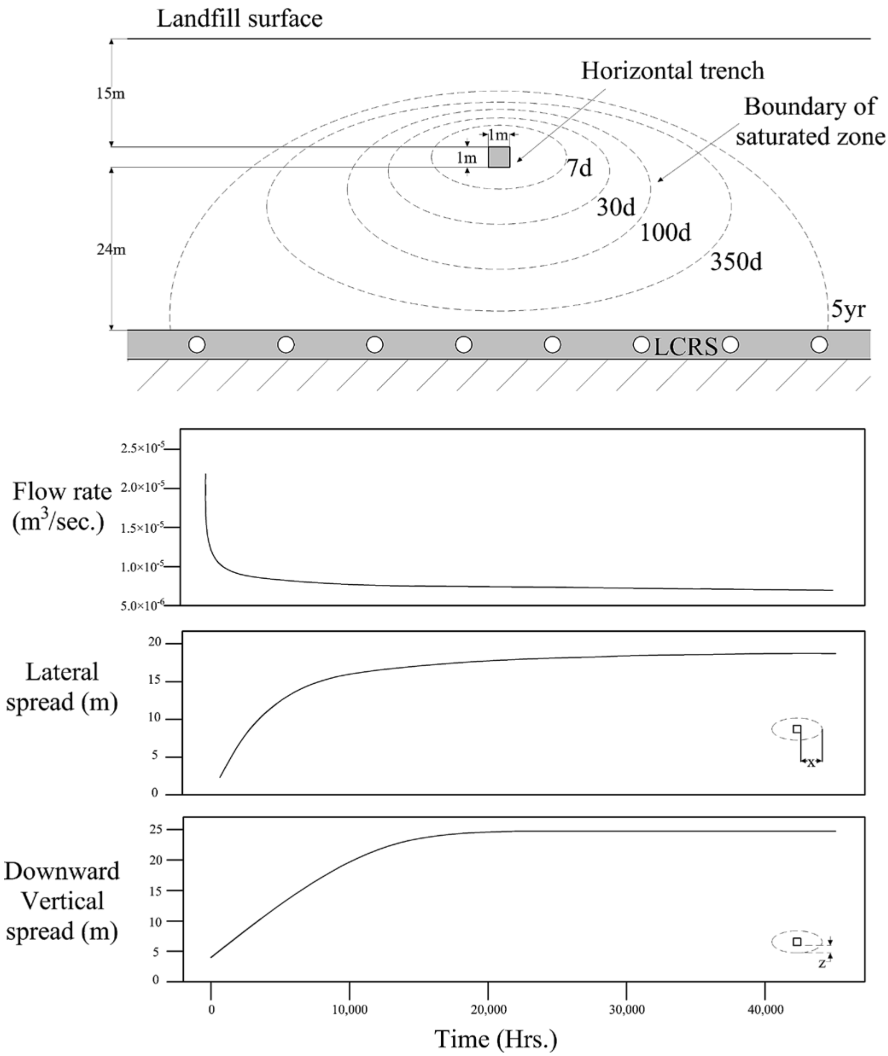

Fig. 9.22 Example output of from a SEEP/W simulation of pressurized liquids addition into a horizontal trench

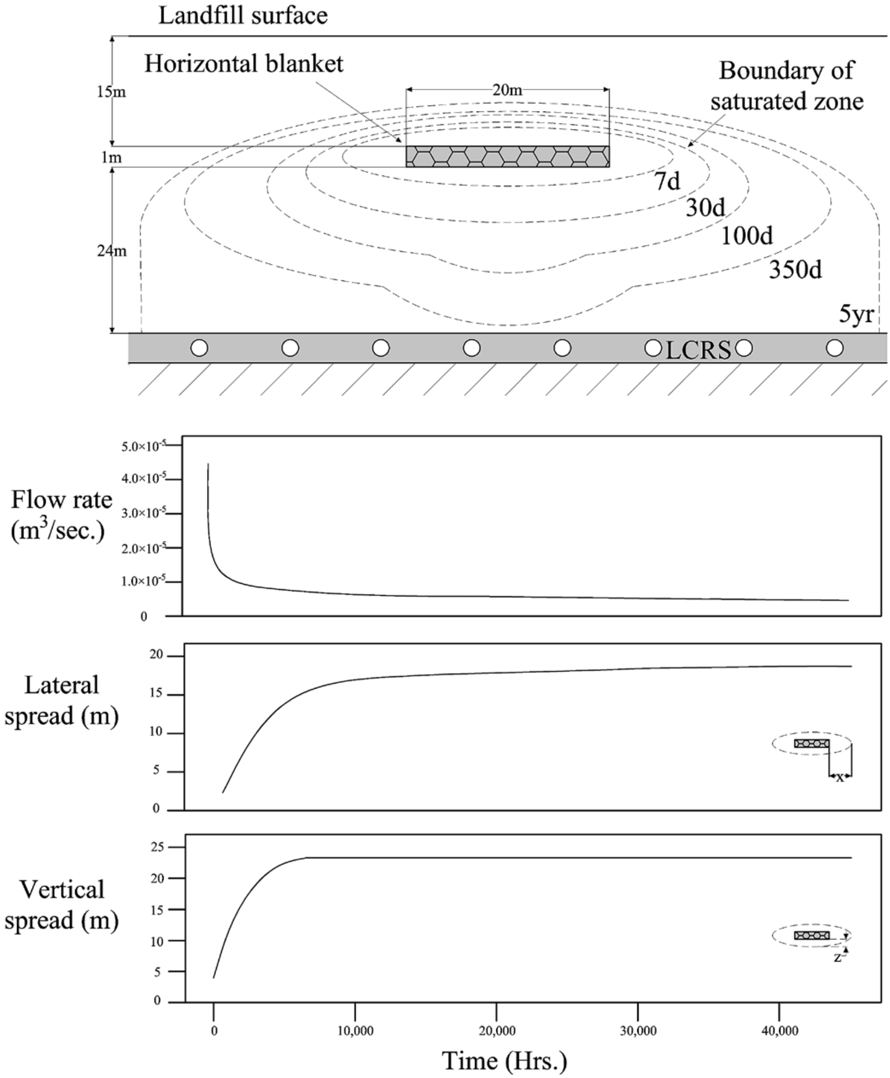

Fig. 9.23 Example output of from a SEEP/W simulation of pressurized liquids addition into a horizontal blanket

9.4 Flow Rates

9.4.1 Operational Experience

The performance of horizontal liquids addition systems has been studied at a number of landfill sites. Some of the data reported provide either total volumes or general ranges of liquids added, but without corresponding addition pressures, addition times, or operational characteristics. Miller and Emge (1997), for example, reported the qualitative performance of horizontal injection trenches in distributing liquids to MSW in a landfill. In a review of leachate recirculation rates for several different landfills, Bareither et al. (2010) reported volumetric dosing rates to range from 0.178 to 0.939 m^3 per m of pipe (for dosing periods of less than 1 day).

Townsend and Miller (1998) evaluated the hydraulic performance of horizontal injection trenches at a lined landfill in FL, US (Alachua County Southwest Landfill; see Chap. 4). Leachate was recirculated into the waste mass using 7.6-cm (3-in) diameter perforated horizontal injection lines installed in 1 m by 1 m (3.3 ft by 3.3 ft) horizontal trenches and at three different depths during landfill operation; shredded tires were used as a bedding media in most of the lines. The trenches were approximately 33 m (100 ft) apart horizontally and 4.5 m (15 ft) apart vertically. The lengths of the injection lines ranged from 100 to 220 m (330–720 ft). Approximately 30,000 m^3 (7.9 million gal) of leachate were recirculated over a period of 19 months. All the injection lines were characterized in terms of flow rates and associated leachate back-pressures. The maximum leachate recirculation rate per unit length of injection line was reported to be 3.0×10^{-3} m^2/min (0.22 gpm/ft). The fluid conductance ranged from 9.9×10^{-5} to 5.4×10^{-4} m/min (0.00243–0.0113 gpm/ft^2). Trenches without bedding initially had lower fluid conductance values, but with time, these values approached those in the trenches with shredded tires. Fluid conductance values were lower for those trenches buried deeper in the landfill.

Pressurized liquids addition into buried horizontal trenches were closely monitored at the Polk County North Central Landfill (see Chap. 4). Leachate was recirculated into more than 100 trenches (approximately 1 m deep by 1 m wide) with lengths up to 220 m (720 ft). Distribution pipes were constructed of 10-cm (4-in.) diameter HDPE with 0.95-cm diameter perforations (0.375-in). Bedding materials used included shredded automobile tires and broken glass. In several cases no bedding material was used (excavated waste was placed back into the trench after pipe installation). More than 100,000 m^3 (25 million gal) of leachate were added to the landfill. Larson (2007) and Kumar (2009) measured fluid conductance values, which were found to decrease with the cumulative volume of liquids added. For trenches where a cumulative 1.24 m^3 of leachate per m of pipe (100 gal per ft) were added, the average κ was 1.2×10^{-4} m/min (0.029 gpm/ft^2), ranging from 2.1×10^{-4} to 5.2×10^{-3} m/min (0.005–0.13 gpm/ft^2). For trenches where a cumulative 2.48 m^3 of leachate per m of pipe (200 gal per ft) were added, the average κ was 4.9×10^{-4} m/min (0.012 gpm/ft^2), ranging from 9.8×10^{-5} to 2.0×10^{-3} m/min (0.002–0.05 gpm/ft^2). Measured κ values were similar for shredded tires and crushed glass. In the first stages of liquids addition, κ values for trenches with bedding were greater than those without bedding media, and were greater for trenches closer to the surface compared to deeper locations in the landfill. As liquids addition proceeded, these differences decreased.

Doran (1999) reported field experience with leachate recirculation using horizontal injection lines at a landfill in Minnesota. Leachate was recirculated into a 5.2-ha (12.8-acre) landfill using a set of 11 injection lines installed in a 0.6 by 0.6 m

(2 by 2 ft) trench. A total of approximately 1,500 m^3 (0.4 million gal) of leachate was recirculated using horizontal injection trenches. A flow rate of approximately 2.2×10^{-4} m^3/min-m (25 gpm/ft) of injection line was used. The maximum flow rate was reported to be 0.38 m^3/min (100 gpm) (Doran 1999). Less information is available regarding blanket performance; Khire and Haydar (2005) report adding leachate to a buried horizontal blanket at rates ranging from 0.9 to 2.6 m^3/h per m of blanket width.

9.4.2 Flow Estimation Methods

Similar to the design methods for vertical systems (presented in Chap. 8), the designer can estimate the achievable flow into horizontal devices using a fluid flow-modeling program. Example modeling output was presented previously in Figs. 9.22 and 9.23 for both a buried horizontal trench and a blanket, each simulated at constant pressure. Again, similar to both surface systems and vertical wells, the flow rate decreases with time as the wetting front expands into the landfill, ultimately reaching a steady-state condition.

Several methods have been developed that provide a simplified approach to estimate achievable flow into buried horizontal devices without the need for modeling. Xu et al. (2014) conducted a series of SEEP/W simulations for a range of operating conditions and developed best-fit relationships to predict achievable flow into horizontal trenches. The following relationship for flow rate was developed:

$$Q = 1.82 \cdot K_z \cdot P \cdot \sqrt{A} \tag{9.1}$$

where Q = the flow rate per unit blanket length (L^3 T^{-1} L^{-1}); A = waste anisotropy (K_x/K_z); and P = injection pressure (L). The ratio of Q/K_Z represents the fluid conductance (κ).

Jain et al. (2010b) developed an approach using dimensionless parameters and design charts to estimate steady-state flow rate in a buried horizontal liquid addition device. The approach was developed to be equally applicable to trench and blanket systems. SEEP/W simulations were conducted over a range of conditions that would reasonably be encountered at a landfill site. The parameters evaluated included the depth and width of the trench or blanket, and the pressure within the device, which could be a hydrostatic pressure either less than or greater than the thickness of the trench. The simulation results were used to formulate dimensionless parameters and design charts to allow for the determination of steady-state flow. The simulation results were presented in a series of dimensionless charts to broaden the scope of application for the results beyond the range of individual parameter values used for modeling.

The first step in determining steady-state flow rate is calculation of the dimensionless variable η as follows:

$$\eta = \frac{w^2}{l^2} \cdot A \tag{9.2}$$

Where w is the depth of the trench, l is the width of the trench, and A is the anisotropy (K_X/K_Z). The variable η indicates the dominant flow direction, vertical or horizontal. A low η value signifies a flow dominant in the vertical direction, whereas a high η value indicates a flow primarily in the horizontal direction. A trench would tend toward a greater η value compared to a blanket.

The designer then identifies a target injection pressure head (p_I). Trenches are frequently operated at liquid pressures that exceed the depth of the trench. For blankets, depending on the thickness and area of the blanket, the liquid pressure may be limited to a liquid depth less than the thickness of the blanket (in this case, the liquid depth is treated as the depth of the device). Dividing the target injection pressure head (in units of water column depth) by the depth of the trench, the dimensionless injection pressure head, p_{ID}, is calculated as:

$$p_{ID} = \frac{p_I}{w} \tag{9.3}$$

Now that the values of p_{Id} and η have been determined, the steady-state dimensionless flow rate, q_s, for a horizontal source can be estimated using the chart presented in Fig. 9.24.

Figure 9.24 is similar to Fig. 7.9 presented in the discussion of surface systems (Chap. 7), but provides P_{ID} values greater than 1; this allows for the consideration of the pressurized addition only possible in a buried system (not a surface source).

Once q_s has been estimated, the steady-state flow rate (Q_S) into the horizontal device can be calculated as

$$Q_{hs} = q \cdot l \cdot K_z \tag{9.4}$$

where the terms are the same as previously defined.

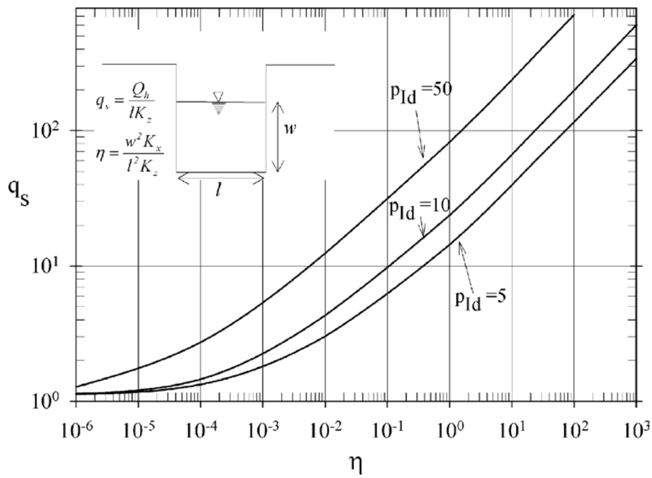

Fig. 9.24 Design chart for estimating steady state flow (q_s) into a horizontal source (trench or blanket)

9.5 Saturated Zone Profiles

The ability to estimate the size and shape of the saturated zone surrounding a horizontal trench can be a helpful tool for the designer in determining the appropriate location and spacing of devices. Again, flow patterns are idealized and the designer must factor this into the final design. Figure 9.20 presents a definition sketch of critical parameters associated with the system modeled.

Townsend (1995) developed an equation to estimate the steady-state zone of influence of a horizontal injection trench, as shown in (9.5)

$$X = \frac{Q}{2\pi K_z} \tan^{-1}\left(\frac{X}{Z} \sqrt{\frac{K_z}{K_x}} \right) \tag{9.5}$$

This can be expressed in a form such that Z can be solved directly and a saturated zone profile can be easily plotted.

$$Z = \frac{X\sqrt{\frac{K_z}{K_x}}}{\tan\left(\frac{2X\ \pi\ K_Z}{Q} \right)} \tag{9.6}$$

This relationship was derived on the assumption that the injection trench could be treated as a line source and the surrounding media was homogenous. Based on Townsend's equation, the maximum upward movement (Z_{max}) and lateral spread of moisture from the trench (X_{trench}) are presented in (9.7) and (9.8), respectively.

$$Z_{\max} = \frac{Q}{2\pi\sqrt{K_x K_z}} \tag{9.7}$$

$$X_{trench} = \frac{Q}{4K_z} \tag{9.8}$$

Once the injected liquid reaches the maximum lateral distance, gravity and the saturated zone will only expand in the vertical direction until it reaches the leachate collection system (neglecting any channeling or preferential lateral flow paths). Using Townsend's Equation, the maximum lateral spread distance ($X_{trench,max}$) can be calculated, as shown in (9.9).

$$X_{trench,\max} = \frac{Q}{2K_z} \tag{9.9}$$

Xu et al. (2013), as part of the work referenced in the previous section, developed a series of equations based on SEEP/W modeling results to predict the saturated zone surrounding a horizontal liquids addition trench. With this approach, the lateral spread of liquids from a horizontal trench at the maximum distance from the trench ($X_{trench,\ max}$) can be determined. Using the estimate for Q for a horizontal trench (9.1), $X_{trench,max}$ can be solved as:

$$X_{trench,\max} = \frac{Q}{2K_z} = \frac{1.82P \cdot K_z \cdot \sqrt{A}}{2K_z} = 0.91P \cdot \sqrt{A} \tag{9.10}$$

When Xu et al. (2014) simulated the zone of saturation surrounding a horizontal trench over a range of typical landfill conditions and used this to develop an equation for the saturated zone, the results differed somewhat from the solution presented in (9.5) and (9.6). The lateral spread at the trench was found as:

$$X_{trench} = 0.65 X_{\max} \tag{9.11}$$

Which is 30 % greater than that estimated by the Townsend (1995) equation. In a similar manner, Xu et al. (2014) also modified the Townsend (1995) equation for the shape of the saturated zone as follows:

$$Z = \frac{X\sqrt{\dfrac{K_z}{K_x}}}{\tan\left(\dfrac{2X\ \pi\ K_Z}{Q\ R}\right)} \tag{9.12}$$

where R is a correction factor defined as:

$$R = \begin{cases} 1.3 & Z < 0 \\ 1.3 - 0.3\left(\dfrac{X - X_{trench}}{X_{\max} - X_{trench}}\right) & Z \geq 0 \end{cases} \tag{9.13}$$

With this equation, a modified form of the saturated zone equation presented earlier can be calculated that better reflects the results of modeled porous media flow simulations.

9.6 Device Spacing

The engineer must specify the number of horizontal devices for installation and their locations. The information presented in Sect. 9.4 allows the engineer to estimate the flow rate that can be added to a given horizontal device. This, coupled with the liquid addition targets discussed in Chap. 6, can be used to provide a preliminary estimate of the number of devices.

Engineers often specify device spacing based on the distance needed to provide adequate moisture distribution within the landfill. The methods in Sect. 9.5 allow for the estimation of steady state zones of impact of a line source, and thus may be useful for device spacing. However, the engineer should also factor operating time into the design. The time needed to reach steady state may be large, and thus in cases where more rapid coverage is desired, closer spacing may be necessary. Jain et al. (2010b) provides a methodology for determining the time needed to reach steady-state conditions.

Design charts developed in the Jain et al. (2010b) approach allow X_{trench} to be solved as a function of the steady state dimensionless flow rate, q_s. The equations developed by Townsend (1995) and Xu et al. (2014) corresponded to a line source, whereas design chart developed by Jain et al. (2010a, b) can be used to estimate the zone of impact of a horizontal source as a function of not only waste properties but source (trench or blanket) dimensions as well. The following equation defines x_{Ids}, which is equivalent to the ratio of X_{trench} at steady-state ($X_{trench,s}$) and the trench width, l (see Fig. 9.25).

$$x_{Ids} = \frac{x_{trench,s}}{l} \tag{9.14}$$

Once the designer estimates dimensionless flow rate (q_s) for selected source dimensions, injection pressure, and waste properties, q_s can be used to estimate X_{Ids} using the design chart presented in Fig. 9.26.

Using (9.14), X_{trench} occurring at steady state can be determined. As discussed earlier, in order to reach steady state, a certain volume of liquids must be added to the device to fully saturate the surrounding zone of impact. Figure 9.27 provides the relationship between the dimensionless parameter, η, the dimension injection

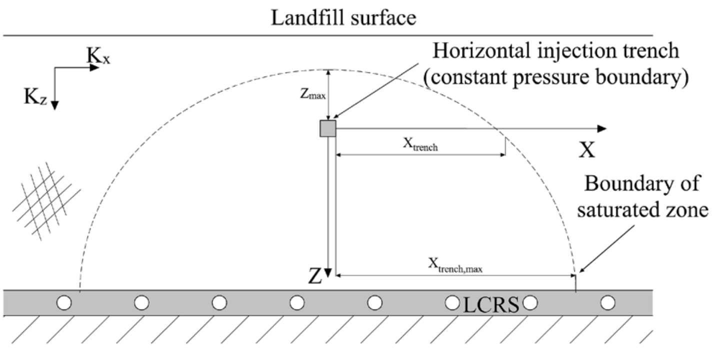

Fig. 9.25 Definition sketch for major dimensions associated with estimate of pressurized liquids addition into a buried horizontal device in a landfill

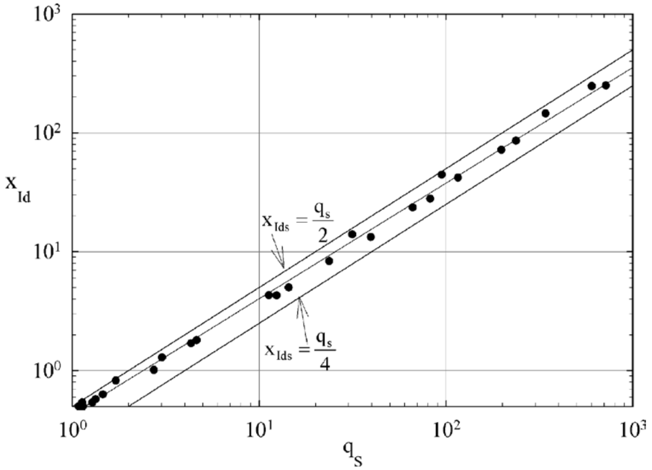

Fig. 9.26 Design chart for x_{Ids} as a function of q_S

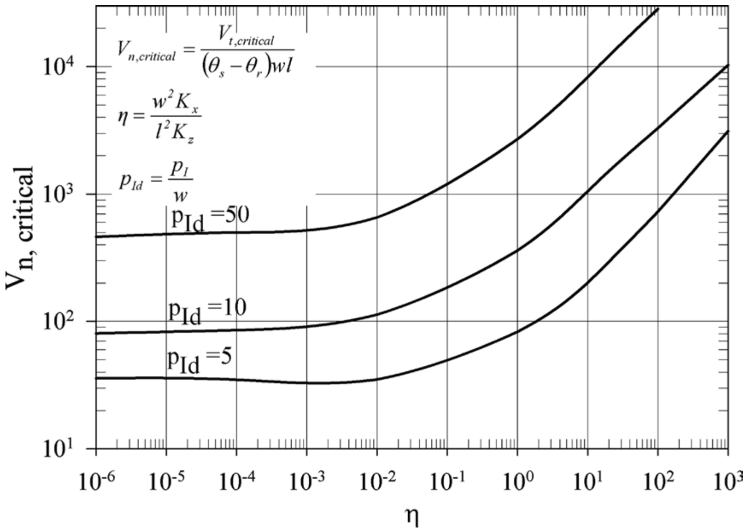

Fig. 9.27 V_n, critical as a function of η for varying p_{Id}

pressure head (P_{Id}), and the critical number of pore volumes, $V_{n,critical}$, required to reach steady-state for a single device.

To evaluate the suitability of the pore volume to meet the design and operation objectives of the system, the total volume of liquids needed to achieve a fully saturated zone at steady state should be calculated. This value, along with the necessary time required to reach steady state, can be used to determine a suitable design

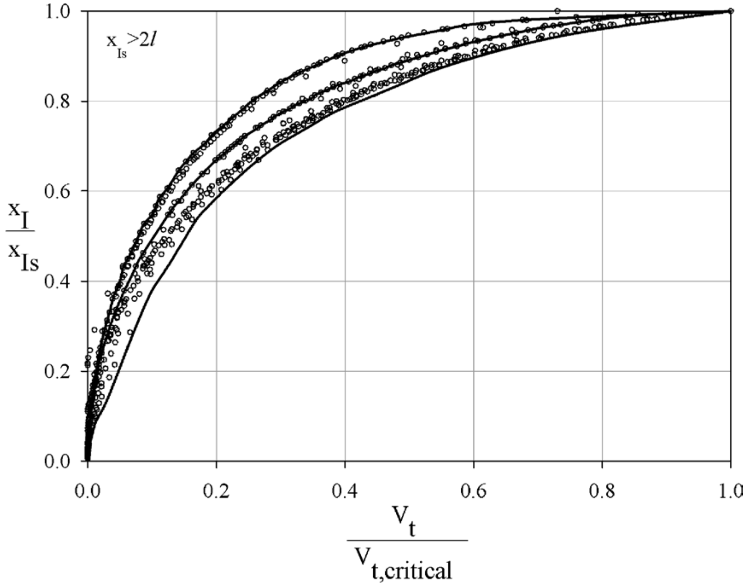

Fig. 9.28 Design chart for the fraction of maximum lateral extent ($X_{trench}/X_{trench,s}$) attained as a function of $V_t/V_{t,critical}$

spacing. The volume of liquids added to a single device required to form a fully saturated zone at steady state, $V_{t,critical}$, can be determined as follows:

$$V_{n,critical} = \frac{V_{t,critical}}{lw(\theta_n - \theta_r)} \tag{9.15}$$

where $(\theta_n - \theta_r)$ is the drainable porosity of the waste.

The designer can estimate the magnitude of X_{trench} at any volume added less than steady state (V_t) using Fig. 9.28, which presents a design chart the ratio of X_{trench} to $X_{trench,s}$ as a function of V_t to $V_{t,critical}$. Figure 9.28 shows the range of modeling result for Jain et al. (2013); this figure demonstrates that approximately 80–90 % of $X_{trench,s}$ is reached by adding only 40 % of $V_{t,critical}$. Utilizing the ratio found using Fig. 9.28, X_{trench} can be estimated; an appropriate spacing for horizontal wells would be a value twice that of X_{trench}.

The designer may also need to predict the depth of the saturated zone beneath the trench as part of evaluating appropriate device spacing (Z_I; see Fig. 9.25). Figure 9.29 presents a design chart for estimating the magnitude of Z_I that would occur when X_{trench} reaches steady state ($Z_{I,S}$). Figure 9.29 plots the $Z_{I,S}$ as a function of the ratio of $V_{n,critical}$ to q_s; determination of both of these values has previously been presented.

In a similar manner as described for X_{trench}, the value of the H that occurs prior to steady state conditions can be estimated. Figure 9.30 presents the $X_I/X_{I,S}$ as a function of V_t to $V_{t,critical}$. A line segregating the simulation results into two groups

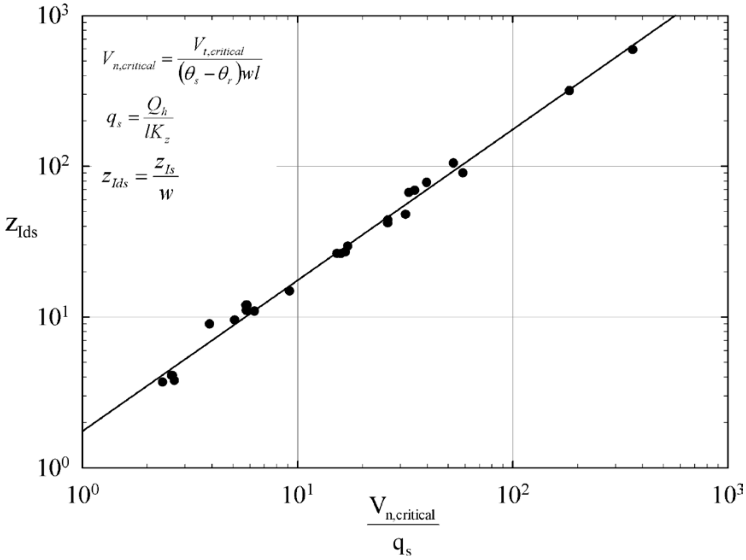

Fig. 9.29 Design chart for z_{Ids} as a function of q_S

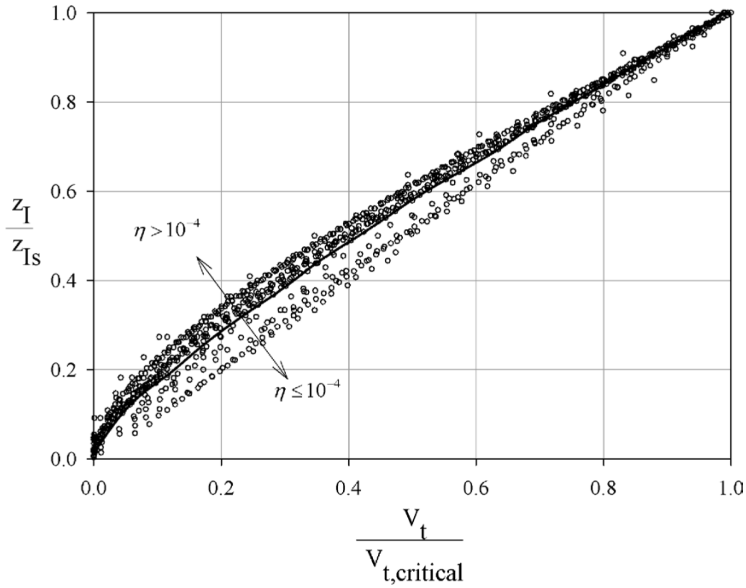

Fig. 9.30 Fraction of maximum vertical extent (z_{Is}) attained as a function of fraction of volumes of moisture needed ($V_{t,\ critical}$) to reach steady state

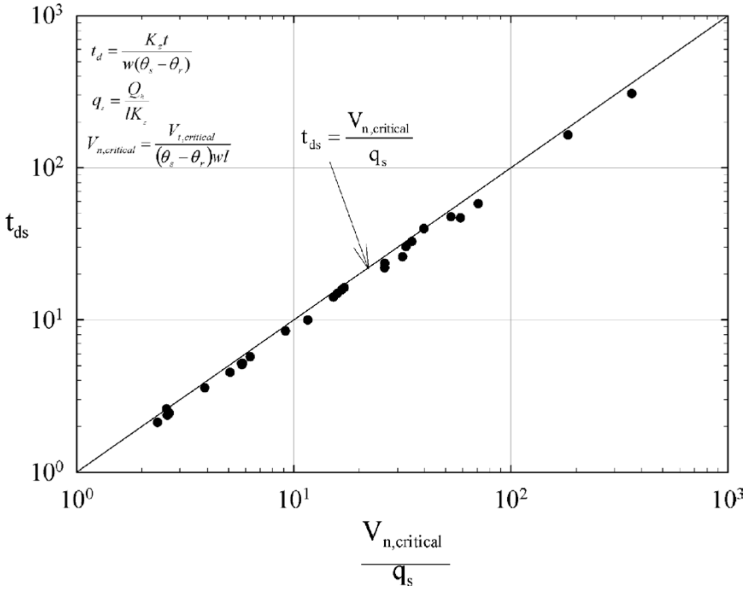

Fig. 9.31 Design chart for t_{ds} as a function of $V_{n,critical}/q_s$

($\eta \le 10^{-4}$ and $\eta > 10^{-4}$) is shown; data from simulations with $\eta > 10^{-4}$ fell above the line, whereas data from simulations with $\eta \le 10^{-4}$ fell below the line. Approximately 40–55 % of the vertical zone of impact can be achieved with the addition of 40 % of liquids volume needed to achieve the steady-state vertical extent of the zone of impact.

Finally, the time to reach the steady state (t_{ds}) can be estimated with an estimate of the ratio of $V_{n,critical}$ to q_s. The design chart (presented in Fig. 9.31) can also be used for estimating the ratio of the average flow rate resulted from an given liquids addition pressures to flow rate resulting at steady state; this value would be equal to the value of $V_t/V_{t,critical}$ divided by the value of t/t_s.

9.7 Operation, Monitoring and Closure

An operations plan for the horizontal liquids addition system should be prepared by the design engineer and included as part of the site's overall operations plan (see Chap. 3). Specific operation details will include target injection lines, liquids addition rates, operation times, and operation pressure. The engineer will specify these parameters based on the objectives of the system, site-specific constraints, and using the design methodology outlined in the previous sections. At sites where landfill gas collection is employed, the designer must closely integrate construction and operation considerations of horizontal recirculation systems with the phasing and operation of gas collection systems (see Chap. 13).

While completely automated systems can be designed and constructed, most designers elect to implement systems that still require routine operator interaction that is largely manual. Similarly, while liquids addition can be practiced over a 24-h period, many designers elect to implement systems that only are operated during working hours and thus involve a startup and shutdown effort on a daily basis. This allows the operator flexibility to collect data largely corresponding to periods where the system is operating and reduces the likelihood that issues (e.g., seeps) occur during hours when the landfill is not open. Typical operator duties are described in more detail in Chap. 15, but entail initial inspection, setting of appropriate valve settings, system startup and initial adjustment, monitoring and recording of data, and shutdown. Performance data should be routinely recorded.

Similar devices as those used for horizontal liquids addition are also used at many sites for gas collection (see Chap. 13). Thus, designers and operators may try to use horizontal lines for the dual purpose of liquids addition and gas collection. Experience by many operators attempting this, however, has shown that after substantial amounts of liquids have been added (i.e., those needed to achieve the type of moisture distribution described in the previous sections) these devices are not effective for gas collection (Townsend et al. 1994). While waste decomposition may be enhanced thus producing more biogas, the pore space surrounding the liquids addition devices is largely filled with liquids, which ultimately restricts gas travel to the device. The use of liquids addition devices for gas collection is discussed in greater detail in Chap. 13.

When horizontal liquids addition devices are no longer used (for liquids addition or gas extraction), they need to be appropriately abandoned. In addition to removing manifold pipe and associated infrastructure, this should include necessary capping (and possibly plugging) of the pipes and potentially placing low permeability soil or concrete over the pipe penetrations. Failure to adequately seal the pipes could result in future leachate seeps or gas escape along the preferential paths resulting from the trench and pipe.

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Chapter 10
Leachate Collection and Removal Systems (LCRS)

Abstract The basic function and importance of leachate collection and removal systems are first presented in Chap. 2, but Chap. 10 significantly expands this introduction and provides a discussion of the major design and operation considerations of LCRS in the context of sustainable landfilling. Leachate impingement on bottom liner systems, techniques to predict leachate head on the liner as a result of added liquids, settlement considerations, and clogging mechanisms and avoidance procedures are presented. Each LCRS concept is presented with a particular focus on how sustainable landfilling approaches can influence the designer's and operator's approaches to prevent excessive build-up of liquids on the bottom liner system, which is one of the most critical pieces of infrastructure that protects the environment from potential impacts of landfills.

Keywords Landfill • Bioreactor • Leachate • Recirculation • Collection • Pipe • Clogging

10.1 Leachate Removal Fundamentals

The function and general configuration of the leachate collection and removal system (LCRS) were described in Chap. 2. For landfills with elevated moisture content, either as a result of purposeful liquids addition, site stormwater management practices, or incoming waste properties, the importance of the LCRS for a lined landfill cannot be overstated; this chapter is thus devoted to this landfill component. The LCRS will in most regulatory jurisdictions be required to maintain leachate depth on the liner to less than a specified threshold (in the US, this depth is less than 0.3 m). Moreover, a properly functioning LCRS is critical to limit leachate discharges from seepage at the landfill base (refer to Chap. 11) and to minimize slope stability problems (refer to Chap. 12). Therefore, the successful removal of liquids from a LCRS is an important component of all landfill designs, especially at facilities practicing sustainable operation by accelerating waste stabilization.

The components of a LCRS include a liner system graded (sloped) to promote gravity drainage, drainage media to route the liquids rapidly off of the liner to targeted conveyance points, drains consisting of perforated pipes, and pumping sys-

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tems to remove leachate from the landfill. In essence, the LCRS is a high-permeability drainage layer placed between the low-permeability liner system and the waste. Other components of the LCRS include its accompanying pipes and sumps and a liquids removal system. Leachate removal is accomplished by gravity drainage from sheet flow over the sloped liner, as well as from rock drains and perforated pipes that intercept the sheet flow at intervals necessary to minimize the depth of ponded leachate on the liner. The rock drains and pipes route the leachate to a low point (i.e., sump) from which the leachate is periodically pumped from the landfill or allowed to gravity drain to a collection point outside the landfill. In some cases, the pipes penetrate the liner system and discharge leachate to an external pump station (Fig. 10.1a). Alternatively, pumps can be installed within the landfill unit (Fig. 10.1b).

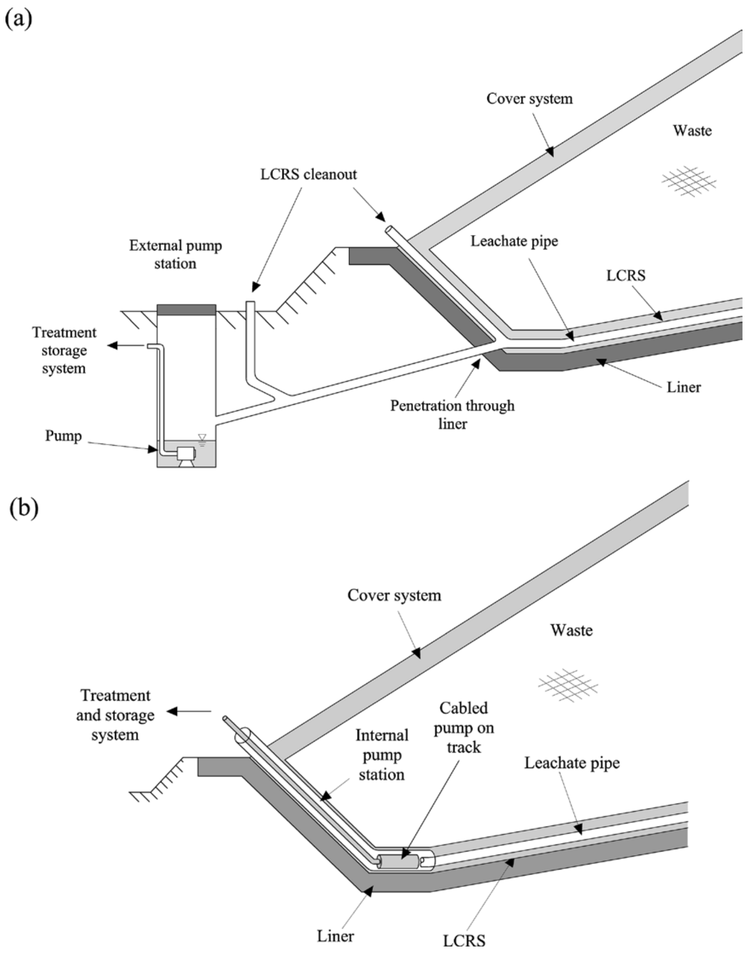

Fig. 10.1 Illustration of two methods for pumping leachate from the landfill (**a**) internal pump station (**b**) internal pump station

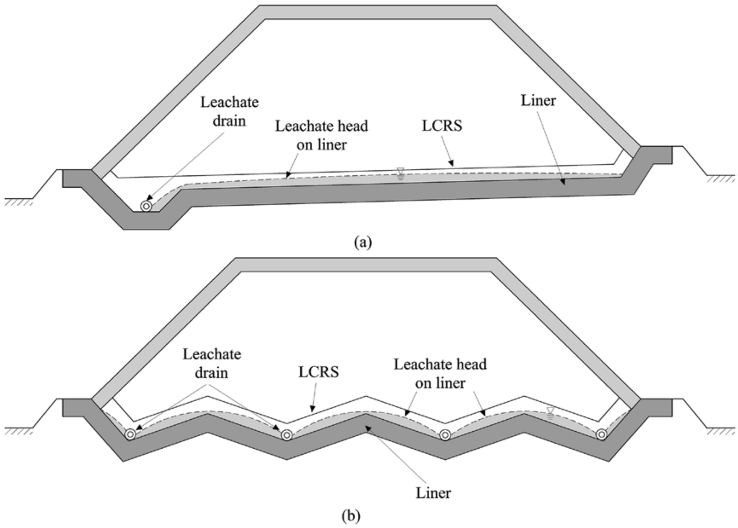

Fig. 10.2 Illustration of two typical leachate collection and removal systems (**a**) planar, (**b**) saw tooth

The specific configuration of a LCRS will be dictated by regulatory requirements (e.g., permitted depth on the liner), site constraints (e.g., area, available grades, presence of the groundwater table), leachate management (e.g., the practice of liquid addition), and availability and selection of drainage materials (e.g., sand, rock, geocomposite). For example, the number of drains required may vary tremendously depending on whether rounded stone or sand is available. Sites practicing liquids addition or those managing wetter wastes will require more robust collection infrastructure than conventional sites. While possible configurations for LCRS design are many, two extremes in design configuration are illustrated in Fig. 10.2. One configuration presents the case where multiple drains are employed (this is often called a saw-tooth configuration). In the other scenario, sheet flow dominates and a minimal number of drains are used (sometimes referred to as a planar configuration). A multi-drain configuration would be required where less permeable drainage materials such as sand are used, whereas planar systems can be utilized if the LCRS is constructed with more permeable drainage media such as rock or a geocomposite.

The use of liquids addition or leachate recirculation at a site can influence LCRS design in three primary ways. First, the increased leachate impingement rate (flow of leachate intercepted by the liner and LCRS) requires more flow removal capacity. Second, the increased unit weight of the waste, a result of the elevated moisture levels and increased waste decomposition, results in greater overburden stress being placed on the landfill foundation, which can, in turn, result in greater differential settlement over the sloped base of the landfill. Accordingly, the slope change of the LCRS due to subsurface settlement needs to be taken into account to ensure adequate drainage and to avoid leachate ponding on the liner.

Third, the potential for clogging the LCRS must be considered. If the LCRS clogs, the hydraulic conductivity of the drainage material decreases and the drainage performance of the LCRS may be reduced. Greater volumes of leachate passing through the LCRS may result in additional clogging concerns.

This chapter provides a fundamental overview of LCRS design and operation issues that should be assessed as part of the planning and implementation for any landfill, especially when liquids addition is practiced and at landfills with inherently high moisture levels. Readers are encouraged to consult additional references for more specific landfill design methodologies that pertain to LCRS design (McBean et al. 1995; Qian et al. 2002).

10.2 Predicting Leachate Impingement

10.2.1 Impingement Basics

Leachate impingement is the rate that leachate percolates from the base of the landfilled waste into the LCRS and is expressed in units of flow rate per unit area (L^3/T per L^2). Where liquids addition is practiced, the impingement rate is expected to be greater compared to a traditional landfill. Although added liquid will at first remain in the waste, once field capacity is reached, some fraction of the added moisture will migrate through the waste and intercept the LCRS. The concept of field capacity and how it is typically used in estimating moisture addition volumes was discussed in Chap. 6.

The engineer must make an appropriate assumption for impingement rate as part of the LCRS design process. Approaches for determining impingement rate include (i) using leachate flow data collected from similar landfills already in operation, (ii) conducting a landfill water balance, and (iii) using conservative estimates of hydraulic conductivity of the waste and factoring possible impacts of any liquid addition, as appropriate. While using existing leachate flow data from other sites to estimate impingement (by normalizing leachate flow to the contributing landfill area) provides a valuable comparison, possible differences in site features and operation in most cases still necessitates an independent estimate of impingement for the design proposed.

In Chap. 5, methods for predicting moisture flow in landfills and performing landfill water balances that forecast leachate generation were reviewed. Several approaches of differing complexity may thus be employed to estimate impingement; however, in some locations (e.g., US), regulatory agencies require use of a standard methodology, the HELP model. A description of HELP was provided in Chap. 5, and the following section summarizes issues of importance when applying HELP to predict impingement at landfills where liquids addition is practiced.

10.2.2 Prediction Using HELP

As presented in Chap. 5, the HELP model is a widely used tool for performing a water balance on landfills and it includes features that allow for simulation of liquids addition (Schroeder et al. 1994). Most engineers utilize HELP output results to determine (a) the maximum head on the liner and (b) the leachate generation rate necessary for sizing the various components of the leachate removal and management system. Inherent in these data is the impingement rate, which HELP provides as an output both in LT^{-1} units and L^3T^{-1} units (the L^3 T^{-1} units correspond to the input area designated in the HELP simulation). The maximum impingement rate is the lowest saturated hydraulic conductivity of the profile layers above the liner, but is not greater than maximum daily infiltration rate.

Xu et al. (2012) presented a discussion of the different techniques that can be used as part of HELP simulations to account for liquids addition in landfills and to predict the resulting impingement rate, and these techniques are summarized herein. The HELP model provides several options for incorporating additional liquids beyond rainfall, including utilizing the HELP model's leachate recirculation feature, the model's subsurface inflow feature, and a technique referred to as the rainfall modification method, where precipitation inputs are manipulated to approximate liquids addition.

The leachate recirculation feature (LRF) in HELP's soil and design input screen allows the user to define a percentage of the leachate generation collected in the LCRS to be added to a designated landfill layer and is conceptually illustrated in Fig. 10.3. The LRF method is widely applied when simulating a landfill where the primary motivation is to manage leachate through recirculation, but not to bring the landfill to optimal conditions for waste stabilization. The LRF method does not allow the designer to simulate the addition of a specific volume of liquid to a waste layer and can only simulate the recirculation of a defined percentage of leachate

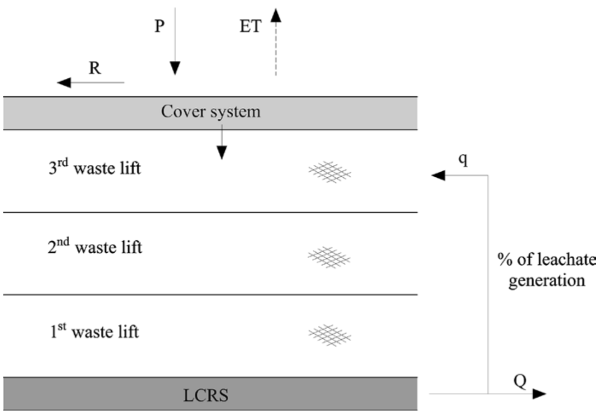

Fig. 10.3 Schematic of liquids addition methods used in the HELP leachate recirculation method

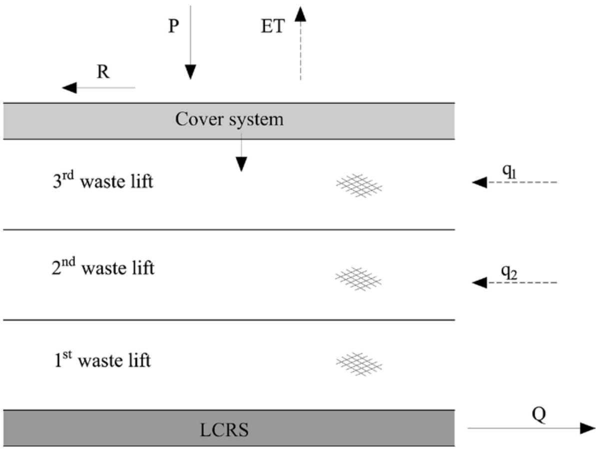

Fig. 10.4 Schematics of liquids addition methods used in the HELP subsurface inflow method

collected from the LCRS. For modeling the scenario where a specific liquid volume will be added (e.g., to reach field capacity), the ability to select the actual volume of liquid injected into a layer is necessary.

The subsurface inflow (SSI) feature of HELP simulates lateral groundwater flow into a defined layer in the simulated landfill (Schroeder et al. 1994). Contrary to the leachate recirculation feature which allows liquid to be added to just one layer, the SSI feature permits the addition of a specified volume of liquid to any number of layers (conceptually illustrated in Fig. 10.4). With this feature, the liquids addition rate is constant throughout a simulation and liquids are added continuously. Since liquids addition systems at operating landfills are frequently operated intermittently, and because flow rates can vary dramatically from day to day, the SSI feature in HELP (which is based on an average liquids addition rate) might underestimate the maximum impingement rate.

The third method, referred herein as the rainfall modification (RFM) method, uses the weather data files in the weather data input screen to simulate liquids addition by adjusting the evapotranspiration and runoff inputs, and by modifying the precipitation data files to account for the liquids added to the landfill. It allows for a defined volume of liquid to be added and distributed daily throughout the year into any layer, as conceptually illustrated in Fig. 10.5. The RFM method is the only HELP liquids addition method that can simulate specific changes in the liquids addition regime throughout the year. To model leachate recirculation using the RFM approach, layers of a landfill are divided into several groups, depending on the leachate addition scheme. The surface layers above where liquids are added are simulated in HELP as normal. The leachate impingement rate migrating from the surface layer is obtained from the output file and added to the leachate volume for recirculation, and these values serve as the input rainfall file for the next layer. The rainfall data and evapotranspiration climate inputs must be modified for underlying

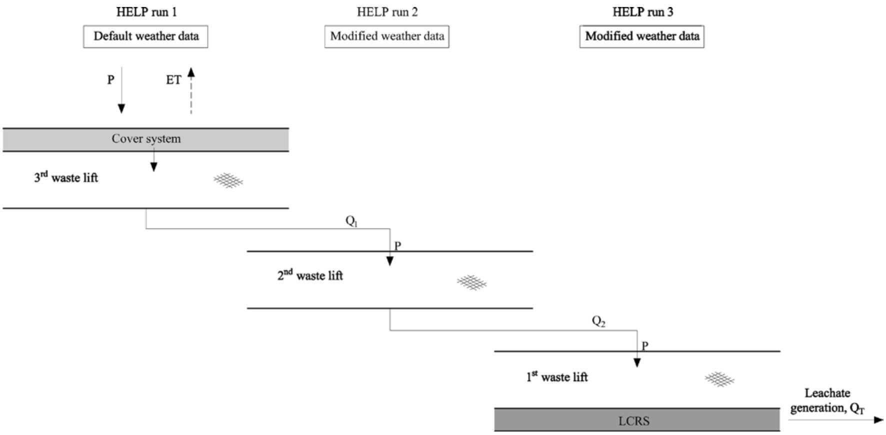

Fig. 10.5 Schematics of liquids addition method used in the HELP rainfall modification method

waste layers, which are not affected by external weather conditions. Since the RFM allows for daily control of the added liquid volume, any combination of liquids addition can be simulated. The RFM can simulate temporal and limited spatial variation of liquids addition, which allows for a more realistic assessment of potential impingement changes as a result of liquids addition system operation.

Xu et al. (2012) also provided several observations regarding other aspects of HELP the designer should consider for landfills where liquids addition is practiced. Selecting an appropriate model simulation time is important. An insufficient modeling period may not capture the leachate entry into the LCRS. Even if the design objective is for the majority of the added liquid to remain within the landfill as stored moisture (i.e., utilizing absorption capacity), the LCRS must be designed with sufficient capacity to handle the increased impingement rate occurring under fully wetted conditions.

The designer should also closely evaluate the appropriate input waste characteristics used in the model input. The HELP default for hydraulic conductivity of the waste, for example, may be too large. An early HELP default for hydraulic conductivity was 1×10^{-3} cm/s, and the current default is 2×10^{-4} cm/s for compacted MSW (Schroeder et al. 1994). As described in Chap. 5, this value is likely substantially greater than true conditions for well-compacted MSW at modern landfills. Also as indicated in Chap. 5, hydraulic conductivity will decrease with depth in the landfill. The designer should carefully consider appropriate selection of hydraulic conductivity, as well as moisture content, field capacity, and porosity, when setting up the model run. HELP allows the designer to assign different waste characteristics to distinct layers within the landfill, which permits simulation of changing waste properties deeper in the landfill.

10.2.3 Impingement Prediction for Specific Liquids Addition Methods

The maximum impingement rate predicted by HELP corresponds to the lowest saturated hydraulic conductivity of the waste or soil layer above the LCRS. In other words, if liquids are added at a rate greater than the hydraulic conductivity of the waste, the impingement rate will be the same as the hydraulic conductivity and the excess moisture will be stored within the waste. Thus, an alternative and more conservative approach to determine impingement in HELP includes assigning the vertical hydraulic conductivity of the waste as the impingement rate.

As outlined in Chaps. 7, 8, and 9, liquids may be added to distinct landfill areas at different times. While the impingement rate obtained from the HELP model is evenly distributed over the LCRS, the impinging liquids may vary spatially at landfills where liquids addition is practiced, especially when liquids are added under pressure. This is conceptually illustrated in Fig. 10.6, where the saturated zones that could result from a horizontal trench (Fig. 10.6a) and a vertical well (Fig. 10.6b) are shown along with an indication of enhanced impingement below the liquid addition devices (relative to that which would be predicted using HELP by treating the impingement rate as equal to the hydraulic conductivity). For some designs it might be important to consider how LCRS performance could be affected by pressurized liquids addition devices located near the base of the landfill.

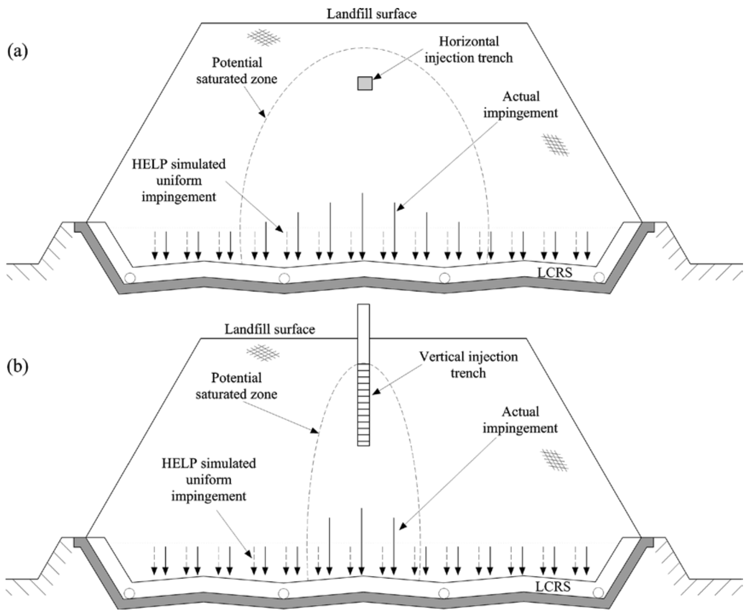

Fig. 10.6 Conceptual illustration of potential differences in impingement rates as predicted using HELP and actual distribution for (**a**) horizontal trench systems and (**b**) vertical well systems

When the designer desires or is required to account for increased impingement due to pressurized liquids addition into a specific device, a fluid flow model similar to those described in other chapters can be developed and applied. A simplified approach using the saturated zone equations presented in Chaps. 8 and 9 can also be to estimate the enhanced impingement. Under steady-state conditions, the impingement rate (e) occurring at the base of the waste underneath a specific device can be approximated as the flow rate added to the device (Q) normalized to the area through which the added leachate is entering the LCRS (A_i), such that:

$$e = \frac{Q}{A_i} \tag{10.1}$$

As has been described in earlier chapters, the wetted zone resulting from a liquids addition device increases in dimension as the zone moves vertically downward from the device and ultimately approaches steady state. At distances far from the device which are close to steady state, the impingement is approximately equal to the vertical hydraulic conductivity ($e = K_z$), but closer to the device, the gradient is greater than 1 and the impingement will be greater than the vertical hydraulic conductivity ($e > K_z$).

The saturated zone equations (presented in Chaps. 8 and 9) are used to solve for impingement rate occurring where the saturated zone under a liquids addition devices intercepted the LCRS (Xu et al. 2014). The impingement rate (e) for a horizontal trench located a distance Z above the LCRS can be approximated as follows.

$$e = \frac{\pi K_z}{\tan^{-1}\left(\frac{x}{z}\sqrt{\frac{K_z}{K_x}}\right)} \tag{10.2}$$

Where K_Z is the vertical hydraulic conductivity, K_X is the lateral hydraulic conductivity, x is the horizontal distance of the saturated zone from the trench at the LCRS boundary, and z is the vertical distance between the trench and the LCRS boundary.

The impingement rate (e) for a vertical well with a bottom located a distance z above the LCRS can be approximated as:

$$e = \frac{K_z}{\left(1 - e^{-1.6 D/L}\right)^2} \tag{10.3}$$

Where L is the length of the well screen and D is the distance from the top of the well screen to the top of the LCRS (see Chap. 8).

10.3 Predicting Leachate Head on Liner

The engineer designs the LCRS to prevent the maximum liquid level (leachate head) ponded on top of a liner from exceeding a design or regulatory threshold. The design requirement for both MSW and hazardous waste landfills in the US is 1 ft (0.3 m) or less of head on the liner. Several design methodologies have been developed to predict leachate head over an impermeable sloped drainage path of an LCRS. The following sections describe methods for single layer (granular and geonet) and multi-layer systems.

10.3.1 Single Layer Granular System

Several equations have been developed to solve for the maximum depth of leachate above a sloped liner overlain by a granular drainage media with a drain at the downstream end. The maximum depth is calculated by first assuming the maximum leachate inflow rate occurs under steady-state conditions while the LCRS is operating properly (e.g., leachate flows freely through the drains and does not back up onto the primary drainage slopes). The methods for calculating head on the liner incorporate the following factors: (i) drainage path length (L); (ii) drainage path slope (L L^{-1} or degrees); (iii) leachate impingement rate (L T^{-1}); and (iv) hydraulic conductivity of drainage material (L T^{-1}). These factors are schematically illustrated in Fig. 10.7, which provides a definition sketch to supplement the design equations

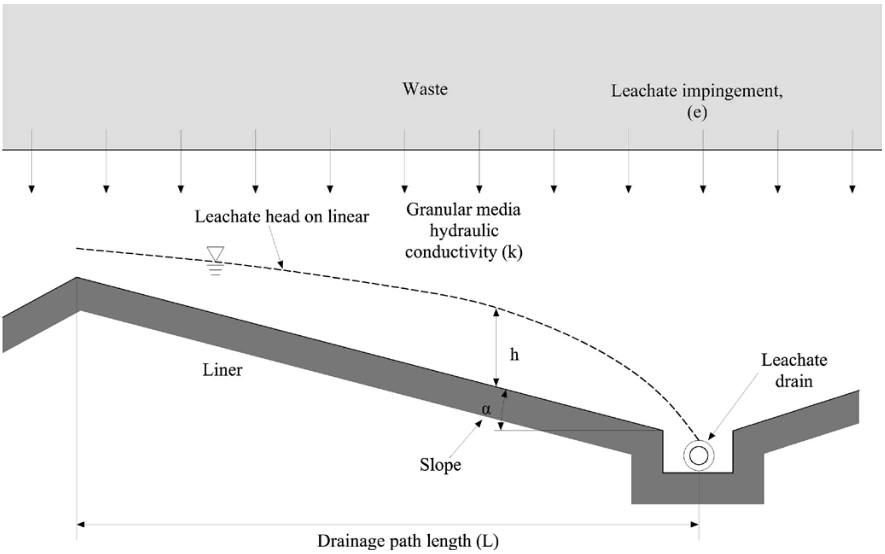

Fig. 10.7 Definition sketch of the four main factors affecting head on a liner

Table 10.1 Summary of analytical equations from Moore, McEnroe, and Giroud to predict the leachate head on a single liner

Method	Analytical equation
Moore (1980)	$h_{max} = L\sqrt{\frac{e}{k}}\left[\frac{k\tan^2\alpha}{e} + 1 - \frac{k\tan\alpha}{e}\sqrt{\tan^2\alpha + \frac{e}{k}}\right]$
McEnroe (1993)	$R = \frac{e}{k \cdot \sin^2\alpha}$
	$S = \tan\alpha$
	$A = \sqrt{(1-4R)}$
	$B = \sqrt{(4R-1)}$
$R < \frac{1}{4}$	$h_{max} = L(S)(R - RS + R^2S^2)^{\frac{1}{2}}\left[\frac{(1-A-2R)(1+A-2RS)}{(1+A-2R)(1-A-2RS)}\right]^{\frac{1}{2A}}$
$R = \frac{1}{4}$	$h_{max} = L\,[S]\left[\frac{R(1-2RS)}{1-2R}\right]\exp\left[\frac{2R(S-1)}{(1-2RS)(1-2R)}\right]$
$R > \frac{1}{4}$	$h_{max} = L(S)(R - RS + R^2S^2)^{\frac{1}{2}}\exp\left[\frac{1}{B}\tan^{-1}\left(\frac{2RS-1}{B}\right) - \frac{1}{B}\tan^{-1}\left(\frac{2R-1}{B}\right)\right]$
Giroud et al. (2000)	$\lambda = \frac{e}{k \cdot \tan^2\alpha}$
	$j = 1 - 0.12\exp\left\{-\left[\log\left(\left(\frac{8\lambda}{5}\right)^{5/8}\right)\right]^2\right\}$
	$h_{max} = L\left(\frac{\sqrt{1+4\lambda}-1}{2} \times \frac{\tan\alpha}{\cos\alpha}\right) \times j$

discussed in this chapter. The differences in methodologies presented result from different derivation approaches and assumptions.

Table 10.1 presents three different design equations commonly used for predicting maximum leachate head on the liner (h_{max}) as a function of drainage path slope (α) and length (L), granular drainage media hydraulic conductivity (K), and leachate impingement (e). The Moore equation (Moore 1980) was published first and is still used by some designers as a quick conservative estimate. The McEnroe equation (McEnroe 1993) and the Giroud equation (Giroud et al. 2000; Giroud and Houlihan 1995) were more rigorously derived and are considered more accurate. The HELP model utilizes the McEnroe equation for its estimate. Figure 10.8 shows results for the Moore and Giroud equations over a range of conditions; the McEnroe and Giroud equations have been found to give very similar results.

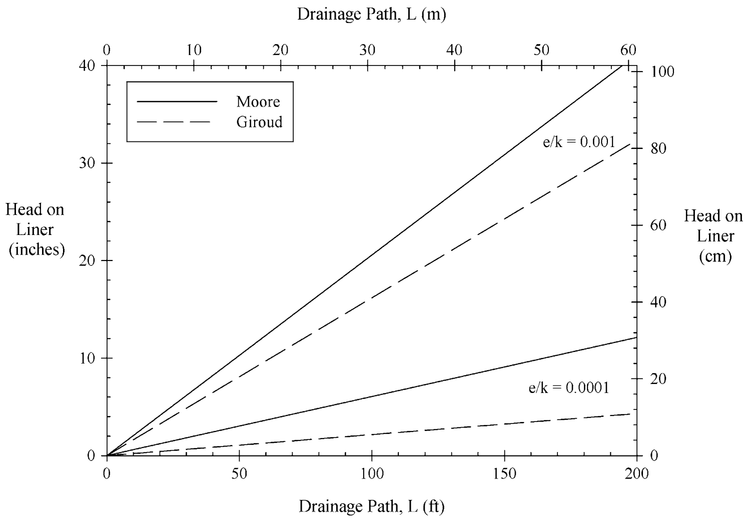

Fig. 10.8 Comparison of maximum head on the liner calculated using the Moore, McEnroe and Giroud equations

10.3.2 Single Layer Geonet System

In some LCRS designs, synthetic drainage products (i.e., geonets) are used to provide leachate conveyance. In these designs, a geonet is placed directly on the geomembrane liner and is overlain by a layer of soil or other granular media. The design will include a geotextile to separate the geonet from the overlying soil (or a geocomposite consisting of a geonet and geotextile bonded together). Because the thickness of a geonet is small (<0.01 m), when a designer specifies a geonet with sufficient capacity to handle all of the leachate flow for the required impingement rate, the depth of leachate will be well below the regulatory requirement.

The flow capacity of a geonet is most often described by its transmissivity, T (L^2/T). The engineer will specify a geonet that provides necessary capacity for the predicted leachate generation or impingement rate. In the case where the geonet must provide sufficient capacity to handle all of the leachate flow within its thickness, required transmissivity (T_{REQ}) will be solved as follows:

$$T_{REQ} = \frac{Q}{i\,w} = \frac{e\,l}{i} \tag{10.4}$$

Where Q is the total leachate flow rate collected over an area (width (w) by drainage path (L)), e is the impingement rate, and i is the slope of the drainage path. The designer specifies a geonet that delivers needed transmissivity at the anticipated design load and after applying a series of safety factors (to account for potential reductions in hydraulic conductivity due to factors such as creep, intrusion and clogging) have been applied. The maximum head on the liner in this case would be:

$$h_{max} = \frac{eL}{K\tan(\alpha)} \tag{10.5}$$

where,

$$K = T/t \tag{10.6}$$

and t = the thickness of the geonet.

10.3.3 Multi-Layered System

Since the maximum allowable leachate head on the primary liner will be greater than the thickness of the geonet, some LCRS designs will additionally utilize the flow capacity provided by the granular media overlying the geonet. This demands an alternative technique for estimating maximum head on the liner, which has been provided by Giroud et al. (2004). This technique is illustrated in Fig. 10.9.

This method requires assumptions regarding the hydraulic conductivity of both drainage layers. Hydraulic conductivity (K) of the geonet can be determined from the transmissivity (T) and thickness (t) as described in the previous section. The first

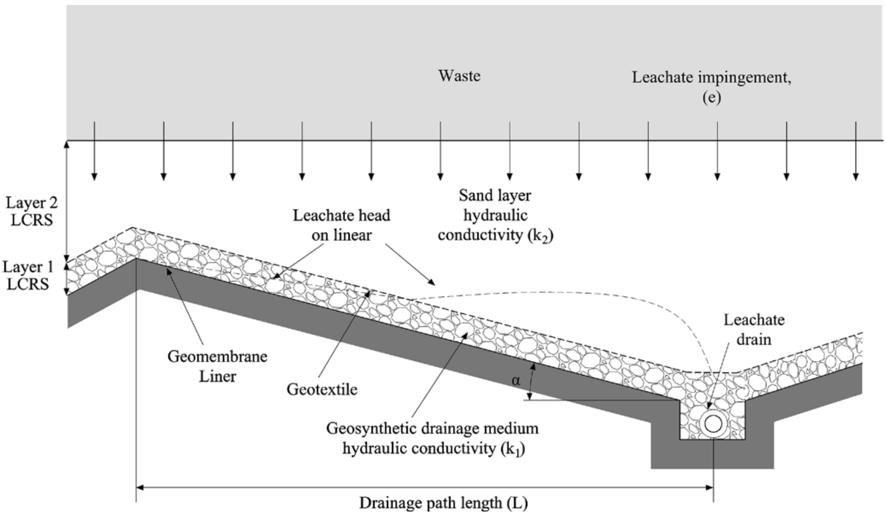

Fig. 10.9 Definition sketch for two-layered LCRS

step in the method is to calculate the length of geonet that handles all of the leachate flow (L_u).

$$L_u = \frac{t_1\, K\, k_1 \sin(\alpha)}{e} \tag{10.7}$$

If L_u is greater than the total length of the drainage path (L), the geonet can handle the complete flow, and similar to the previous case, the maximum head on the liner will be:

$$h_{\max} = \frac{e}{k_1 \tan(\alpha)} L \tag{10.8}$$

In the case where $L_u < L$, leachate extends above the geonet in the granular drainage layer, such that:

$$h_{\max} = t_1(\cos\alpha) + j_2 \left[\frac{\left(\sqrt{1+4\lambda_2} - 1\right)\tan\alpha}{2} \right] \times \left[L - \frac{T_{k,1}(\sin\alpha)}{e} \right] \tag{10.9}$$

Where,

$$\lambda = \frac{e}{k_2 \tan^2(\alpha)} \tag{10.10}$$

$$j_2 = 1 - 0.12 \exp\left\{ - \left[\log_{10}\left(\frac{8\lambda}{5}\right)^{5/8} \right]^2 \right\} \tag{10.11}$$

Where the terms represent those previously defined. This equation allows the engineer to predict the combined depth of liquid above the liner in both the geonet and the drainage media above it.

10.4 Foundation Settlement Considerations

The engineer designs the LCRS as a combination of sloped liner areas and sloped pipes or drains to route leachate to designated removal points. As these slopes are often not great in magnitude (a few percent or less), changes to bottom liner elevation as a result of differential foundation settlement must be considered. If the soils beneath the landfill settle in a manner that causes the liner base grade to change, the performance of a gravity drainage system can be compromised. It is thus standard

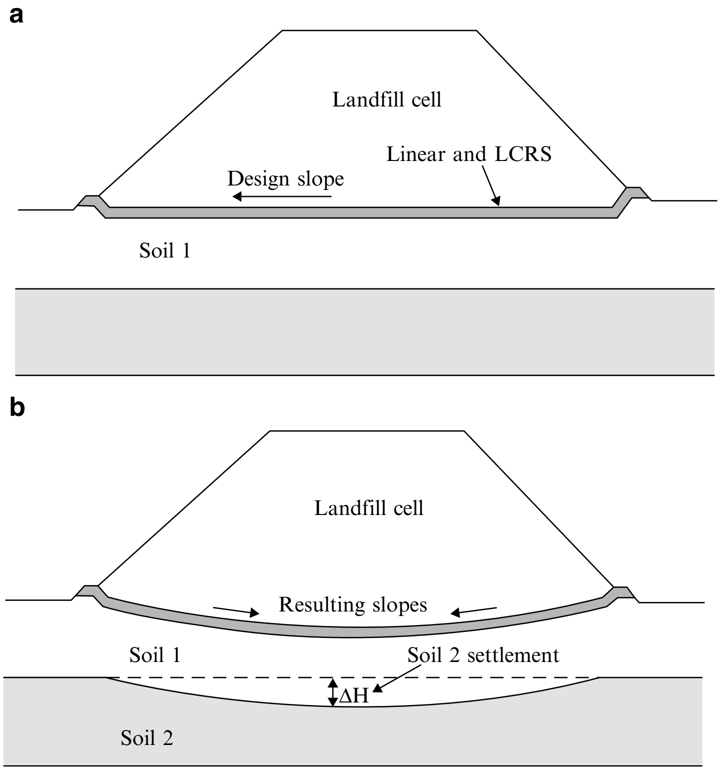

Fig. 10.10 Conceptual schematic of foundation settlement due to waste load (**a**) shortly after placement of the landfill (**b**) long-term deformation showing the conceptual change in the slope of the LCRS from the settlement of soils 1 and 2

practice for the design engineer to predict the landfill foundation settlement that is expected to occur and to develop a grading plan for the liner foundation and pipes that accommodates long-term foundation settlement. Since landfills where liquids addition is practiced may be subject to greater differential settlement as a result of greater loads (due to wetter waste), and because LCRS performance is especially important at these facilities, incorporation of predicted settlement into a landfill's bottom grading design is essential.

The greatest magnitude of foundation settlement will occur toward the interior of the landfill, where the greatest waste depths and resulting overburden pressures are placed on the underlying soils. Figure 10.10 conceptually illustrates the process of landfill foundation settlement. Prior to construction of the landfill, soil layers exist in an assumed steady-state condition with respect to applied pressure from overlying materials. Upon construction of the landfill unit, stresses are imparted on the underlying soil layers, which in turn can cause settlement. In Fig. 10.10, a soil layer in the landfill's foundation settles non-uniformly in response to the differentially applied load, and this causes the LCRS to slope inward unless appropriately anticipated and accounted for in the design.

The degree of settlement will depend on the location and properties of soil layers in the landfill foundation, the configuration (i.e., slope and height) of the landfill, and the loads produced from the landfill as a result of the weight of the landfilled materials. The geotechnical design of a landfill foundation is a much more detailed procedure than presented here and a complete review is outside the scope of this book; geotechnical engineering references should be consulted (Holtz and Kovacs 1981; Bowles 2001; Coduto 2001; Das 2010). The purpose of this section is to offer the landfill design engineer a basic overview of the techniques used as part of landfill foundation analysis and to emphasize the importance of this design consideration for wet landfills.

The design of a landfill grading plan that accounts for foundation settlement begins with a detailed geotechnical characterization of the subsurface geology of the site. This will include conducting soil borings and in-situ tests to characterize subsurface soils (e.g., standard penetration test (SPT), cone penetration test (CPT)) and to retrieve samples for testing. The engineer will use the field measurement data and the results provided from samples tested in the laboratory to estimate the amount of subsurface settlement likely to occur upon completion of the waste fill. A variety of methods have been developed to examine the settlement of large foundations (Bowles 2001; Coduto 2001; Das 2010), although most techniques are focused on building foundations. The engineer must often rely on basic soil deformation principles; Table 10.2 provides two fundamental equations to predict the settlement of a soil layer, one for immediate settlement based on a linear stress–strain relationship, and one based on classic soil consolidation theory.

Immediate settlement occurs rapidly as a result of a direct strain response to a stress, and is based on the assumption that the soil deforms in response to a constant stress–strain modulus over the stress range of interest. The engineer would apply this method to layers of unsaturated soils or those in the saturated zone not expected to undergo consolidation. The stress–strain modulus can be estimated from in-situ

Table 10.2 Examples of methodologies for predicting the settlement of soil layers as a function of added load

Mechanism	Equation
Immediate settlement	$\Delta s = \frac{\left(\sigma^*_{v2} - \sigma^*_{v1}\right) \cdot H_0}{E_s}$
Consolidation settlement	$\Delta s = C_c \frac{H_0}{1+e_0} \log \frac{\sigma^*_{v2}}{\sigma^*_{v1}}$

Δs = settlement of soil layer [L]
H_0 = thickness of soil layer undergoing settlement [L]
E_S = stress–strain modulus $[(F/L^2)^{-1}]$
C_C = compression index
e_0 = initial void ratio
$\sigma_{v1}{}^*$ = initial average effective stress of soil layer (F/L^2)
$\sigma_{v2}{}^*$ = initial average effective stress of soil layer (F/L^2)
$\sigma_{v2}{}^* = \sigma^*_{v1} + \Delta\sigma_v$ where $\Delta\sigma_v$ is the added load due to the landfill (F/L^2)

measurements such as SPT blow count (referred to as N values) or CPT pressures (Bowles 2001). Low-permeability soil layers (i.e., those dominated by clay minerals) can undergo time-dependent settlement (consolidation) as a result of pore water exiting the soil skeleton under the added pressure from the applied load. While methods exist to estimate time dependent consolidation, the engineer will most often be interested in the ultimate settlement, and thus the equations presented in Table 10.2 can be used. Estimates for the consolidation coefficient and initial void ratio can be determined by collecting and analyzing in-situ soils, or by using to field measurement correlations that relate valves to SPT and CPT data.

To ensure that the LCRS operates appropriately and flows in the correct direction, it is necessary to estimate the stress resulting from the waste load ($\Delta\sigma_v$ from Table 10.2); several methods can be used to estimate stress. One method simply involves assuming that the weight of the landfilled waste mass above a point in the foundation is transmitted directly to the soil underneath, without any distribution. A second, more elaborate method estimates the distribution of the overlying landfill weight into the soil using either a numerical program or classic geotechnical design charts for load distribution.

In the first approach, the added load ($\Delta\sigma_V$) at a point underneath the landfill will be the weight of the material (q) directly above it, such that:

$$\Delta\sigma_v = q = \gamma H \tag{10.12}$$

Where γ is the specific weight of the landfilled material and H is the thickness of the landfilled material at that point.

In the second approach, the spatial pattern of waste mass distribution is also considered. In this case, added loads from the landfill are assumed to be distributed into the underlying foundation soils. Geotechnical engineers have derived mathematical relationships for stress distribution within an idealized soil, such that the added vertical stress in the soil under an applied load ($\Delta\sigma_V$) is some fraction of the applied load (q_o), which can be solved as:

$$\sigma_z = q_0 I \tag{10.13}$$

Where I is an influence value representing the fraction of q_o occurring at a point of interest. This influence value can be determined mathematically or using influence charts (Holtz and Kovacs 1981), or can be predicted using numerical solutions in commercially-available software packages.

Once settlement has been estimated for distinct locations along the landfill foundation, the differential settlement between points can be determined. The engineer will select points that correspond to critical drainage pathways corresponding to the designed LCRS. When the calculated settlement causes grade reversal in the designed LCRS, the design of the LCRS must be revised to accommodate the maximum expected settlement so that the necessary slopes for gravity drainage will still be maintained.

10.5 LCRS Clogging

As described previously, the prediction of leachate head on the liner depends on several factors, including the hydraulic conductivity (or transmissivity) of the drainage media of the LCRS. The hydraulic conductivity of drainage media such as sand, rock, or geonet is normally measured in a testing laboratory, with clean water serving as the permeating fluid. In a landfill, however, leachate flows through the media, and leachate contains an array of suspended and dissolved chemicals or organisms that might impact the hydraulic properties of a drainage medium, especially with prolonged exposure. A number of studies have documented a reduction in flow properties of LCRS components after prolonged exposure to leachate; this phenomenon is commonly referred to as LCRS clogging. This section provides an overview of LCRS drainage media clogging mechanisms, the added concerns related to landfills where liquids addition is practiced, and clogging-specific considerations to address in both design and operation.

10.5.1 Clogging Mechanisms

The phenomenon of LCRS drainage media clogging (or a reduction in hydraulic conductivity) has long been recognized as a potential concern in landfills. Clogging of a LCRS reduces void space such that the permeability decreases and leachate is unable to flow through the system. Several different clogging mechanisms have been identified to result from leachate (Brune et al. 1991; Rowe et al. 1995), including physical clogging as a result of particulate transport, chemical clogging from mineral precipitation, and biological clogging caused by microbial growth; these different mechanisms likely act in combination.

Particulate clogging results when fine materials (clayey soils, ashes, or other waste materials) migrate into the LCRS and reduce the void space of granular material or deposit as a low permeability layer on the surface of a geotextile. Avoidance of particulate clogging will be addressed for most civil engineering drainage applications by specifying appropriate material particle size distributions (in the case of granular materials) and opening size (in the case of geotextiles). However, some particulates may be formed within the landfill as a result of chemical precipitation.

Biological growth in the LCRS can contribute to clogging by occupying granular media void space, coating geotextile surfaces, and contributing to mineral precipitation (Brune et al. 1994; Rowe and Fleming 1998; Fleming et al. 1999; Maliva et al. 2000; Bouchez et al. 2003; VanGulck et al. 2003). Biological growth within a LCRS accompanies the decomposition of organics and other constituents found within leachate. The microorganisms within an LCRS that are known to contribute to biological clogging are methanogens, iron-reducing bacteria, denitrifying bacteria, sulfate-reducing bacteria, slime-forming bacteria (those that generate extracellular polymers that make the biofilm look like mucous), manganese-reducing bacteria, and other facultative anaerobes (Fleming et al. 1999; Rowe and Fleming 1998).

Chemical clogging results when dissolved chemicals in the leachate precipitate to form solid-phase minerals that act to reduce pore space. The mineral precipitates in some cases form solid masses that cement granular materials together or plug pipes or similar openings, while at other times they form small discrete particles similar to a fine soil or ash. The most common mineral precipitate identified from previous LCRS studies is calcium carbonate; this chemical precipitate can result from the chemical conditions that often occur when incinerator ash and MSW are co-disposed in landfills, but also is formed as part of biological growth in MSW landfills (see below). Other elements commonly found in mineral precipitates include magnesium, iron, manganese, and sulfur.

Materials clogging a LCRS are known to have both organic and inorganic components, and chemical precipitation and biological growth should in most cases be discussed together (Rowe and Fleming 1998). Biological growth can also cause inorganic components within the leachate to precipitate and accumulate within the LCRS (Brune et al. 1994; Fleming et al. 1999; Maliva et al. 2000; Bouchez et al. 2003; VanGulck et al. 2003). Degradation of volatile fatty acids by microbial activity is well known to result in the formation of calcium carbonate. In LCRS where high-BOD leachate drains over stone, biofilms will develop similar to a trickling filter in a wastewater treatment plant, and this biological activity will result in the production of calcium carbonate.

Biological growth and chemical precipitation can create conditions that enhance each other. For example, chemical gradients in sulfide, alkalinity, and pH from microbial activity facilitated the precipitation of metal sulfide and calcium carbonate in a study by Brune et al. (1991). Sulfate-reducing bacteria have been demonstrated to cause calcium carbonate and iron salts to precipitate out and clog the LCRS drainage media (Rohde and Gribb 1990; Rittman et al. 1996). Iron-reducing bacteria and sulfur-reducing bacteria can also increase the pH and generate sulfide, which can result in precipitation of insoluble metal sulfides (Cossu et al. 1999).

10.5.2 Clogging Potential in Sustainable Landfill Operations

Clogging issues have been suggested to be a greater concern for facilities operated to enhance biological waste stabilization for the following reasons: (a) the larger amounts of leachate passing through the LCRS during the landfill's life; (b) the potential differences in biological activity that might occur during sustainable landfill operations; and (c) the critical role that a successfully operating LCRS plays in terms of slope stability at bioreactor landfills (Chap. 12). The degree to which clogging occurrs has been demonstrated to be greatest under higher mass loading rates to the LCRS (Fleming et al. 1999; Rowe et al. 2000). While landfills subjected to liquids addition result in greater leachate flow, the concentrations of biodegradable organic matter (BOD) are expected to become lower than conventional landfills more rapidly.

To the authors' knowledge, there is no dramatic evidence from landfills implementing technologies to enhance stabilization that suggests that these facilities are experiencing exacerbated problems with clogging compared to other landfills. Much of the clogging reported in the literature has been reported at landfill sites where BOD values were very large, often occurring in colder climates. In landfills with healthy microbial populations responsible for active waste decomposition, temperatures are often very warm and resulting leachate BOD concentrations are relatively low. Thus, liquids addition at facilities that result in less-than-optimal conditions where BOD remains high (e.g., waste stabilization remains in the acid phase) and leachate production rates are high could exacerbate clogging concerns. A potential remedy in this case would the use of targeted air addition to increase temperatures (see Chap. 14).

10.5.3 Addressing Clogging in Design

The typical method through which an engineer accounts for clogging in the LCRS design process is to apply a reduction factor to the hydraulic conductivity (granular media) or transmissivity (geonets) used as part of the head-on-liner design equations presented earlier in this chapter. Through this approach, the LCRS is designed to maintain less than the target leachate depth even when clogging occurs. Detailed design procedures associated with incorporating reduction factors for the LCRS are provided in Qian et al. (2002).

Other design practices can also be implemented to reduce chances of clogging problems and provide the operator better ability to address problems if they do occur. Sufficient cleanout lines should be provided in the design so that all pipes can be readily inspected and cleaned; pipe lengths should be limited to that which can be accessed with available equipment. When geotextiles are used as part of the design, configurations should be avoided where large of amounts of leachate flow are routed through small geotextile areas. Where feasible, the operations plan should discourage the occurrence of fine particulate material in waste or cover soil in proximity to the LCRS. An added redundancy is the placement of a geocomposite layer (geonet bonded to a geotextile) directly above the liner to facilitate more rapid drainage.

10.5.4 Addressing Clogging in Operation

As discussed in Chap. 16, leachate flow and liquid level monitoring should be a routine practice at landfills where the additions liquids or wet wastes is practiced. Changes in leachate production over time may provide some indication of less efficient collection due to LCRS clogging. Interpreting this change can be complicated, however, as several factors affect leachate production (e.g., climate, stormwater management practices). More telling will be changes in the locations where leachate collection occurs and the presence of ponded liquids or seeps in places where these conditions formerly were not present.

A more direct assessment of LCRS performance is monitoring of LCRS gravity drainage pipes. Many landfill permits require periodic inspection and cleaning of LCRS pipes, hence the necessity to install cleanout lines as a means to provide internal pipe access. This includes inspection with cameras and jetting with high pressure water and specialized cleaning devices. At sites where calcium carbonate clogging is evident and cannot be removed with high-pressure jetting, cleaning with acid solution has been used with some success.

The inspection and cleaning of pipes does not, however, provide direct evidence of clogging in other LCRS locations such as granular drains, geonets, geotextiles, or the sand drainage blanket. Monitoring leachate depths on the liner (see Chap. 16), coupled with flow measurements, may provide an indirect measure of internal LCRS clogging, but access to the LCRS for remediation is difficult because of the large depth of waste that would need to be removed. In cases where clogging appears to be a problem, but remediation is not feasible, other actions that the operator may need to implement include reducing leachate generation in that area (e.g., early closure), cessation of liquids addition, and increased leachate or groundwater monitoring.

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Chapter 11
Leachate Control, Storage, and Treatment

Abstract By necessity, the addition of liquids as part of sustainable landfilling operations adds to the amount of liquids that must be managed by a site. Challenges associated with landfills containing elevated moisture include controlling stormwater, managing seeps, and providing sufficient storage and treatment capacity. The impacts from sustainable landfilling practices (i.e., liquids addition) on each of these areas are presented. Strategies to reduce impacts from liquids addition (such as seepage prevention and control), accommodate additional leachate production, and provide leachate treatment that integrates with sustainable landfill objectives, are presented and discussed.

Keywords Landfill • Leachate • Seep • Surface water • Treatment • Storage

11.1 Leachate Management Fundamentals

Integrated liner systems and LCRS are fundamental design features of modern engineered landfills, and are installed with a primary objective of minimizing deleterious impacts of leachate on the environment. Leachate management considerations do not end with the construction of these features, however. Leachate removed from the landfill must be handled and disposed properly. Leachate migration from the landfill via other possible routes, namely the exposed surfaces of the landfill, must be guarded against. While the proper management of leachate is an important element at all landfills, it is even more critical at facilities where liquids are added or recirculated as part of implementing sustainable landfill technologies.

Leachate forms predominantly as a result of rainfall and the manner that stormwater is controlled plays a major role in the overall water balance of a landfill. At sites where the moisture content is elevated, such as those where liquids addition is practiced, contamination of stormwater as a result of exposure to leachate outbreaks or seeps on the landfill surfaces is more likely, and thus such outcomes must be planned for as part of both design and operation. Occurrence of leachate seeps at wet landfills such as bioreactors is relatively common, meriting a discussion of causes, remedial steps, and preventative measures as part of this chapter.

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Although some landfill sites might be equipped with a force main that allows direct discharge of leachate to an off-site treatment facility, leachate that is pumped or gravity-drained from the LCRS is normally stored on site in a tank, pond, or similar device, whether as a part of, or prior to, leachate treatment. The degree to which leachate is treated on site depends greatly on facility-specific constraints and objectives, and ranges from simple storage with only minimal changes in leachate chemical concentrations to comprehensive treatment plants designed to produce an effluent of sufficient quality for on-site discharge. As leachate recirculation represents one of the practices implemented to promote rapid waste stabilization, the need for external leachate treatment might differ for these sites in comparison to traditional landfills. Alternatively, specific treatment objectives that compliment leachate recirculation might be a desired approach. The later part of this chapter summarizes standard practices for leachate storage and treatment, and focuses on issues related to leachate management at sites implementing technologies such as liquids addition and leachate recirculation.

11.2 Controlling Stormwater Run-on and Runoff

Chapter 6 outlined a general approach for assessing moisture needs for landfill operators attempting to maximize waste stabilization through liquids addition. Because of the relatively large target volume of liquids that may be required to achieve operational goals, additional sources of moisture beyond that resulting from leachate generation may be required. The amount of leachate produced at a landfill site is strongly dictated by site stormwater management practices and the nature of the incoming waste material. Therefore, an important topic of discussion with respect to leachate is the management of stormwater run-on and runoff.

Rainfall intercepted by the landfill surface, typically referred to as stormwater, is normally considered leachate when it comes into contact with solid waste or other leachate. While much of the production of landfill leachate results from moisture infiltrating through the surface of the landfill into the waste, the flow of water over the surface of the landfill as a result of rainfall runoff can also add to leachate volumes. The majority of excess leachate observed at a landfill immediately after a large storm event is, in fact, produced as a result of stormwater that flows directly to the LCRS at the interface of the compacted waste and the liner system, or other direct channels to the LCRS (i.e., highly permeable cover layers). Run-on control describes the steps an operator takes to route non-impacted stormwater intercepted by the soil or vegetation on the landfill surface away from areas of exposed waste, thus preventing leachate formation. Similarly, runoff control describes the process of routing clean stormwater to a designated discharge location and stormwater impacted by leachate to an appropriate collection area.

The area of a landfill where waste is exposed to the environment after deposition and compaction and prior to the placement of daily cover (or cover with additional waste)—typically referred to as the working or active face—presents a source for potential leachate generation. The working face should be maintained in a manner to divert clean stormwater from covered areas away from the exposed waste to as great of an extent as possible. This is accomplished through grading of surrounding areas (e.g., sloping the covered landfill surface away from the working face) and the use of soil diversion berms. Rainwater that directly intercepts the exposed waste or runs onto the exposed waste is allowed to infiltrate into the landfill.

Given the need for substantial liquids addition volumes at landfills targeting accelerated waste stabilization, the operator has the ability to maintain some control of the volume of liquids introduced to the landfill through the manner in which stormwater is managed. Ponding of liquids on the surface of a landfill, unless it is part of a permitted surface pond application system, will normally be prohibited. However, given the ability of waste to absorb water, the purposeful allowance of stormwater onto the working face promotes liquids addition to the landfill. Care must be taken, however, to avoid conditions that prevent waste from being covered in a timely manner or that result in an outcome in conflict with a facility's permit.

11.3 Managing Leachate Seeps

Seeps, which are also referred to as weeps, springs, or breakouts, result when leachate migrates laterally to the side slope of the landfill instead of downward to the LCRS. Seeps may be observed at all exposed landfill surfaces, but are most commonly observed on side slopes or at the base (toe) of the landfill. The seep may be evident because of a discoloration, malodor, or the presence of insects (see Figs. 11.1, 11.2, and 11.3). A primary concern with seeps is the potential for leachate migration beyond the landfill's footprint. Accordingly, seeps pose problems for

Fig. 11.1 Seep emergence from side slope of landfill

Fig. 11.2 Seeped leachate ponding at base of landfill slope

Fig. 11.3 Leachate seep flowing at base of landfill slope next to access road

landfill operators because they can contaminate stormwater and lead to prohibited discharges as well as cause odors, attract insects, pose slope stability concerns, and interfere with operations. Given the importance of addressing seeps at landfills with high moisture levels and those practicing liquids addition, this section focuses on seep causes, prevention, and mitigation issues. The information here follows that presented by Xu et al. (2013).

11.3.1 Seep Formation

Several factors contribute to leachate seepage at landfills, including the permeability of cover soil or waste layers, changes in waste properties at various depths, stormwater management practices, and the presence and operating conditions of liquids addition systems. Standard sanitary landfill operation practice (see Chap. 2) includes the placement of cover soil on the working face of the landfill at the end of each working day. Available site soils are often used as cover material, although alternative materials such as tarps and other wastes (e.g., ground wood, ash) are also commonly utilized. The properties and deployment of soil and alternative cover materials may contribute to seepage in different ways. Natural soils that have a low hydraulic conductivity (e.g., clay) and municipal waste incinerator ash (which typically has a low hydraulic conductivity), often create perched zones of leachate within the waste. The accumulation of leachate in these perched zones results in the migration of leachate horizontally towards the landfill side slopes, as conceptually illustrated in Fig. 11.4. The impact of low permeability cover layers was illustrated through fluid flow modeling by McCreanor and Reinhart (2000).

High-permeability soil layers, such as mulch and sand, likewise contribute to leachate seeps by providing a highly conductive horizontal layer (relative to compacted MSW) that results in a preferential flow path or short-circuiting of leachate towards the side slopes of the landfill instead of vertically downward (Fig. 11.5). Cover materials with similar hydraulic conductivity provide less lateral leachate migration and more uniform vertical movement (Soh and Hettiarachchi 2009). Operational practices to mitigate the impact of cover materials are discussed in the following section.

As discussed in Chap.5, and as demonstrated in laboratory and pilot-scale landfill experiments (e.g., Powrie and Beaven 1999), waste hydraulic conductivity decreases as depth increases, a result of increasing overburden pressure and effective stress. As conceptually illustrated in Fig. 11.6, decreasing hydraulic conductivity

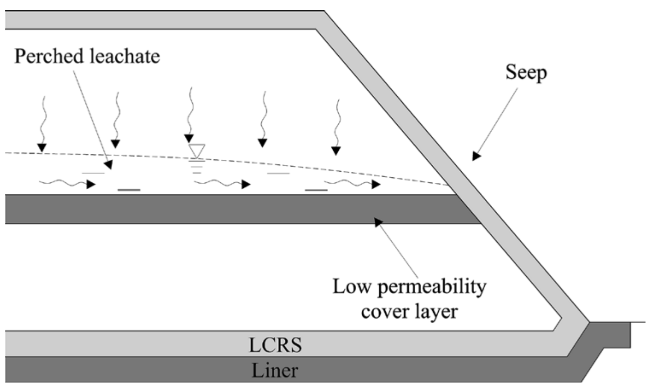

Fig. 11.4 Schematic of leachate seepage at a landfill caused by low permeability

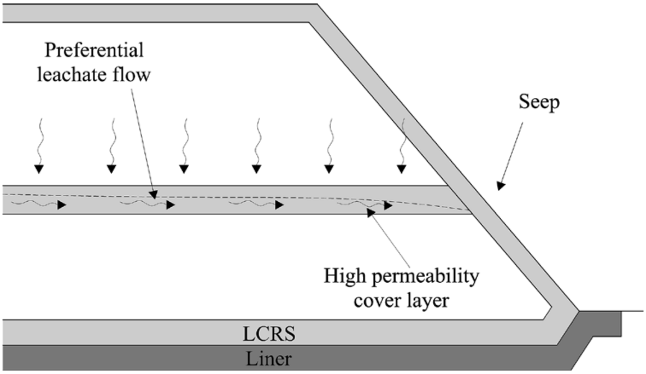

Fig. 11.5 Schematic of leachate seepage at a landfill caused by high permeability

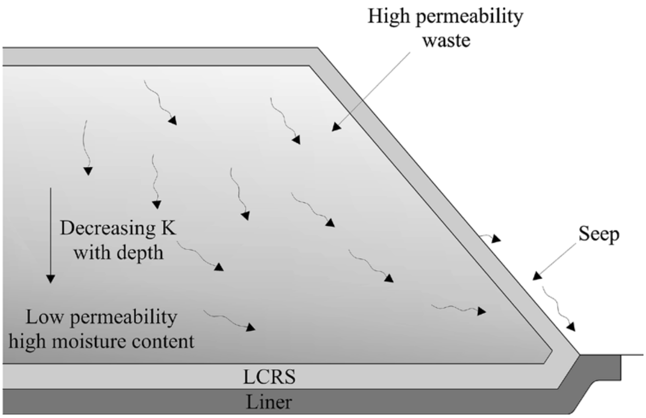

Fig. 11.6 Schematic of leachate seepage at landfills caused by decreasing hydraulic conductivity with depth

with depth in landfills coupled with compacted waste's anisotropy and subsequent tendency for preferential lateral flow, lead to a wider lateral spread of moisture distribution with depth, which in turn may cause leachate seepage at the side slope. Since volumetric waste moisture contents at deeper sections of the landfill are generally higher (since porosity is reduced), leachate seeps are often most common at the base of large landfills with elevated liquids levels.

In some cases, seeps on the side slope or base of a landfill may be the result of highly permeable cover materials used on side slopes. As illustrated in Fig. 11.7, when stormwater flows through permeable cover material along an exterior landfill slope, the water contacts waste and creates leachate, which can then seep out at the bottom of the landfill. In cases where the cover material is high in organic matter or iron, the stormwater can become discolored and have an appearance similar to leachate. Such occurrences are common when ground wood or yard trash is used as a cover material on steep slopes.

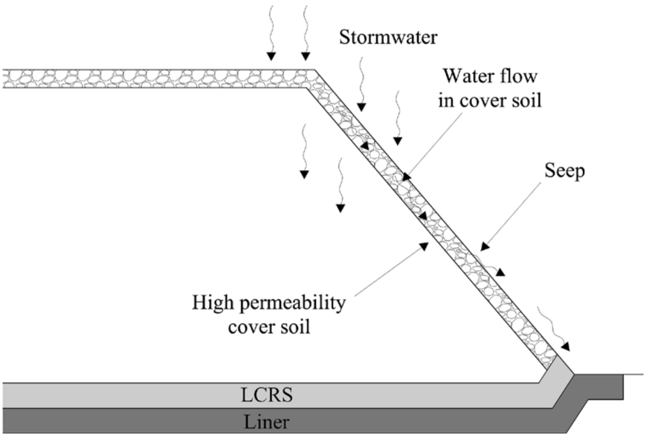

Fig. 11.7 Schematic of leachate seepage caused by high-permeability cover at the side slope

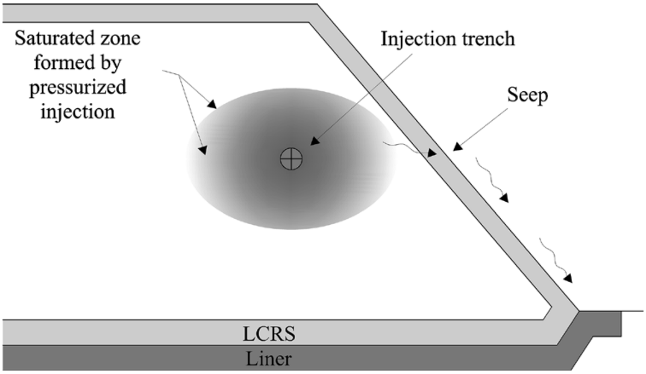

Fig. 11.8 Schematic of leachate seepage at a landfill caused by high injection pressure

The addition of liquids to the landfilled waste has the potential to contribute to leachate seeps. As described in Chaps. 8 and 9, landfill operators at large facilities often rely on adding liquids under pressure to distribute liquids within the landfill. Without the addition of pressure, it may be difficult to distribute liquids within the landfill in the desired time period. Leachate seepage occurs when the saturated zone reaches the side slope surface as conceptually illustrated in Fig. 11.8. The size of the saturated zone formed by the added liquids depends to a large extent upon the liquids injection pressure. The higher the injection pressure, the larger the saturated zone, which in turn results in a larger lateral spread. The flow modeling techniques described in earlier chapters can be used to estimate the degree to which pressurized liquids might migrate to the landfill side slope.

11.3.2 Seep Prevention Strategies

Landfill engineers and operators can employ several strategies to prevent, minimize or otherwise control seeps at landfills. Such measures may be implemented during the design stage of a liquids addition system, as well as during construction and operation the system. The landfill operator also has a great ability to impact the potential for seeps by practicing certain fundamental waste and cover soil placement practices; examples of these practices are highlighted in the following sections.

The selection and placement of cover material requires special attention during landfill operations and planning. An ideal cover soil would be one where the permeability of the cover soil is similar to the disposed waste—however, numerous other factors come into play when determining the optimal type and amount of cover material (e.g., availability, cost, meeting minimum regulatory requirements for vector reduction, litter prevention, and other considerations). The use of alternative cover materials such as foams or tarps that result in less heterogeneity in landfilled materials serve to reduce stratification and resulting pathways for liquids short-circuiting. When site conditions dictate that potentially problematic cover materials (from a seepage perspective) be used, operators often attempt to scrape as much of the soil from the underlying waste surface as possible before placing the next waste lift. This practice of soil scraping has positive and negative economic impacts on operations: scraping provides additional airspace for new waste disposal, but the time and equipment requirement to scrape the soil might be more costly. Even if only a fraction of the soil layer is removed, a reduction in heterogeneous stratified layers will minimize lateral movement of liquid to the landfill slope. Landfill operators with low permeability cover soils sometimes dig "windows" in the cover to promote liquids to drain from one lift to the next.

Some sites receive large amounts of low-permeability granular wastes such as ash, and they are often allowed by permit to use these materials as daily cover. Lateral movement of leachate along compacted ash layers has been found at several sites to result in seep problems. The economic benefit of such practices (i.e., receiving an approved soil-like material for daily cover for free, a reduced cost, or even with a tipping fee) must be weighed against longer term operational and maintenance issues related to seep control. One strategy includes using ash as cover on interior landfill surfaces and avoiding its use in areas near side slopes. Ash disposed toward the edge of the landfill should be mixed with other wastes to avoid the formation of distinct layers.

One strategy to avoid seeps involves grading waste lifts adjacent to the side slope (and, by extension, grading the layers where cover material is placed) towards the interior of the landfill. As shown in Fig. 11.9, the cover soil layer is sloped near the edge of the landfill to drain inward and thus preclude added liquids from reaching the landfill surface and emerging as a seep. This operational practice would also need to consider the impact on stormwater management, as the development of an inward gradient could cause more stormwater accumulation near working areas if not otherwise diverted.

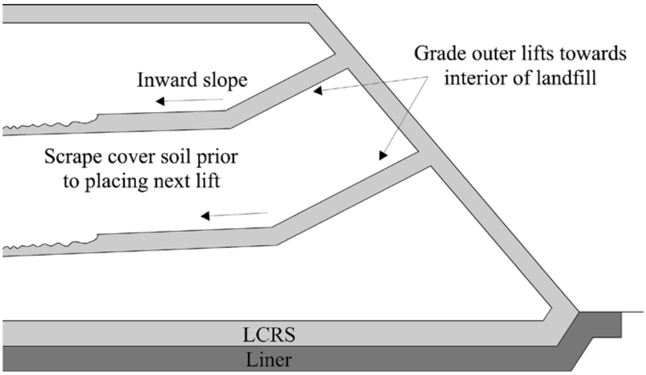

Fig. 11.9 Cover removal and lift grading strategies to minimize seeps

For sites with GCCS, efficient operation of the GCCS can aid in seep control. Preferential flow paths out the side of the landfill caused by landfill gas migration can promote the flow of leachate through these same paths. A well-operated GCCS will induce a negative pressure within the landfill and direct gas movement towards gas collection points, and by extension reduce the preferential flow paths that leachate can travel. When directing gas movement (and, to a degree, liquids movement) toward gas collection points, the accumulation of liquids can occur at gas collection points. This can be remedied by installing temporary or permanent pumps to remove liquid build-up (discussed in Chap. 13).

The extent to which seeps are likely to occur will be largely influenced by the moisture content of the waste itself and the degree to which liquids addition occurs. As discussed in Chap. 6, facilities that specify large liquids addition volumes will require aggressive approaches to meet the design targets in the form of more liquids addition devices and/or greater liquids addition pressures. When such a strategy is pursued, the engineer and operator must expect that seeps will occur and must therefore take steps both in system design and in development of the operations plan to address these events. Alternatively, the objective at some sites might be to apply a more conservative approach and add less liquid with a goal of preventing seeps from occurring (e.g., designing liquids addition devices to be far away from side slopes and specifying low injection pressures). These two approaches are conceptually illustrated in Fig. 11.10 for a landfill employing horizontal liquids addition. In one approach, injection lines are added throughout the landfill to penetrate as much of the waste mass as possible (Fig. 11.10a). In the conservative approach, the number of liquids addition devices is deliberately minimized and maintained at a conservative distance away from the side to avoid seeps (Fig. 11.10b).

Designers and operators can take some steps when constructing liquids addition devices to minimize seeps. Liquids addition systems that employ horizontal trenches often place injection lines on consecutive or alternating waste lifts, with each line penetrating the side of the landfill and connecting to an external distribution manifold

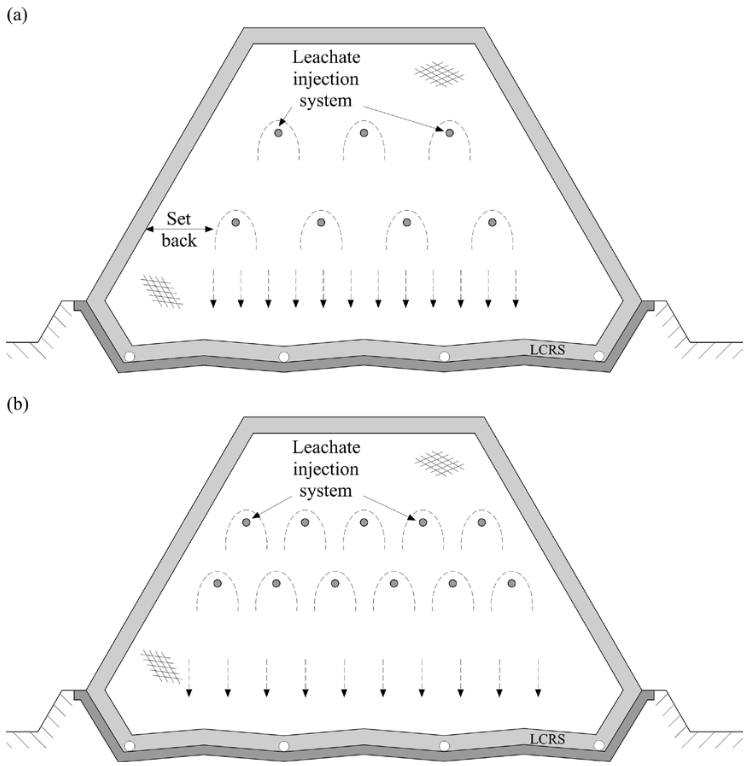

Fig. 11.10 General approaches for seepage control at a bioreactor landfill (**a**) operate conservatively to avoid seeps, (**b**) operate to manage seeps

(see Chap. 9). Pipe perforations begin after a specified setback distance away from the side slope. In practice, seep collars can be constructed to reduce the preferential flow of leachate along the pipe and towards the side slope. For example, clay can be placed in a horizontal trench between the side slope and the start of perforations and compacted in place. An additional construction technique for horizontal trenches includes sloping the pipes toward the interior of the landfill to encourage gravity drainage into the landfill, rather than toward the side slope.

Adjusting the number of penetrations into the landfill caused by liquids addition devices represents another approach to minimizing leachate seeps; fewer side slope penetrations will result in fewer seepage issues. Adjusting the location where injection device perforations begin may also prove a useful seep prevention strategy, particularly since injection pressure is greatest at the point of the first penetration of the injection device. Starting perforations more toward the interior of the landfill and then branching toward exterior areas should reduce seep potential; this strategy is illustrated in Fig. 11.11. In Fig. 11.11a, each injection device has a penetration into the landfill, which allows for greater control of injection parameters into a device, but results in a large amount of penetrations; pressure is greatest at the point

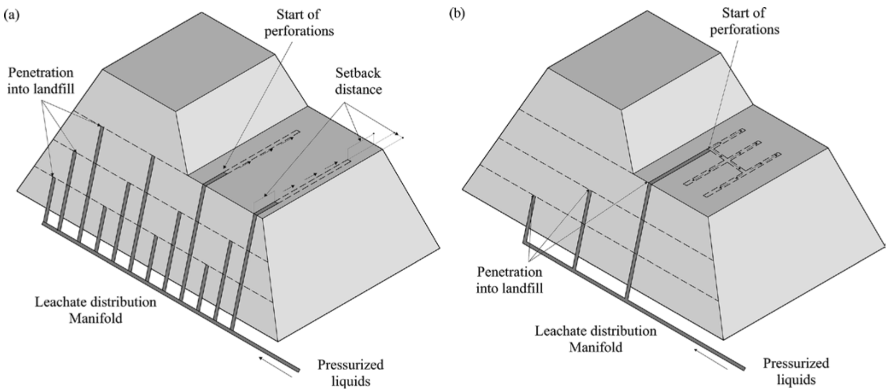

Fig. 11.11 Schematic of approaches for the penetration of horizontal leachate injection line (**a**) approach with multiple penetrations, (**b**) approach with limited penetrations

where the penetrations first start, nearer the landfill slope. In Fig. 11.11b, multiple injection lines are tied together by a manifold in the interior of the landfill and a single side slope penetration is constructed—this reduces liquids addition control for individual devices but reduces the number of side slope penetrations.

The use of a distribution blanket instead of buried trenches may have a similar result as the case shown in Fig. 11.11b. In the case of a buried distribution blanket or a design with minimal side slope penetrations, the design and construction must be performed to mitigate the potential for failure of the line, since failure would preclude the ability to distribute liquids to a large area. Possible failure modes to be planned for include crushing, clogging, or pipe disconnection.

When specifying the distance that a liquids addition device must be kept from the landfill side slope to avoid seepage, factors such as waste properties, device configuration, and planned operation should be considered. The techniques described in Chaps. 8 and 9 for predicting the extent of liquids migration from a device (a function of flow rate, pressure, waste characteristics, and operation time) can be used to estimate the location of the saturated zone with respect to the slope and thus to determine a necessary setback distance. Xu et al. (2013) examined appropriate setback distances to avoid seeps and found that for typical design and operating conditions the influence zone from vertical wells placed adjacent to or on a side slope should not intercept the landfill surface and the appropriate setback distance (X_D) from a horizontal trench to the edge of the landfill could be approximated as:

$$X_D = \frac{Q}{3K_z}$$

when $K_X/K_Z > 20$ and where Q is the liquids flow rate per length of trench and K_Z and K_X are the vertical and horizontal hydraulic conductivity values, respectively. As described earlier, however, the presence of waste or soil layers of high or low permeability could result in liquids migration over much large distances.

11.3.3 Seep Management Strategies

Regardless of the steps taken to prevent seep formation, the operator should routinely inspect for the presence of seeps and have contingencies in place to address seeps when they are observed. The designer should include a seep management plan as part of the site's operations plan. Once leachate seepage occurs, the seep must be promptly addressed to avoid further environmental issues. Operators may use several methods to address seepage issues, but regardless of the approaches employed, the appropriate procedures and supplies must be readily available to quickly address observed problems.

With respect to the seep management plan, all necessary landfill personnel should be trained to identify seep-related situations such as wet areas on the surface of the landfill, surface cracks, and erosion. This can be accomplished as part of a routine visual inspection of the landfill site. Inspection components most often include: (a) examination of the landfill surface and side slopes for signs of seeps (depending on the size, configuration, and cover type, this may be performed by walking the site or observing from an on- or off-road vehicle), (b) examination of exposed liquids piping for signs of leakage, (c) examination of liquid, air, and gas pipes and hoses for signs of breakage or wear, (d) visual inspection of the storm water management system, and (e) visual inspection of the valve positions. These daily inspections should be conducted by one or more trained individuals and recorded on an inspection sheet or using a form loaded onto a laptop or tablet computer.

The conventional practices for addressing seeps often involve placing additional cover soil (usually a low-permeability clayey soil) on top of the area of concern followed by compaction of the material. Depending on the magnitude of the seep source, this may only provide a temporary solution, as liquids may migrate around the compacted soil to reemerge somewhere else on the slope. Figure 11.12 illustrates this conventional soil-compaction approach along with expanded strategies that allow the moisture to be redirected away from the slope. A more detailed approach includes excavating the area of the seep, adding stone (or some similar drainage media), and providing a drain or chimney that permits leachate to be directed back into the landfill or the LCRS.

For sites with a high likelihood of seeps, such as those employing a more aggressive strategy for liquids addition, the design of a robust toe drain at the base of the landfill represents a useful control strategy. The toe drain should be designed and constructed to allow the operator to connect slope drains that are constructed as seep locations are identified and remediated. Since a prime location for leachate seeps is at the base of landfill slope, benches, or access roads, the design of seep drains as part of this infrastructure can be incorporated into the landfill liner system design and into the long-term operations and closure plan for the landfill.

Future planning for long-term landfill cover and closure is an integral part of the planning process for leachate seeps at landfills practicing aggressive liquids addition strategies. Some operators pursue a "close-as-you-go" approach where components of a final closure system are constructed on outer landfill slopes as they reach final

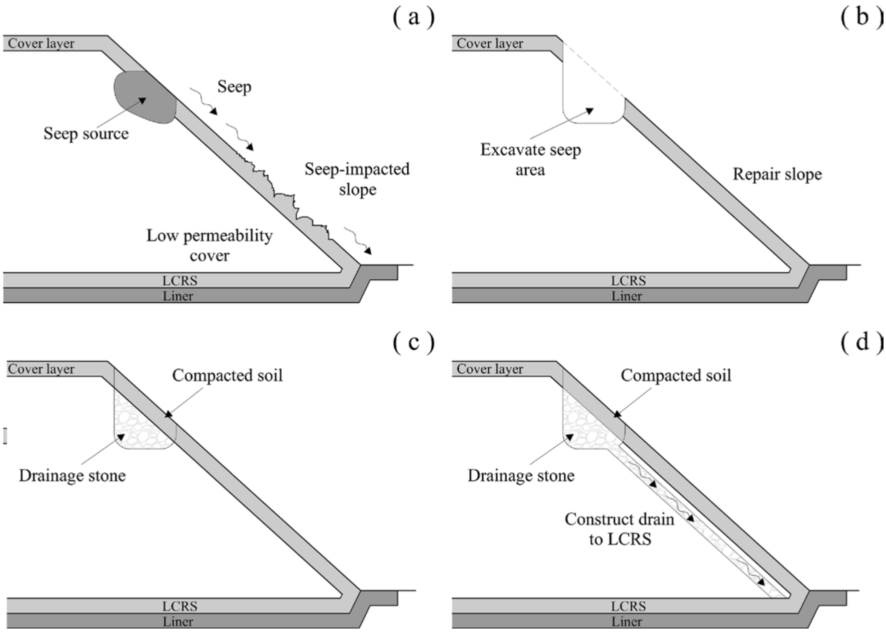

Fig. 11.12 Strategies for addressing a side slope seep: (**a**) seepage occurring; (**b**) excavation; (**c**) filling and compaction; (**d**) placing a surface drainage system

grade (this approach is discussed in greater detail in Chap. 17). Such a practice enables the engineer to link a toe drain system for seep control to future vertical phases of landfill construction over time. In scenarios when accelerated slope closure is not feasible, alternative side slope cover strategies may integrate well with seep control. For example, placing exposed geomembrane caps or geosynthetic rain covers on the side slopes as a means of shedding rainfall and minimizing erosion can reduce seepage problems. Such systems could tolerate a greater degree of leachate seepage compared to traditional cover systems, though the integration of slope and toe drains would need to be implemented. Creative management of the interface of the bottom liner system with the side slopes and eventual cover system—especially systems that integrate stormwater runoff, seep control, and gas recovery—should be considered.

11.4 Leachate Storage

An integral component at nearly all landfill facilities is the leachate storage system. At facilities practicing on-site treatment, leachate storage might be integrated into treatment operation. At facilities where off-site leachate disposal is practiced (unless the discharge point is located very close to the landfill, or where leachate is recirculated to the landfill), storage will be necessary to provide necessary equalization of flow

Fig. 11.13 HDPE lined leachate storage pond equipped with floating aerators

and to provide holding capacity when off-site discharge or recirculation is not possible. The selection of a storage system depends on considerations such as the type of waste disposed, volume of leachate expected, available space, and cost. Common storage mechanisms include ponds, lagoons, and tanks.

Lined leachate ponds or lagoons are commonly used at landfill sites. The liner system is similar to the one used for the barrier layer at the bottom of the landfill. In some cases, a double liner with a leak detection system might be employed. A common practice includes placing floating aerators in the pond to provide initial leachate treatment and reduce odor emissions (Fig. 11.13); the aeration system provides oxygen and promotes mixing. Solids accumulated on the bottom of a storage pond may need occasional removal. This can be accomplished by draining the pond and removing residues by hand or using a vacuum truck. Care must be taken to avoid damaging the liner system.

If the leachate storage unit is not covered, the volume of leachate requiring management will be influenced by local climate conditions. In dry areas, a net loss in leachate may result because of evaporation. In wet climates, however, a net addition of water as a result of rainfall will add to the total volume of leachate. A solution to this problem for ponds in wet climates is to place a floating geomembrane cover on top of the leachate (Fig. 11.14). Rainwater that accumulates on top of the geomembrane can be periodically removed using a pump.

Some facilities employ leachate storage tanks or structural basins, with primary construction materials including steel, fiberglass, and concrete (Figs. 11.15 and 11.16). For some storage systems, the top of the tanks remain open to the atmosphere, and often include manifold diffusers for air addition. In other systems the tanks are closed

Fig. 11.14 HDPE lined leachate storage pond equipped with surface rain cover

Fig. 11.15 Fiberglass leachate storage tanks surrounded by secondary containment system

to the atmosphere, with either a floating cover or a fixed cover that vents to the atmosphere. Just as with leachate ponds and lagoons, the sediment that builds up in the bottom of the tanks must be occasionally removed. Secondary containment for tank systems is provided using an outer concrete vault or wall, or by placing the entire tank in a lined unit.

Fig. 11.16 Glass-lined steel leachate storage tanks surrounded by secondary containment system

11.5 Leachate Treatment

Leachate collected from an engineered landfill requires appropriate treatment prior to any discharge to the environment. As with leachate storage, several methods of leachate treatment are available. Treatment options include sending the leachate to an off-site domestic wastewater treatment facility, on-site pretreatment followed by off-site treatment, and complete treatment and discharge on-site. The type of leachate treatment method selected depends on facility-specific conditions. One of the primary sustainable landfilling practices described in this book has been recirculating leachate collected from the disposal facility's LCRS back to the landfilled waste. While this practice provides some reduction of constituent concentration (e.g., BOD), additional treatment beyond recirculation to the landfill must be planned for. At most sites, a time will arrive when leachate must be removed from the landfill and treated prior to safe discharge to the environment. In this section, leachate treatment fundamentals applicable to landfill sites are described, followed by a discussion of special considerations for facilities implementing sustainable practices.

In Chap. 2, fundamental chemical constituents in MSW landfill leachate and their changes over time were described. The choice of treatment process utilized at a landfill site depends on the constituents requiring treatment and the degree of treatment required—these factors are dictated by regulatory limits and available final disposal options. For example, a landfill requiring effluent from leachate treatment to meet drinking water standards prior to discharge will require a much different type of treatment system compared to a facility that must only meet the pretreatment requirements of a local wastewater treatment facility. Table 11.1 summarizes many leachate treatment strategies that the landfill operator may consider.

Table 11.1 Leachate management and treatment strategies

Management option	Description or discussion
Off-site treatment	Leachate is hauled via a tanker truck or pumped through a force main or gravity sewer to an off-site wastewater treatment facility. Treatment charges may be dependent on leachate constituent concentration
On-site pretreatment followed by off-site treatment	In some cases, off-site facilities place constituent limits or surcharges that warrant some degree of on-site treatment prior to off-site transport
On-site treatment and discharge	A treatment system is constructed on-site and treated effluent is discharged to the environment through land application, surface water discharge, or deep well injection
Management within the landfill	As part of sustainable landfill operations, leachate can be recirculated to the landfilled cell it originates from, or perhaps another landfill cell. This technology may provide for some degree of chemical constituent treatment. This approach is normally combined with one of the other approaches

One of the most common and desirable methods for managing leachate is through discharge to an existing wastewater treatment facility not associated with the landfill. Leachate transport is typically accomplished using a force main (a direct pipe connection) or tanker trucks. Since leachate quantities should be small compared to influent volumes for a domestic wastewater treatment facility, this method of management offers the advantage of diluting some of the more difficult-to-treat constituents. Municipal landfills are often subject to pretreatment standards prior to discharge to a domestic wastewater treatment facility, and if these pretreatment standards are not met, the wastewater treatment facility may either stop accepting the leachate or charge a higher price to receive the leachate. If pretreatment standards pose a substantial challenge, construction and operation of infrastructure for pretreatment on-site may be necessary. Alternatively, a more distant wastewater treatment plant may be willing to accept the leachate for treatment, but hauling costs would increase. In addition to municipal facilities, private wastewater treatment facilities may be available, though costs and travel distances may be greater.

When off-site treatment options become too limited, construction and operation of an on-site treatment facility may be necessary. A variety of methods are available for treating leachate on-site, and the method selected depends on the fate of the leachate and the regulatory requirements associated with the discharge location. Given the nature and variability (with respect to quantity and quality) of leachate, the treatment system design should allow flexibility to modify capacity and treatment processes required. Earlier in Chap. 2, general categories of leachate chemical constituents were outlined and the type of treatment technology most effective for each constituent category differs. Table 11.2 summarizes leachate treatment options associated with these categories. The rest of the chapter summarizes some of the more common treatment technologies used for landfill leachate as well as treatment issues to be considered at facilities implementing sustainable landfill practices.

Table 11.2 Technologies utilized for leachate constituent classes

Leachate constituent class	Treatment technologies
Organic matter	Early-phase leachate with a high BOD or a BOD: COD close to 1.0 requires some form of biological treatment, such as an aerated lagoon, rotating biological contactor, or an up-flow anaerobic sludge blanket. Stabilized leachate with a BOD: COD of 0.1 can be reduced in concentration with chemical precipitation or other physical-chemical processes
Inorganic ions	Limited removal options are available and these constituents are normally managed through dilution, evaporation, or membrane separation
Nutrients	Ammonia nitrogen is the primary nutrient constituent, and can be removed biologically using phased aerobic and anaerobic treatments. Can also be removed using physical-chemical technologies such as air stripping at an elevated pH
Trace chemicals	Trace chemicals are normally sufficiently dilute to not drive the treatment process. They are removed as part of other treatment operations (e.g., volatilization, precipitation)

11.5.1 Conventional Leachate Treatment Processes

The dominant treatment processes used at domestic wastewater treatment operations are those relying on microorganisms to degrade or otherwise transform wastewater constituents into desired end products. Biological treatment will normally be the least expensive option for wastewater dominated by biodegradable organic matter. Both aerobic and anaerobic biological treatment methods are utilized. Engineers have developed numerous configurations and approaches to achieve efficient biological wastewater treatment. The methods for optimizing the biological degradation involve controlling the dissolved oxygen level, adding nutrients, increasing the concentration of microorganisms, and maintaining desired environmental conditions such as pH, temperature, and turbulence.

Aerobic treatment processes depend on microorganisms grown in oxygen-rich environments to oxidize organic compounds to carbon dioxide, water, and microbial biomass. Aerobic biological systems include aerobic reactors such as activated sludge basins, rotating biological contactors, aerobic filters, and continuous-flow aerobic reactors. Anaerobic treatment will use a similar biological flora as occurring inside an active anaerobic landfill and is performed in enclosed tanks (Fig. 11.17). Detailed information of the design of biological wastewater treatment operations are provided in a number of fundamental texts on the subject (Aluko and Sridhar 2005; Grady et al. 2011; Metcalf et al. 2013), and application of specific biological leachate treatment technologies has been well-described in the literature (Timur and Ozturk 1997; Diamadopoulus et al. 1997; Inanc et al. 2000; Borghi et al. 2003; Bulc et al. 2003).

A major difference in leachate and domestic wastewater is the relative biodegradability of the organic matter. Most of the organic matter in domestic wastewater is biodegradable (BOD:COD approximately = 1.0). As discussed in Chap. 2, leachate in early stages of stabilization is high in biodegradable organic matter, but in older more stable leachate, BOD:COD is low. Thus, a large fraction of the organic matter

Fig. 11.17 On-site leachate treatment plant consisting of multiple biological and physical treatment operations

will not be reduced in concentration using conventional biological wastewater treatment operations. Research has therefore been focused on combining biological leachate treatment with other physical and chemical leachate treatment technologies (e.g., Baumgarten and Seyfried 1996; Bae et al. 1997; Lin and Chang 2000; Cecen and Aktas 2001; Gulsen and Turan 2004; Fang et al. 2005).

Another major application of biological leachate treatment in addition to organic matter removal is treatment for ammonia nitrogen. Wastewater treatment facility operators commonly integrate the combined nitrification and denitrification process into the overall facility design (Grady et al. 2011) and this is certainly true for leachate (Aktas and Cecen 2001; Uygur and Kargi 2004; Berge et al. 2005). For landfills as a whole, this has been extended into an approach where leachate is externally denitrified and then recirculated to the landfill for nitrification; this technology and similar approaches are described in more detail in Chap. 14.

Multiple physical treatment unit operations have been employed for leachate treatment, from basic solids separation steps (settling, filtration) to absorption techniques for removal of specific chemical contaminants (e.g., activated carbon). A variety of chemical treatment techniques have been evaluated to meet specific leachate treatment objectives. Lime is a common chemical additive used to increase pH, a step which provides for ammonia stripping and metal precipitation. Chemical coagulants, most notably alum (aluminum sulfate) and iron salts (ferric sulfate, ferric chloride) have been widely employed as a method to remove organic matter from leachate (Comstock et al. 2010; Amokrane et al. 1997; Kurnianwan et al. 2006; Tatsi et al. 2003). In this process, solutions of coagulants are added in mixing tanks, sometimes as part of biological treatment, and after the coagulants form, they are allowed to settle in subsequent clarifiers, where the sludge is removed and dewatered.

Fig. 11.18 A bank of spiral wound reverse osmosis membranes used as a polishing step in an integrated leachate treatment operation

An alternative to chemical coagulation for reducing recalcitrant organic matter concentrations is the addition of chemical oxidizing agents. The primary objective of this approach is to oxidize refractory organics to carbon dioxide or to less harmful, more biodegradable substances that may be removed in a subsequent biological process (Bila et al. 2005). Traditional oxidants for leachate treatment include ozone (O_3), hydrogen peroxide (H_2O_2), potassium permanganate ($KMnO_4$), and calcium hydrochloride (Steensen 1997; de Morais and Zamora 2005; Wiszniowski et al. 2006).

Dissolved ions such as chloride, potassium, sodium, and calcium (which along with organic matter contribute to the bulk of the TDS in leachate) belong to a chemical class that has limited options for removal. In many treatment operations, these constituent concentrations are primarily addressed through dilution. Leachate added to a domestic wastewater treatment facility will result in dilution of salts, and when treated leachate is discharged to surface water or groundwater, dilution may be sufficient to meet water quality limits in the water body. If very low TDS levels are required prior to discharge, treatment options focus on processing the leachate into separate concentrated and dilute fractions. Evaporation systems (which often utilize landfill gas as a fuel) evaporate water creating a salt cake or sludge that is disposed in the landfill. Membrane systems, such as reverse osmosis and nanofiltration, have been used to separate leachate into a concentrated fraction (recirculated back to the landfill) and a dilute fraction (discharged on-site) (Linde et al. 1995; Ahn et al. 2002; Ushikoshi et al. 2002). A variety of membrane types and configurations can be employed (Fig. 11.18 shows a bank of spiral wound RO membranes at a leachate treatment facility). With both of these approaches, the operator uses the landfill to manage the bulk of the solids, while removing excess moisture as a dilute stream.

Leachate treatment using natural systems such as wetlands has been utilized, in many cases as a final treatment step after treatment in aerated basins and before discharge to a

Fig. 11.19 Wetlands leachate treatment system located adjacent to an operating landfill

water source (Kadlec and Knight 1996; Kadlec 1999; Bulc et al. 1997; DeBusk 1999). Wetlands treatment may function better in warmer climates that allow the vegetation to flourish for a greater portion of the year. A variety of wetland configurations have been employed, including natural wetlands, aquatic plant systems, constructed subsurface flow wetlands, and constructed surface flow wetlands (Fig. 11.19). Much of the performance data on wetlands treatment has been collected for systems designed to remove pollutants from municipal and industrial wastewaters. However, the pollutant-removal mechanisms that have been identified in wetlands receiving domestic or industrial wastewater should operate in a similar manner for the treatment of landfill leachates. Wetlands treatment provides both physical and biological treatment mechanisms to remove pollutants such as nitrogen, phosphorus, metals, and organic compounds.

11.5.2 Leachate Treatment Considerations for Sustainable Landfill Operations

Landfill operators implementing technologies such as enhanced waste stabilization through liquids addition will often manage much of the leachate through recirculation back to the landfill. Leachate recirculation also provides some degree of leachate treatment, and thus may influence the type of leachate treatment approach selected. One important recognition is that even when leachate recirculation is planned to provide the predominant leachate management mechanism, providing an additional form of leachate management is critical (e.g., during times of regular maintenance, system upset, or regulatory issues). At some point in landfill operation, after stabilization is largely reached, there is only limited further benefit to leachate recirculation.

Since the landfill itself acts as a biological treatment unit for added leachate, the additional design of an on-site biological leachate treatment system may not be the most efficient use of resources. A more effective approach would be to rely on an

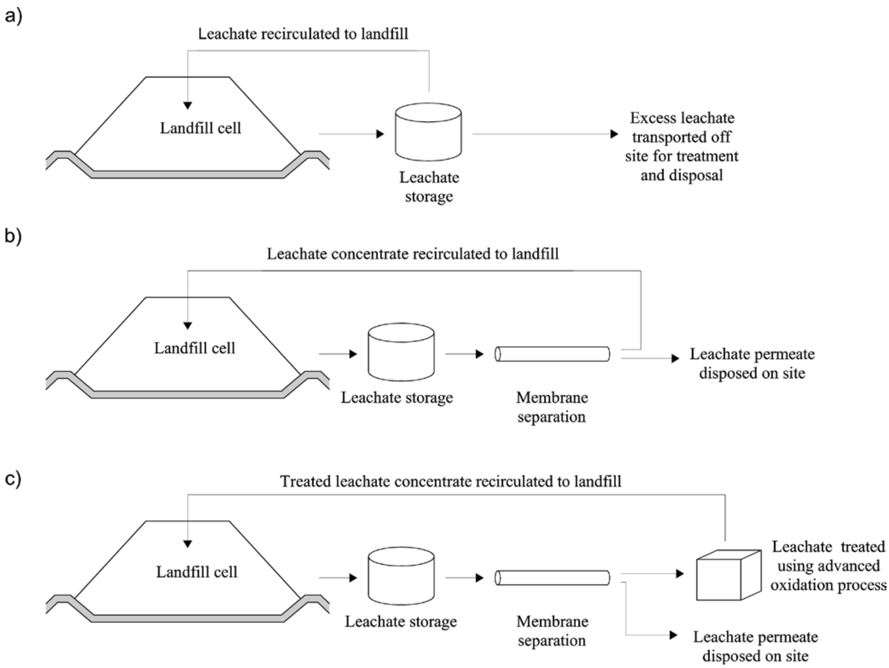

Fig. 11.20 Leachate treatment strategies for landfill practicing leachate recirculation

off-site treatment plant to handle excess leachate, and where on-site treatment is desired or necessary, to implement technologies that complement a landfill with liquids addition. Several leachate treatment approaches have potential to integrate with leachate recirculation activities and goals. For instance, leachate evaporation can be used as a means of reducing leachate volumes and, if the landfill is still active, residual solids can simply be disposed in the disposal operation.

One approach used in conjunction with leachate recirculation to produce an effluent of quality to be discharged on site while recirculating the rest of the leachate is reverse osmosis (RO) or similar membrane systems (Fig. 11.20). In this process, leachate is separated into dilute (permeate) and concentrated streams by placing the leachate under pressure in contact with a RO membrane. RO membranes have been found to be successful in rejecting most pollutants, including salts, dissolved organic matter, and heavy metals (Linde et al. 1995; Ahn et al. 2002; Ushikoshi et al. 2002). These systems do not require the degree of permeate production as RO systems designed for desalination of drinking water, and thus can be performed under much less pressure. This technique can be used in combination with leachate recirculation to remove net moisture from the landfill.

Another strategy that lends itself to those facilities practicing leachate recirculation is the use of oxidizing chemicals to transform some of the recalcitrant organic matter in the leachate to a form that can be biologically consumed (and turned to biogas) within the landfill. For example, Fenton's reagent has been extensively investigated and applied to treat landfill leachate (Gau and Chang 1996; Bae and Kim

1997; Yoon and Cho 1998; Kang and Hwang 2000; Lin and Chang 2000; Zhang et al. 2006), and this chemical process has been specifically evaluated as a technique that could be used with landfills practicing leachate recirculation (Batarseh et al. 2007). The reaction involves H_2O_2 and a ferrous iron catalyst; the decomposition of H_2O_2 is enhanced by the ferrous iron acting as a catalyst, resulting in the generation of hydroxyl radicals that can oxidize the refractory organics. Lopez et al. (2004) reported that approximately 60 % of COD was removed by Fenton's reagent pretreatment and the BOD_5/COD ratio was increased from 0.2 to 0.5

At some point, active recirculation of leachate or other liquids will cease and then leachate management will primarily consist of removal of leachate collected in the LCRS and appropriate treatment and disposal. Leachate volumes should diminish over time as free liquids migrate out of the landfill under gravity. The long-term rate of leachate generation will depend on the effectiveness of the closure system for diverting rainwater from infiltrate into the waste. Final determinations of how landfill leachate will be managed depend on regulatory post-closure care requirements designed to protect human health and the environment. These issues are discussed for the landfill as a whole in Chap. 17.

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Chapter 12
Slope Stability

Abstract Similar to leachate management considerations, the implementation of liquids addition as part of sustainable landfilling can impact the properties and behavior of landfilled waste. One key aspect that the designer must consider is the impact to above-grade slope stability. Fundamentals of slope stability are first presented followed by a discussion of the factors related to landfills practicing liquids addition. A series of slope stability simulations are presented in the context of different liquids management scenarios, and the role that factors such as injection pressure and LCRS drainage are illustrated. A series of charts providing necessary setback distances are presented to give the designer a sense of pressure limitations when liquids are added near side slopes.

Keywords Landfill • Leachate • Slope • Stability • Failure • Slide • Recirculation

12.1 Landfill Slope Stability

Assessing the stability of a landfill side slope is a primary element in the design process for all landfills. The engineer evaluates the stability of cover material components on the slopes of the landfill and the internal stability of the waste mass (waste plus soil) itself. A thorough assessment of slope stability is especially important at landfills where liquids addition is practiced, as elevated pore-water pressures in a landfill resulting from added liquids and generated gases can lead to a decrease in the effective stress placed on the waste and on waste-soil or waste-geosynthetic interfaces. In addition, changes in waste properties due to biological decomposition of the waste can result in strength changes of the landfilled material.

Several landfill side slope failures have been attributed, at least in part, to elevated liquid levels within the landfill (Blight 2008; Hendron et al. 1999; Stark et al. 2000; Thiel and Christie 2005) and the consequences of these failures have been severe, including multiple human deaths in some cases (see Fig. 12.1 for an example catastrophic failure in the Philippines). Koerner and Soong (2000) discussed the influence of leachate in landfills on slope stability. The role of leachate under several different scenarios was described, including perched zones of leachate within the landfill, leachate head on the liner, and added pore pressures resulting from liquids

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Waste Management Principles and Practice, DOI 10.1007/978-1-4939-2662-6_12

Fig. 12.1 Slope failure at the Payatas landfill, Philippines (Photo courtesy of Scott Merry)

addition. The potential role of landfill gas pressure was highlighted as an issue by Merry et al. (2006). In a review of six landfill slope failures from sites around the world, Landva and Dickinson (2012) found that the properties of decomposed waste played a key role in the observed failures.

Slope stability assessment is an extensive engineering topic unto itself, and entire design texts and software packages are devoted to such analyses (Abramson et al. 2002; Das 2005; Duncan and Wright 2005; GeoSlope International Ltd 2007; Krahn 2007). This chapter is devoted to slope stability because of the great importance of slope stability considerations at landfills that add liquids to the waste mass (GeoSlope International Ltd 2007).

12.2 Slope Stability Fundamentals

The factor of safety (FOS), defined as the ratio of the shear strength (s) of the media (or the interface between different media) to the shear stress (τ) required to maintain equilibrium, is a term commonly used to quantify the ability of a slope to prevent or resist movement compared to forces that would cause slope movement. The FOS is represented as follows:

$$FOS = \frac{Shear\,strength(s)}{Shear\,stress(\tau)} \tag{12.1}$$

Components of shear strength include frictional resistance ($\sigma_V \tan\phi$) and cohesion (C) among the particles that make up the object. This is illustrated as follows:

$$s = C + \sigma_V \tan\phi \tag{12.2}$$

where ϕ is the internal angle of friction between the soil or waste particles where the shear failure occurs, σ_V is the vertical stress, and C is the cohesion (which represents the internal forces that bond the particles together). As described in Chap. 5, the friction angle of MSW varies over a wide range but is typically measured from 20° to 35°. Cohesion values for MSW have been reported to range from 0 to 30 kPa.

The presence of pore water pressure (u) reduces the effective stress between particles, such that:

$$s = C + (\sigma_V - u)\tan\phi = C + \sigma_V^* \tan\phi \tag{12.3}$$

where σ_V^* is the vertical effective stress. The FOS can thus be expressed as:

$$FOS = \frac{c + (\sigma_V - u)\tan\phi}{\tau} \tag{12.4}$$

A slope failure is expected to occur when the shear stress exceeds the shear strength (i.e., FOS < 1.0). The plane where the failure occurs is referred to as the *slip surface*. Typical engineering practice is to design for FOS of 1.2–1.5. Shear strength as described above refers to an internal quality related to a single medium (e.g., soil, waste), but similar concepts apply to the interface between two media (Koerner 2005). When two types of media are involved, the interface friction angle between the two media (typically denoted as δ) and the adhesion (typically denoted as A) must be measured or otherwise estimated. Throughout the remainder of this chapter, slope stability concepts are discussed and illustrated by describing a given medium with an internal angle of friction and cohesion; the role of interfaces between different materials is discussed, but not quantitatively examined. The design engineer must recognize appropriate interfaces between different media in the system and design accordingly.

A common engineering practice for assessing landfill slope stability is to use a computer-based slope stability model with site-specific inputs. Examples of slope stability model input parameters include landfill configuration (e.g., height, slope), waste characteristics (e.g., friction angle, cohesion), and characteristics of the interface between the waste and other landfill components (e.g., soil, geosynthetics). As discussed previously, a slope failure can result from several different factors. An increase in pore-water pressure (as might occur when liquids are added or not appropriately drained) reduces the effective stress and the resulting shear strength. A reduction in media properties such as friction angle and cohesion (as might occur when waste decomposes) can likewise reduce shear strength. Changes in configuration (such as a slope change or the removal of a soil at the base of a slope) can result in a decrease in those forces restraining movement.

A slope failure has the potential to occur during several different phases of landfill construction and operation, including liner construction, waste placement, and after landfill closure (Abramson et al. 2002). Figure 12.2 illustrates common slope

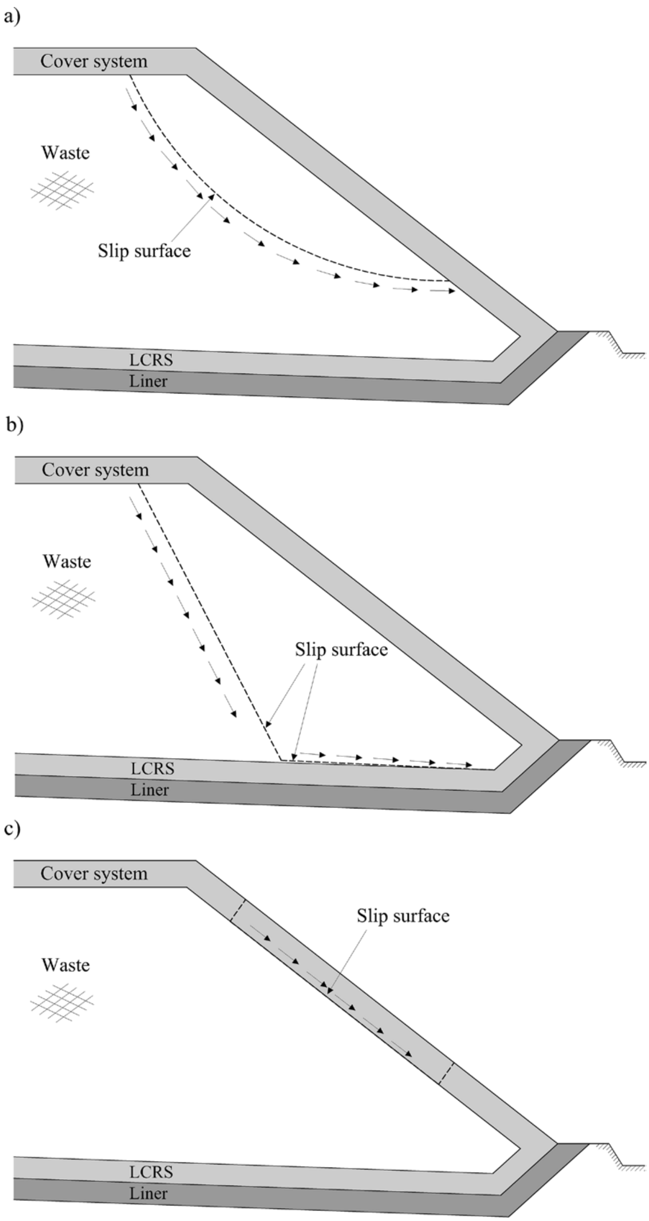


Fig. 12.2 Basic slope failure modes at landfills: (**a**) a circular failure; (**b**) a block failure; and (**c**) a veneer failure

failure modes in the context of a given landfill configuration or operational scenario. The three modes shown in Fig. 12.2 include circular failure and block failures within (and possibly beneath) the waste and veneer failure on the side slope. Other slope failure modes can be considered as a combination of the basic failure modes (Abramson et al. 2002).

With a circular failure, often referred to as a rotational failure, the failure occurs within the waste mass (Abramson et al. 2002). The slip surface is often illustrated and modeled as a circular arc to simplify the calculation process. In general, circular failures are more common in slopes composed of homogeneous material. A block failure occurs along a weak failure plane within the waste mass or at the interface between the waste mass and the surrounding infrastructure (e.g., the landfill liner system and the interface between the waste, soil, and geosynthetic layers resting above or as part of the liner). A veneer failure, also referred to as a cover failure, may be more likely to occur during the construction of a landfill cover system, and usually occurs along weak interfaces between the waste and geosynthetics on the landfill slope. Water seepage and loads applied by large construction equipment in the cover system are typical contributors to veneer failure (Abramson et al. 2002).

12.3 Methods for Assessing Slope Stability

One of the basic methods to evaluate the FOS during slope stability analysis is the ordinary method of slices, which was developed in the 1920s. As illustrated in Fig. 12.3, the method of slices examines slope stability by assuming a circular failure plane. In this method, a trial circular slip surface is drawn in the cross section of the slope, and the slip surface is divided into several vertical slices of equal width (ΔL). The weight of each slice can be resolved into two components: one normal to the base of the slice (W_n) and one parallel to the base (W_p). It is the parallel portion (W_p) that tends to cause sliding. Waste cohesion and higher internal friction angles can increase resistance to failure. The cohesion is equal to the product of waste

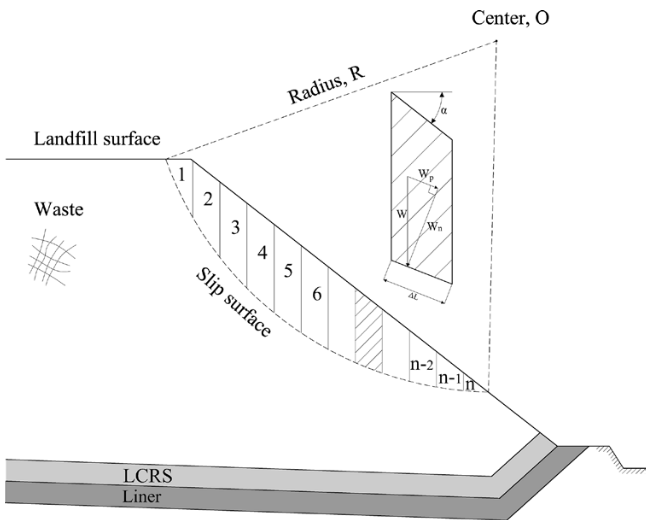


Fig. 12.3 Typical slice and forces for the ordinary method of slices, where W is the slice weight; W_n is equal to $W\cos\alpha$; the normal force is on the bottom of the slice; W_p is equal to $W\sin\alpha$; the sliding force is on the bottom of the slice; and ΔL is the length of each vertical slice

cohesion (c) and the slice width (ΔL), and the internal friction is equal to normal force, W_n, multiplied by the friction coefficient ($\tan\phi$). The FOS can then be calculated as follows (Liu and Evett 2001):

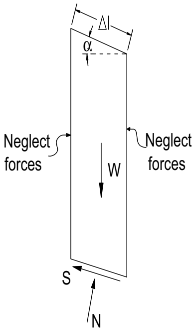
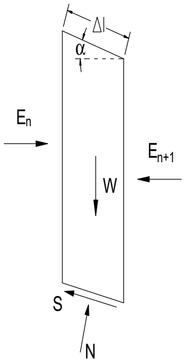
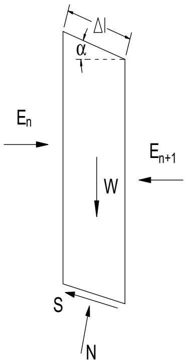
$$FOS = \frac{c \cdot \Delta L + \sum W \cos\alpha \cdot \tan\phi}{\sum W \sin\alpha} \tag{12.5}$$

The ordinary method of slices provides a technique to calculate FOS directly and is convenient for hand calculations. However, it is less accurate because it ignores inter-slice forces among the vertical slices. Several similar methods have been developed for FOS analysis that considers inter-slice forces and moment equilibrium. Table 12.1 summarizes the most commonly used methods for slope stability analysis. Refer to other seminal texts for detailed calculation procedures related to these methods (Abramson et al. 2002; Duncan and Wright 2005; Gunaratne 2006; Liu and Evett 2001).

As described in Table 12.1, for more sophisticated methods (Spencer and Morgenstern-Price), an iterative, trial-and-error calculation procedure is needed to satisfy moment and force equilibrium for each slice, which makes hand calculation impractical (Abramson et al. 2002; Krahn 2007). Many computerized programs have been developed for slope stability analysis, and most computer programs can handle a wide variety of slope geometries, shear strengths, pore-water pressures, and external loads, and have the capabilities for automatically searching for the most critical slip surface with the lowest FOS (Duncan and Wright 2005). Commonly-employed computer programs include SLOPE/W, SLIDE, UTEXAS4, XSTABL, and WINSTABL. Each of these programs can investigate different slope failure modes (e.g., circular, block, veneer, combination) that result from variations in site-specific conditions and landfill design (Pockoski and Duncan 2000). When assessing slope stability at a landfill site, the design engineer will use design specifications for site configuration, dimensions, and material characterization. In many cases internal and interface friction angles (as well as cohesion and adhesion) will be determined from laboratory tests on site-specific materials or material combinations. It would be rare, however, for project-specific ϕ and C data for MSW to be collected. The engineer would in most cases use data (or a range of data) gathered from the literature; Chap. 5 presented a review ϕ and C data reported in the literature for MSW.

As pore-water pressures play such a crucial role with respect to slope stability at landfills, the designer should incorporate pore pressures into the simulations for projects where liquids are added or exist present in large amounts. One approach that some designers use involves simulating an elevated liquid level originating at the base of the landfill. This would be representative of typical slope stability analysis in earthen embankments or dams where water seeps as a result of different water levels on each side. For modern landfills with a functioning LCRS, however, such elevated pore pressures above the base of the landfill would not be expected (Koerner and Soong 2000). Pressures would more likely be elevated within the waste mass surrounding liquids addition devices. Many slope stability

Table 12.1 Summary of common methods for slope stability analysis

Method	Figure	FOS calculation
Ordinary method of slices (OMS)		$FOS = \frac{\sum S}{\sum \tau} = \frac{\sum [c'\Delta l + N \tan \varnothing]}{\sum W \sin \alpha}$ c' = cohesion Δl = length of the bottom of the slice N = Wcosα base effective normal stress W = Weight of the slice ∅ = friction angle α = inclination of the bottom of the slice *Note*: *The OMS is one of the simplest methods that use the method of slices to estimate slope stability FOS. In this method, all inter-slice forces are ignored to satisfy equilibrium for the slide mass as well as for individual slices*
Simplified Bishop's method		$FOS = \frac{1}{\sum W \sin \alpha} \sum \left[\frac{c'\Delta l \cos \alpha + (W - u\Delta l \cos \alpha) \tan \varnothing}{m_\alpha} \right]$ $m_\alpha = \cos \alpha + \frac{\sin \alpha \cdot \tan \varnothing}{FOS}$ A trial-and-error calculation procedure is used to solve for the FOS *Note*: *Based on the assumption that the inter-slice forces are horizontal, ignoring the inter-slice shear forces. It satisfies vertical force equilibrium and overall moment equilibrium about the center of a circle*
Simplified Janbu's method		$FOS = \frac{\sum_{i=1}^{n} [C' + W \tan \varnothing] \cos \alpha}{\sum_{i=1}^{n} W \sin \alpha}$ This represents a ratio of the available shear strength and the driving shear force along the failure surface *Note*: *This method assumes that there are no inter-slice shear forces. Janbu's method satisfies vertical force equilibrium for each slice, as well as overall horizontal force equilibrium*

software packages can be integrated with moisture seepage (using the principles described in Chap. 5), allowing the engineer to simulate the interconnected role of pressurized liquids addition and slope stability. In the following section, examples of such an analysis are presented.

12.4 Examining Slope Failure Mechanisms at Wet Landfills

Xu et al. (2012) examined the factors affecting slope stability at landfills practicing pressurized liquids addition by coupling a porous media fluid flow model (SEEP/W) with a slope stability model (SLOPE/W). Pressurized liquids addition using a buried horizontal trench (similar to that presented in Chap. 9) was simulated in the analysis. Slope stability was evaluated under a variety of operating scenarios, including simulations representing clogging of the LCRS, use of different types of cover soil, varying operating conditions to limit leachate seepage, and varying injection pressures.

Figure 12.4 presents the results of a base simulation scenario representative of a landfill where subsurface liquids addition beneath a side slope is practiced. A horizontal injection trench (1 m × 1 m) is located 30 m above the base of the liner in a 50 m deep landfill beneath the side slope (with a configuration of three horizontal to one vertical (3H:1V)) of a lined landfill. In the base scenario, liquids are added under a constant injection pressure of 5 m water column (wc). As discussed in Chap. 9, this amount of injection pressure would fall on the high side of those typically used in liquids addition operations.

A conceptual zone of elevated moisture surrounding the trench is illustrated in Fig. 12.4, along with the FOS that develops over time. The bottom of the landfill is treated as free-draining and represents a well-designed and operated LCRS; the moisture profile therefore is more sharply delineated at a defined distance from the trench. As discussed in Chaps. 5 and 9, the extent of moisture distribution and resultant pore-water pressures is dictated by several factors including the operating conditions (e.g., pressure, flow rate, operating regime), waste properties (e.g., hydraulic conductivity, anisotropy), and trench design (e.g., size, bedding media). In this case,

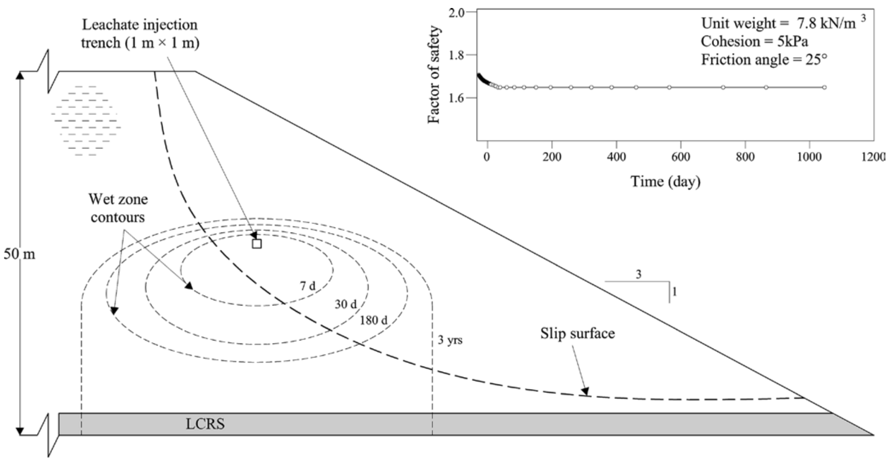


Fig. 12.4 Conceptual liquids addition in a bioreactor landfill

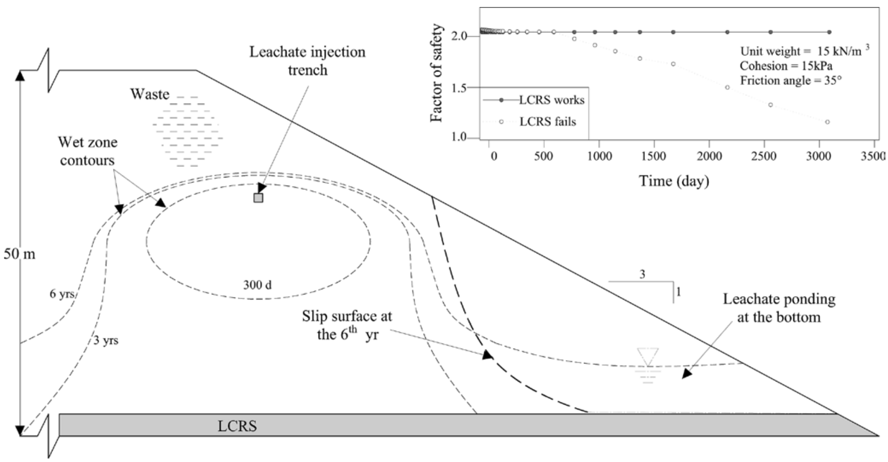


Fig. 12.5 The effect of the LCRS on slope stability, comparing a functioning LCRS (LCRS works) to a poorly functioning LCRS (LCRS fails)

where the LCRS is functioning properly, an FOS of greater than 1.6 is maintained throughout the simulation period. The slip surface associated with the lowest FOS is presented in Fig. 12.4. The simulation results suggest that for the conditions modeled, slope integrity would be maintained even when liquids were added under pressure directly beneath the side slope.

The impact of LCRS performance was evaluated by modifying the base scenario and treating the bottom surface as an impermeable layer (rather than as a freely-draining surface); this simulates a scenario where the LCRS is insufficiently designed, improperly operated, or otherwise clogged or compromised. Consequently, liquids mound on the bottom liner, which results in the development of increased pore-water pressures at the base of the landfill. Figure 12.5 illustrates the conceptual zone of elevated moisture surrounding the trench (with time), along with the FOS that develops over time. The resultant flow rate in this simulation did not differ dramatically from the base scenario, indicating that the flow impedance at the base of the landfill did not have a major impact on the ability to add liquids. However, the FOS decreased to less than 1.5 after about four years; by year 8 the FOS was less than 1.2. The slip surface predicted at the sixth year of simulation (the surface corresponding to the lower FOS) occurs at the base of the landfill slope. While a FOS less than 1 is not reached during the simulation period, the results clearly demonstrate the critical nature of an adequately designed and properly functioning LCRS.

Landfill operators place cover soil (or alternative materials that perform equivalently) on exposed waste throughout the landfill's operating life to comply with regulations. Typically, regulations stipulate the function of the cover material specified (e.g., it must reduce the presence of disease vectors and reduce odors), but the specific material properties are not identified in regulations. Thus, a variety of materials have been used by landfill operators and, in some cases, the material consists

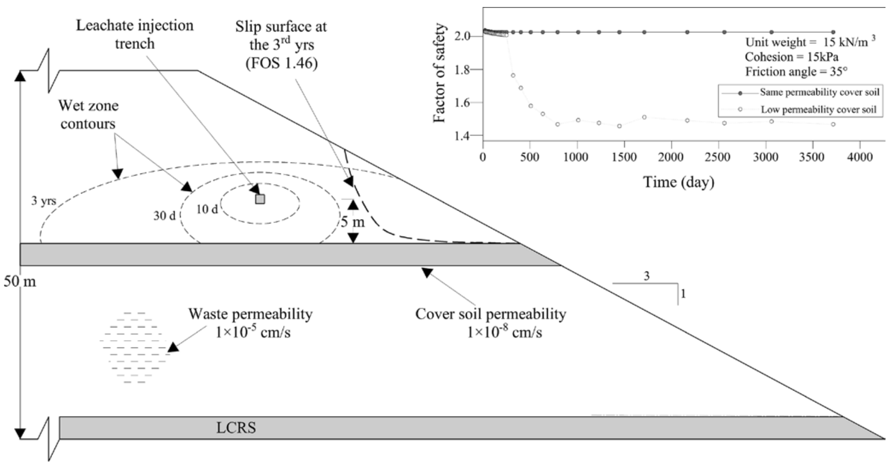


Fig. 12.6 The effect of low-permeability intermediate cover soil on slope stability, compared to cover soil with the same permeability as waste

of low-permeability media such as clayey soil or ash. As discussed in Chap. 11 with respect to leachate seeps, the use of low-permeability materials as cover soil can create lenses that impede moisture flow (McCreanor and Reinhart 1999). The ponding that results from these conditions has the potential to elevate pore pressures within the landfill and thus lead to slope stability concerns.

The conditions of the base scenario were modeled with the addition of a low-permeability soil layer ($k = 1 \times 10^{-8}$ cm/s) 5 m beneath the liquids addition trench. As indicated in Fig. 12.6, the moisture first ponds on the soil layer, then elevated pore pressures develop in the zone above the layer, and eventually leachate travels along the low-permeability medium to the side of the landfill. The slip surface is located in the waste above the low-permeability soil layer. Unlike the scenario simulating an improperly-functioning LCRS, the location of the drainage-impeding low-permeability layer is close enough to the trench to negatively impact the liquids addition rate (with a resultant 60 % less liquids added than the base scenario). The FOS reduces to a value less than 1.5 as a result of the pore water pressures that build up on the low-permeability cover soil layer (Fig. 12.6). Although the FOS did not decrease to less than 1.0 with the input assumptions used in this scenario, the resultant FOS is less than the level typically considered to be acceptable in the design process.

Xu et al. (2012) examined several other factors that might affect slope stability at landfills practicing liquids addition. Parameters such as friction angle, cohesion, and liquids addition system configuration were found to more profoundly affect the results compared to hydraulic conductivity, anisotropy, or unit weight. The practice of managing leachate seeps by placing and compacting low-permeability cover soils on the slope surface at the seep was examined (see Chap 11). Two simulations were conducted, one where a low permeability soil layer was placed on the side slope where a saturated zone from a liquids addition device intercepted the surface, and one where no such layer was present. A modest decrease FOS in the simulation with the low permeability liner on the side slope was observed. The effect of increased injection pressure was evaluated; even though the FOS did decrease with increased injection pressure, even at very high pressures, the FOS did not decrease a dramatic amount for the scenario simulated.

The impact of two contrasting liquids addition strategies was also evaluated. In one strategy, liquids are added to the landfill at a lower flow rate (and thus pressure) continuously. In the other strategy, the same total volume of liquids is added, but in distinct intermittent "pulses" at higher flow rates (and pressures) over short periods of time. The resulting simulations found that while the FOS decreased under the "pulsed" strategy, the decrease was not dramatic. As a comparison, simulations of the elevated "pulsed" injection pressures on a continuous basis resulted in a dramatically reduced FOS. These results support that although high pressure liquids addition reduces FOS, when practiced intermittently with appropriate recovery time between liquids addition events, high pressures may be safely utilized, even beneath the side slope.

Several additional factors should be considered by the design engineer when performing slope stability analyses or interpreting the results of such analyses. Most commercial models allow the designer to integrate water flow (and resulting pore pressures) and slope stability analysis. In reality, fluid flow in a landfill will consist of multiple phases and gas pressures have the potential to contribute to pore pressures (Merry et al. 2006). Most commercial modeling software will not consider gas contributions. As described in Chap. 5, in addition to landfilled MSW being anisotropic with respect to hydraulic conductivity, the hydraulic properties across the depth of a landfill are not constant (i.e., the hydraulic conductivity decreases as the depth within the waste increases). Xu et al. (2012) examined the potential impact of this occurrence by simulating slope stability with pressured liquids addition beneath the slope under conditions where the waste had decreasing hydraulic conductivity with increasing waste depth. The results showed that when hydraulic conductivity reduction with depth was greatest, the FOS decreased to a larger extent.

Multiple conclusions can be drawn from the modeling exercises described above. First, pressurized liquids addition, even when performed under the side slope at high pressures, does not necessarily result in a slope stability concern. The key design and operational challenge to minimize potential slope concerns is to avoid the excessive buildup of pore pressure. From an operational perspective, this can be accomplished by maintaining and monitoring the LCRS, avoiding the creation of low permeability zones within the landfill where leachate can become perched, and allowing appropriate time in between large pressure liquids addition events. Appropriate design of the LCRS is crucial (Chap. 10), as this is perhaps the most critical element in the landfill that must function to avoid a slope failure. The designer should also consider complicating factors in the design and simulation process such as elevated pore pressures due to gas (a properly functioning GCCS will help reduce this potential concern) and the decrease in waste hydraulic conductivity with depth.

12.5 Design Recommendations for Slope Setback Distance

The previous sections described methods for performing slope stability assessments for specific operational conditions and the factors that should be considered most important. One of the lessons learned is that liquids addition may in many cases be accomplished without a major slope stability concern even when the device is located close to or under the side slope. To provide guidance to the designer and the regulating engineer as to an appropriate setback distance (defined as the distance from the side slope to a liquids addition device), Xu et al. (2014) created a series of design charts that indicate minimum setback distance for liquids addition devices and injection pressures. Three different subsurface liquids addition methods were evaluated: horizontal injection trench, horizontal blanket, and vertical well.

Figures 12.7, 12.8, and 12.9 provide setback distance design charts for horizontal trenches, horizontal blankets, and vertical wells, respectively. In each case, the landfill was modeled as having 3H:1V side slopes with a waste friction angle of 25°, a cohesion of 5 kPa, a unit weight of 7.8 kN/m^3, a lateral hydraulic conductivity of 10^{-5} cm/s, and a vertical hydraulic conductivity of 10^{-6} cm/s (Xu et al. 2012 can be used to assess the potential difference in FOS for other conditions). The modeled horizontal devices (trench and blanket) were located at an elevation of 30 m above the base of the liner in a 50 m deep landfill; setback distances were modeled as the distance from the side slope to the device (see Figs. 12.7 and 12.8). Allowable injection pressure is presented as a function of required setback distance needed to maintain the selected FOS (1.0, 1.2, 1.5). The modeled vertical well was located on the side slope and was provided with a screen length of 10 m. The allowable depth of liquid above the top of the screened well section is presented as a function of required setback distance needed to maintain the selected FOS (1.0, 1.2, 1.5).

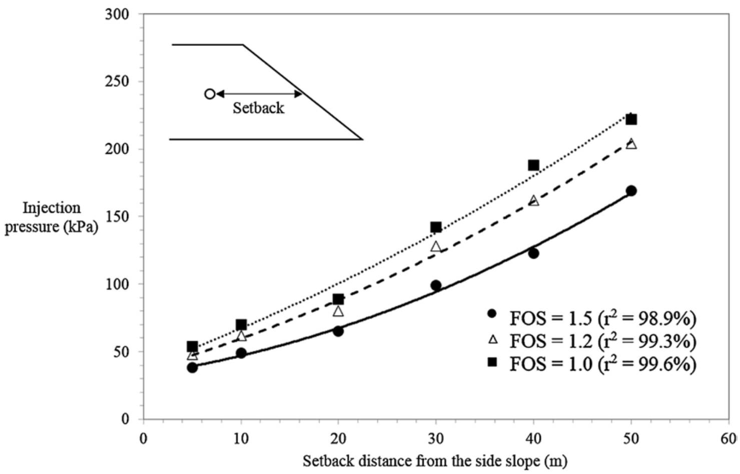


Fig. 12.7 Injection pressure as a function of setback distance for a horizontal trench

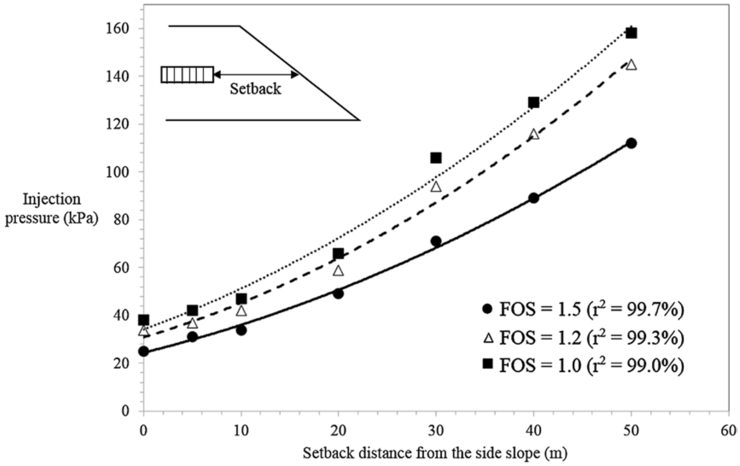


Fig. 12.8 Injection pressure as a function of setback distance for a horizontal blanket

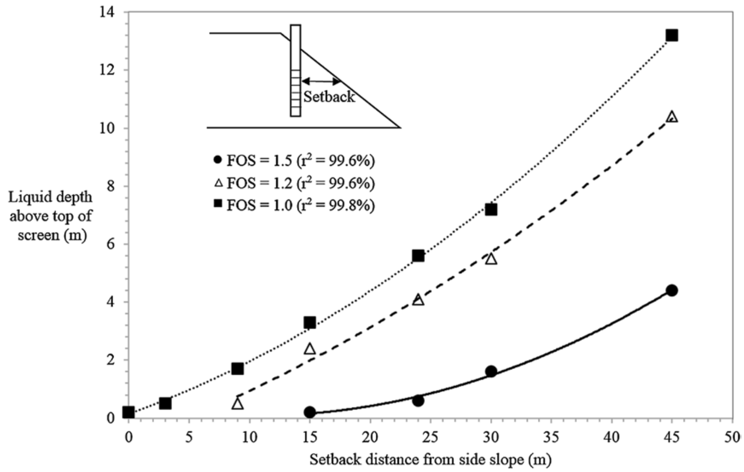


Fig. 12.9 Liquid level above the top of vertical well screen as a function of setback distance

The results presented in Figs. 12.7, 12.8, and 12.9, as well as the example simulations earlier in the chapter, provide the designer a sense of the results that can be obtained with slope stability modeling coupled with pressurized liquids addition. A site-specific slope stability analysis should be included as part of any landfill design involving liquids addition; as new techniques are developed to account for factors not evaluated here, such as the influence of gas flow, the designer should consider these. The results presented in this chapter suggest that liquids addition under pressure can occur without compromising slope integrity, but other site conditions such as LCRS operation, perched liquid levels due to low permeability layers, and changes to physical configuration of the landfill, may result in stability concerns. Even when slope stability is not a concern, the pressurized addition of liquids may still result in issues such as seeps.

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Chapter 13
Landfill Gas

Abstract A key challenge and opportunity provided by sustainable landfilling technologies is the enhanced rate of landfill gas production that occurs. The challenge is associated with the potential for increased fugitive emissions of greenhouse and other potentially harmful gases. The major opportunity with enhanced landfill gas production involves potentially reducing the overall site landfill gas emissions over the facility's lifetime and capturing the additional gas for subsequent conversion into energy. The conceptual basics of landfill gas production and collection are presented, followed by a presentation of design considerations and techniques that can be used to anticipate additional landfill gas production and effectively operate collection systems to capture the additional gas. Multiple diagrams and figures are presented to elucidate the numerous options available to collect landfill gas at sustainable landfills.

Keywords Landfill • Gas • Methane • Collection • Energy

13.1 Importance of Gas Collection in Sustainable Landfill Operation

Previous chapters focused on liquids addition as a means to promote the rapid biological stabilization of landfilled waste. In addition to the liner system, critical elements related to liquids management and leachate control include the leachate collection and removal system (LCRS), infrastructure for leachate storage and treatment, and the devices and delivery system for adding liquids to the waste. Landfill gas (LFG) is the other major pathway for potential escape of harmful pollutants from the waste to the environment, and the gas collection and control system (GCCS) is a critical component of large engineered landfills (Fig. 13.1 provides a conceptual illustration of a landfill GCCS). Given that LFG production results from stabilization of landfilled waste and the potential adverse effects of uncollected gas, a primary objective in sustainable landfill operations is the design and operation of an efficient GCCS.

The increased rate of anaerobic waste decomposition results in an increase in the rate of LFG production, an outcome that can have negative environmental consequences

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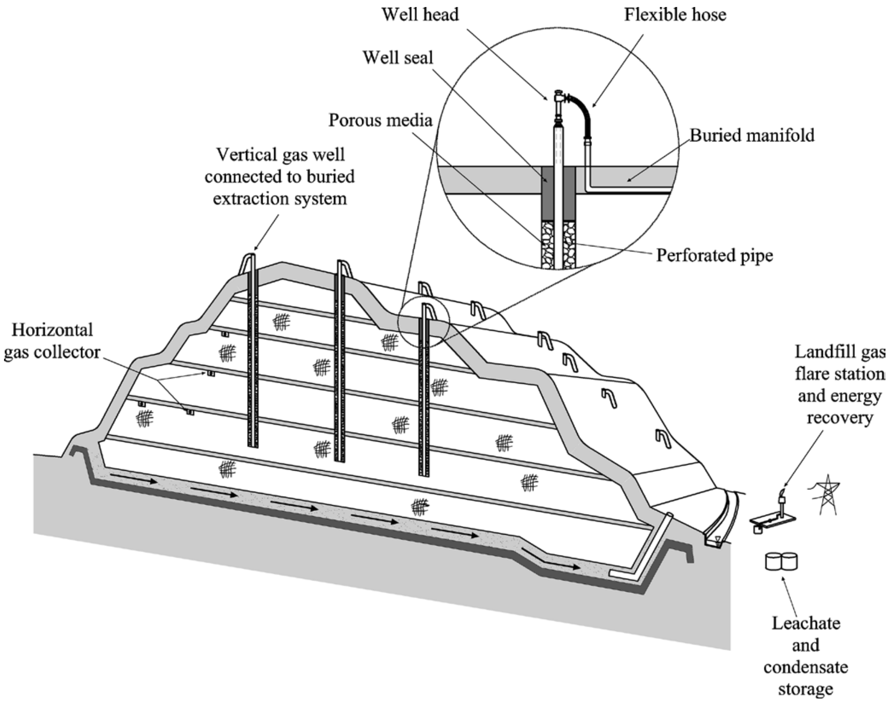

Fig. 13.1 Illustration of LFG collection system infrastructure

(e.g., increased greenhouse gas emissions or other hazardous compounds) if the LFG is not effectively collected or positive consequences (e.g., increased viability of a LFG beneficial use project) when efficiently harvested. Figure 13.2 illustrates a LFG generation rate comparison of a traditionally operated landfill (where liquids contact with the waste is minimized) and a landfill operated to encourage anaerobic waste stabilization (or one containing wastes with initially elevated moisture content). Challenges to efficient LFG collection at wet landfills include the design and operation of a system capable of accommodating the increased volume of gas (which is often produced much earlier in the operating life of a landfill compared to conventional facilities) and providing a GCCS that functions compatibly with the liquids addition infrastructure.

This chapter begins with a brief review of LFG characteristics and GCCS fundamentals, including a summary of the approach typically used by engineers to predict LFG generation. This is followed by a review of the challenges associated with managing LFG at landfills with accelerated gas production, either as a result of elevated initial waste moisture content or deliberately-added liquids. After a description of typical regulatory approaches to LFG control, a series of design steps and strategies are presented to address more rapid gas production. Technologies used to harness the energy content of collected LFG are described separately in Chap. 19.

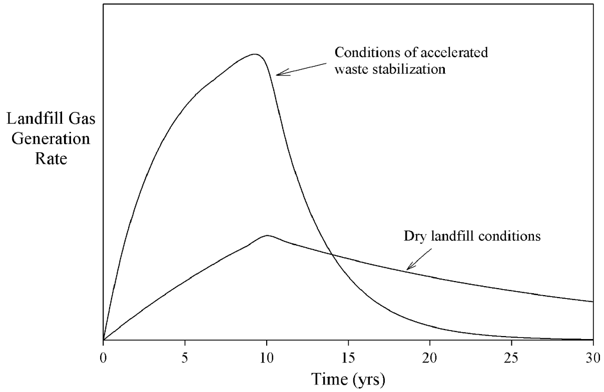

Fig. 13.2 LFG production curves for a traditional facilities and a facility operated to promote rapid waste stabilization

13.2 LFG Generation, Control, and Design fundamentals

13.2.1 GCCS Basics

As discussed in Chap. 2, the methane (CH_4) and carbon dioxide (CO_2) gases produced as a result of biological waste decomposition, along with nitrogen and oxygen from entrapped air and trace gases emitted from the waste, are collectively referred to as LFG or biogas. GCCS are required for a variety of reasons: safety concerns (e.g., preventing formation of explosive mixtures in the atmosphere), environmental protection (e.g., reduction of the emission of toxic constituents and greenhouse gases), reduction of nuisances (e.g., odors), and regulatory requirements (discussed later in this chapter).

Active LFG collection systems employ a series of collection devices or wells (vertical or horizontal) connected through one or more common header pipes. Vertical wells are commonly installed in areas of the landfill that have reached a desired waste depth (typically 30 ft or more); whereas horizontal LFG wells may be installed as early as the first lift of waste. Vertical and horizontal wells each have advantages and disadvantages in terms of cost, ease of installation, and performance.

Vertical wells for gas collection are installed using a large-diameter drill rig (e.g., an auger drill rig) that bores through the waste, creating holes that typically have a 0.6–1 m (2–3 ft) diameter (Fig. 13.3). Perforated or slotted piping, primarily polyvinyl chloride (PVC) or high-density polyethylene (HDPE), is placed in the center of the borehole and surrounded by a backfill of permeable material such as rock (Figs. 13.4 and 13.5). The perforated or slotted pipe transitions to a solid pipe near the landfill surface as a means of reducing the introduction of air into the well or waste once the well construction is finished and a vacuum is applied to the well.

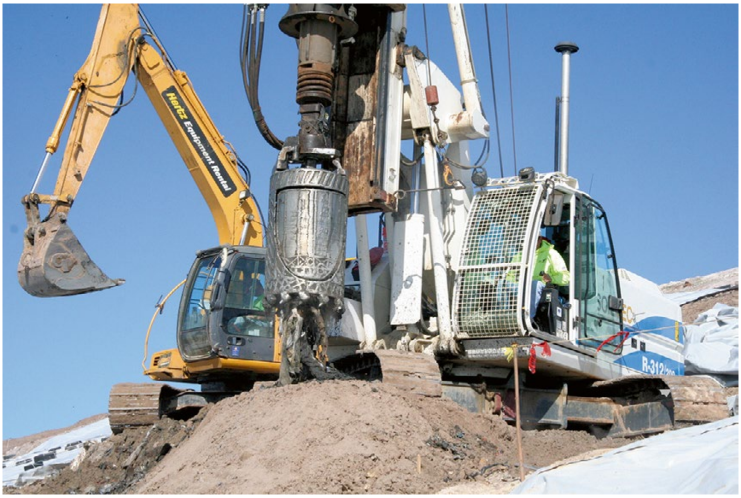

Fig. 13.3 Bucket auger rig for excavating borehole for LFG well

Fig. 13.4 Placement of slotted well pipe into excavated borehole (Photo courtesy of Jones Edmunds)

Conversely, with horizontal wells, a trench is excavated on the surface of a lift of landfilled waste, the trench is partly backfilled with a permeable material, a perforated or slotted pipe is placed in the trench, and the remainder of the trench is backfilled with the permeable material. While a trench is not necessarily required for horizontal collectors, the use of a trench is the common practice in most parts of the world.

Fig. 13.5 LFG well under construction, including protective grate and well pipe; the contractor is measuring the depth of the granular fill surrounding the pipe (Photo courtesy of Jones Edmunds)

For vertical and horizontal systems, the individual collectors are connected to a common header pipe (and manifold) which routes the collected gas to a control system where the LFG is combusted or otherwise processed.

The primary driving force causing LFG to exit a MSW landfill is pressure, and while sufficient gas pressures develop within waste to cause gas to migrate to a well, engineered strategies are normally needed which include applying a vacuum to the well to increase extraction efficiency (referred to as an active GCCS). In the absence of applied vacuum (a passive GCCS), a larger fraction of the gas will migrate to the landfill surface or side slopes and escape to the atmosphere. The vacuum in active GCCS is created using mechanical blowers at one or more control locations; piping that joins individual LFG collection devices, thus allowing vacuum availability at desired points, is routed to the blower system and is often referred to as header piping. Gas wells are connected to the header piping via a flexible hose that can accommodate settlement of the landfilled waste and pipe movement, though sometimes intermediate piping (sometimes referred to as lateral piping) can be used to connect the individual well to the header piping. Control of the applied vacuum and resulting gas extraction is achieved by using a well head that includes a control valve and devices that provide for the measurement of flow, pressure, and temperature. Figure 2.7 provided a photo of a gas well head and pertinent features; Fig. 13.6 illustrates a typical cross section of a LFG well including the wellhead and the connection to the gas collection header. Figure 13.7 shows the construction of a gas collection header.

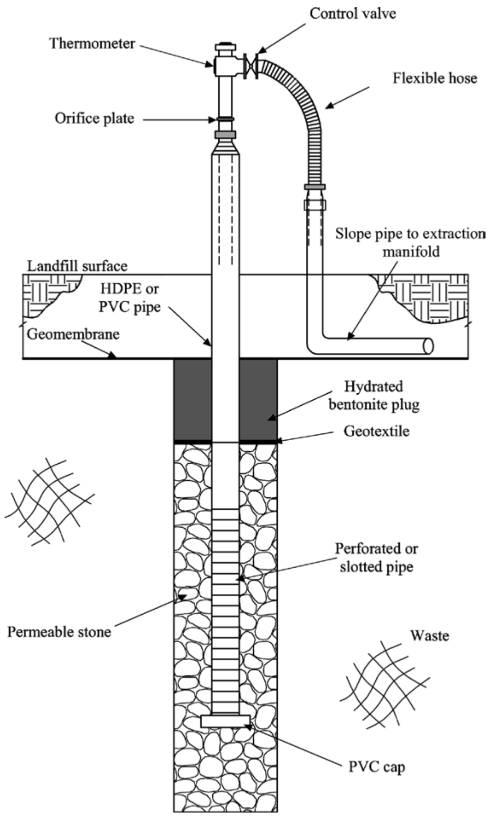

Fig. 13.6 Typical cross section of a vertical LFG well

LFG is typically saturated with water vapor and is produced at a temperature that is usually warmer than ambient conditions. As a result, water condenses in the collection piping. This gas condensate must be removed from the collection pipes at points of low elevation to avoid blocking the LFG system with liquid. The design of typical GCCS includes minimizing the number of low points in the header pipe. Depending on the site configuration and design, condensate removal points or knock-outs will be placed at various locations within the well field and at points outside of the landfill footprint and at the blower extraction area.

LFG collection systems require routine operation, maintenance, and performance optimization. This is normally completed by a trained operator equipped with a portable meter capable of measuring gas pressure, composition, and flow (Chaps. 15 and 16). The operator must adjust valve settings on the well heads at various extraction points to maintain sufficient vacuum to provide gas collection without creating conditions where air is pulled into the landfill or piping system (a potential cause of fires or explosions). In cases where LFG extraction is controlled by automated systems with set points that adjust vacuum to individual gas collectors, an operator still has a role in operating and maintaining these automated systems.

Fig. 13.7 Construction of LFG collection header

At a minimum, collected LFG is combusted using a flare, which can be enclosed or open. The collection and flaring process occurs continuously, and depending on regulatory and permit requirements, may require routine monitoring of several parameters. Where economically practical, the collected LFG is often converted to energy. The energy conversion technologies commonly applied include engines, turbines, and micro-turbines for electricity production, direct use by industry, and clean-up for high-quality applications such as compressed and liquefied natural gas (see Chap. 19).

13.2.2 Prediction of LFG Generation

Chapter 5 introduced techniques for modeling gas flow in landfills; the most common gas flow modeling performed as part of the standard design process is a prediction of the rate of gas generated (this is the amount that would be emitted from the landfill surface or surrounding soils in the absence of any control measures). The typical approach to modeling LFG production is to approximate waste decomposition as a first-order decay reaction, with gas produced in a volume proportional to the mass of waste decomposed. The relationship for the rate of gas production from a unit mass of waste as a function of time may be expressed as:

$$G(t) = 2L_o k M_o e^{-kt} \tag{13.1}$$

where, G(t) = LFG production (m^3 $year^{-1}$) at time t (year); L_o = the CH_4 generation potential (m^3 CH_4 Mg^{-1} solid waste); k = the CH_4 generation rate constant ($year^{-1}$);

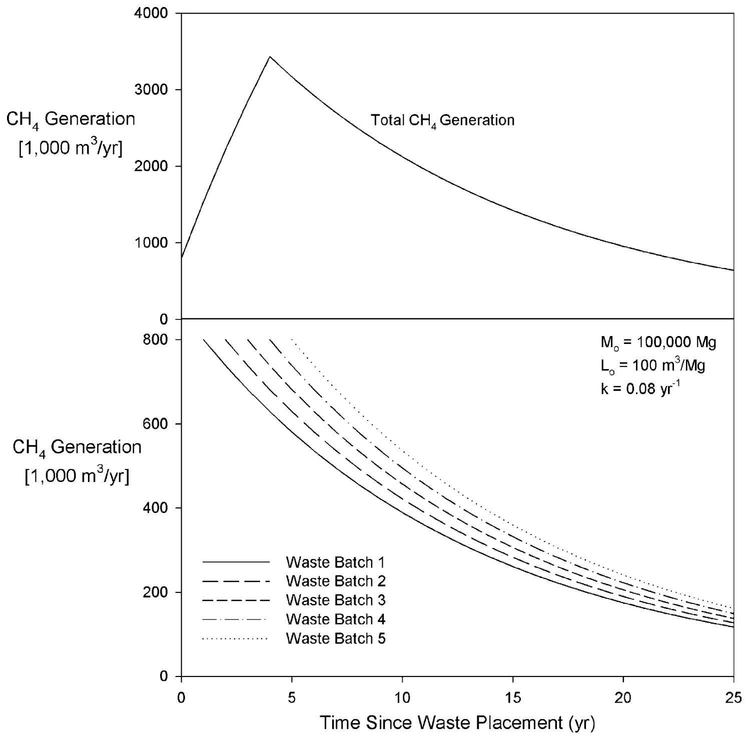

Fig. 13.8 Illustration of first-order LFG production model for five batches of waste

and M_o = the mass of solid waste in the batch (Mg). The factor of 2 is based on the assumption that the landfill comprises 50 % CH_4 and 50 % CO_2; this can be changed if a different biogas composition is anticipated.

Estimated gas volumes produced from individual batches of waste deposited in a landfill over time are normally summed to estimate the composite LFG production rate for the entire landfill using a relationship such as follows:

$$Q_{CH_4} = \sum_{i=1}^{n} \sum_{j=0.1}^{1} kL_o \left(\frac{M_o}{10} \right) e^{-kt_{i,j}} \tag{13.2}$$

where, $Q_{CH_4} = CH_4$ generation at time t (m^3 $year^{-1}$), i is a 1-year time increment, j is a 0.1-year time increment, and the other values remain the same as previously defined. The designer can use estimates of annual waste disposal amounts over the predicted life of a landfill to predict the amount of gas produced, both during the operational years of a landfill, as well as in the years following landfill closure. Figure 13.8 illustrates this technique, predicting LFG generation for landfill disposing waste for 5 years at a rate of 100,000 Mg per year (k = 0.08 $year^{-1}$, L_o = 100 m^3 CH_4/Mg). The cumulative LFG production curve is shown, as well as the individual waste batches used to produce this curve (one batch for each year of waste).

The model described above is the same as that provided in the US federal regulations for LFG emissions, the US AP-42 guidelines for gas generation (US EPA 1998), and the US EPA's LFG Emissions Model (US EPA 2005). While they may differ with respect to complexity and number of parameters included, most major models of LFG production are based on the first-order decay concept (e.g., the Intergovernmental Panel on Climate Change's Waste Model and several region- and country-specific LFG models [Central America, China, Columbia, Ecuador, Mexico, Philippines, Thailand, and Ukraine) developed by the US EPA's Landfill Methane Outreach Program (LMOP 2014)].

13.3 Design and Operation Challenges

Adding liquids in a controlled manner to a MSW landfill, whether during the landfill's operation or after the landfill has been filled, can pose several challenges to the design and operation of the LFG collection system. Table 13.1 presents a summary of the major design considerations related to GCCS design for landfills where liquids are added.

A major impact of liquids addition at landfills is the increased LFG generation that affects several components of the GCCS design. For instance, the modeling of LFG production differs from a conventional landfill since the rate of LFG generation will be increased and the amount of liquid added will impact the projected LFG generation rate. The designer of a GCCS system at a landfill that adds liquids must also consider the impact the increased LFG generation rate has on the timing of the GCCS construction. Ideally, the GCCS elements in areas where liquids are added will be in place before liquids addition commences, since liquids addition increases the LFG generation rate. Early installation of GCCS can capture the must of additional LFG generated, thus reducing emissions and enhancing the viability of a beneficial use project to take advantage of the increased LFG quantity. The remainder of this section examines issues with accelerated gas production and increased liquid levels in the waste.

13.3.1 Accelerated Gas Production

The standard LFG modeling approach is appropriate for a landfill operated conventionally, but the methane generation rate constant, k, will increase at sites where liquids addition is practiced. To appropriately model gas production at wet landfills, the designer can utilize the standard LFG modeling approach, but should adjust as necessary to account for the increase in LFG generation rate, the fact that some parts of the landfill may be wetted while others may not, and the potential that liquids addition may not commence until several years after gas production has already begun.

Table 13.1 Landfill design elements impacted by increased LFG generation at landfills that add liquids

Design category	Example	Specific considerations for landfills that add liquids
LFG collection system	LFG production modeling	Increase in LFG generation rate
		Accounting for wetted fraction of waste
	Collection system header and lateral piping	Collection pipes must accommodate higher gas flows during and after liquids addition operations commence
	Collection system wells	Selection of devices compatible with additional liquids in the landfill and increased settlement of the landfill surface. May be required to incorporate individual well pumping system design
		Consider designs to incorporate LFG collection at the landfill surface beneath an EGC
		Placing LFG collectors in a manner consistent with planned recirculation devices
	Collection system control devices	Selection of blower/extraction system(s) consistent with anticipated LFG generation and collection rates
	Collection system operation	Timing of collection system construction
		Timing of collection system operation
		Recordkeeping for performance assessment and regulatory compliance
	Collection system monitoring	Frequency of measuring LFG flows
		Frequency of measuring surface emissions
		Design for additional monitoring devices (e.g., thermocouples placed in situ)
	Condensate management system design	Design condensate management system to account for higher condensate generation
	LFG beneficial use system design	Account for timing of sustainable landfilling operation and increased gas generation and collection
		Account for anticipated gas flows when selecting end use for collected LFG
Leachate collection system	Layout of pipes, cleanout lines	Integrate LFG collection into leachate collection design
		Operations monitoring to assess quality of gas from leachate collection system
Liquids addition system	Specification of device location and spacing	Selection of liquids addition devices
		Selection of function of devices (liquids addition only, use for LFG collection then liquids addition, etc.)
Cover system	Placement of daily and intermediate cover	Selection of materials compatible with liquids addition and LFG collection
		Timing and placement of covers

Table 13.2 Summary of reported and predicted k values for landfills

Source	k Value (year^{-1})	Description
US EPA (1998)	0.04	AP-42 inventory default (annual rainfall > 25 in./year)
US EPA (1998)	0.02	AP-42 inventory default (annual rainfall < 25 in./year)
IPCC (2006)	0.06–0.1	Recommended for wet temperate/boreal climates
	0.07–0.4	Recommended for wet tropical climates
US EPA (2005)	0.07	Default value for wet landfills
Yazdani et al. (2006)	0.14	3.5-acre pilot wet cell
	0.31	6-acre pilot wet cell
US EPA (2006)	0.041–0.063	Conventional landfill
US EPA (2006)	0.11–0.16	As-built bioreactor landfill
Reinhart et al. (2005)	0.30	LFG collection data from wet landfills (the model includes a lag time and optimum wetting conditions)
Kim and Townsend (2012)	0.47	Predicted from solids decomposition data from Alachua County Southwest Landfill (Chap. 4)
	0.21	Predicted from solids decomposition data from New River Regional Landfill (Chap. 4)

The standard LFG modeling methodology as described in the previous section relies on two primary characteristics of the waste with respect to gas production: the methane potential (L_o) and the methane generation rate constant (k). The L_o should not change as a result of liquids addition; while this term depends on the specific waste stream in question, several estimates are commonly used as part of regulatory compliance or the design process. In the US, the default L_o as part of the Clean Air Act regulations is 170 m^3-CH_4/Mg of waste (US EPA 1996), while a default methane potential listed in the US EPA's compilation of air pollutant emission factors, AP-42, is 100 m^3-CH_4/Mg (US EPA 1998). A variety of researchers have developed estimates for L_o by measuring CH_4 yield from waste samples (Owens and Chynoweth (1993) measured L_o of specific MSW samples to be 118–127 m^3/Mg) or applying waste composition results to L_o for individual waste components (using this technique, Staley and Barlaz (2009) estimated MSW L_o to range from 59 to 64 m^3/Mg). Some researchers have also estimated L_o in conjunction with k by curve fitting of collected LFG data (Tolaymat et al. 2010).

The more influential parameter affecting LFG production projections for wet landfills is the methane generation rate constant, k, which is expected to change markedly. The current default k for traditional landfills in the US is 0.05 year^{-1} L_o as part of the clean air regulations (US EPA 1996). Landfills practicing liquids addition are expected to exhibit k values greater than this, and in recent years, several attempts have been made to quantify k for these facilities. Table 13.2 presents a summary of k values required or recommended by regulatory agencies and from field studies or measurements. Rate coefficients have been measured using LFG collection performance data (Reinhart et al. 2005; Yazdani et al. 2006) and measurements of waste samples collected from landfills (Kim and Townsend 2012).

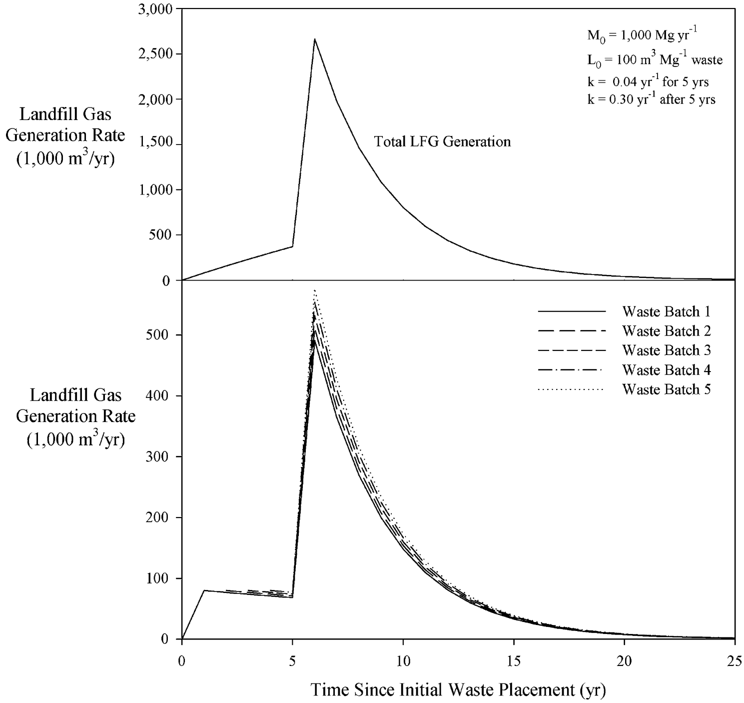

Fig. 13.9 Gas production for a landfill with 5 years (1 year per batch) of waste placed subject to a change in k at year after the last batch of waste has been placed

The standard LFG production modeling approach uses one k value for a given waste batch. At some sites, however, liquids addition may not be initiated for several years; during this time gas production occurs at a lower rate initially and increases later. The standard first-order modeling approach can be modified to simulate waste prior to (k_1) and after (k_2) liquids addition. The term t_c is defined as the time when the rate constant would change from initial (conventional) conditions to accelerated conditions.

For the time period that k_1 is in effect ($0 < t < t_c$), the gas production relationship is as follows:

$$G(t) = 2L_o k_1 M_o e^{-k_1 t} \tag{13.3}$$

when $t > t_c$, the following relationship applies.

$$G(t) = 2L_o k_2 \left(M_o e^{-k_1 t_c}\right) e^{-k_2 (t - t_c)} \tag{13.4}$$

Similar to the batch gas production modeling illustration presented in Fig. 13.8, Fig. 13.9 provides an example modeled gas production where k is changed after a designated period of time. In this example, five batches of waste are placed in a

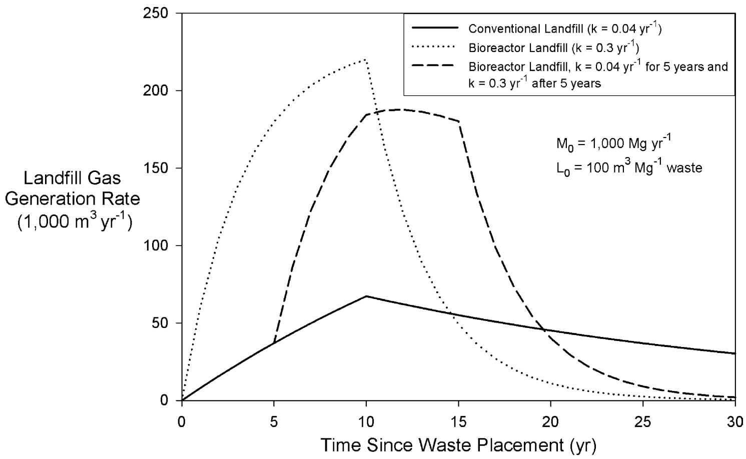

Fig. 13.10 Example LFG production model for 10 years of disposal for (i) landfill with k = 0.04, (ii) landfill with k = 0.3 year^{-1}, and (iii) landfill with k = 0.04 year^{-1} for the first 5 years of each batch and k = 0.3 year^{-1} for times after first 5 years for each batch

landfill over a 5-year period, but at year 5, the k value transition from 0.04 to 0.3 year^{-1}. The bottom part of Fig. 13.9 presents the individual batches while the top part presents the total gas production. This example could be used to forecast gas production from a landfill where gas if added to a landfill for 5 years under standard (dry) conditions, and then at the end of waste placement (corresponding to the end of year 5), liquids addition is commenced and gas production is enhanced. The designer could use this technique to transition different areas of the landfill to wetted conditions at different times.

Figure 13.10 further illustrates this approach for a facility where waste is disposed of for 10 years (each year of waste is modeled as one batch). At the end of 5 years of waste placement, the k for the entire facility (each batch of waste) changes from 0.04 to 0.3 year^{-1}. This process simulates the scenario where liquids addition commences in a given area of the landfill after a specified time period, with the entire landfill being operated in this after for the remainder of landfill operation. Shown for comparison purposes are the gas production curves that result when a k of 0.04 year^{-1} is used throughout and a k of 0.3 year^{-1} is used throughout.

Another factor to consider when modeling gas production at landfill practicing liquids addition is that not all of the waste will be wetted; moisture distribution may only be limited to certain parts of the landfill. Assuming the fraction of landfilled waste in a batch that is wetted as w, the following equations can be used to estimate the gas production from a batch of solid waste that is exposed to liquids at time t_c. For time $0 < t < t_c$:

$$G(t) = 2L_o k_1 M_o e^{-k_1 t} \tag{13.5}$$

and for time $t_c < t < \infty$:

$$G(t) = 2L_o k_1 M_o e^{-k_1 t}(1-w) + 2L_o k_2 \left(M_o e^{-k_1 t_c}\right) e^{-k_2(t-t_c)} w \tag{13.6}$$

Using this approach, the designer can estimate landfill gas production for facilities where only part of the waste is wetted, and where liquids addition in the wetted areas occurs after a specified period of time.

13.3.2 Issues with Increased Moisture

LFG collection system design considerations impacted by liquids addition primarily include the specification of a LFG collection device, methods to route collected gas to the header system, in addition to factors such as timing of LFG collection components. Gas volumes may be greater, but the void space occupied by the gas will be smaller, both because of moisture and because of decreased waste density (and porosity). The addition of liquids results in an increase in the density of the waste, which in turn leaded to greater overburden pressures on deeper layers of the waste (see Chap. 5). The permeability of the waste will decrease and LFG pressures will increase, making LFG collection more difficult in these areas because a greater vacuum is required to collect an equivalent amount of gas. Gas collection devices will be more likely to become flooded and gas migration along other pathways of escape to the atmosphere (migration to the surface of the landfill rather than flooded collection devices) will occur. Effective gas capture at the surface of the landfill becomes more important under these flooded conditions; Fig. 13.11 shows the ballooning of gas under an exposed geomembrane at the landfill surface as a result of gas migration to the surface.

In conventional landfills, where liquids are not added, liquids intrusion into the active LFG collection system (e.g., vertical or horizontal wells) poses challenges such as LFG short-circuiting of wells and trenches as leachate present in the waste matrix migrates to the boreholes and blocks the flow of LFG. Figure 13.12 depicts this phenomenon; liquids present in the landfill as a result of liquids addition intercept a low permeability soil layer and migrate laterally to a gas well, ultimately migrating downward into the well and decreasing collection efficiency. Once a LFG well's perforated area becomes covered in liquid, LFG extraction can no longer occur efficiently at that well, if at all, until the liquid is removed. Many of the processes for leachate preferential flow described in Chap. 11 account for gas well flooding.

13.4 LFG Regulations for Bioreactor Landfills

In regulatory jurisdictions with well-developed rules for landfill design and operation, regulations for LFG collection and control are typically included. At the most basic level, LFG control is required to prevent the off-site migration of LFG through

Fig. 13.11 Ballooning of geomembrane at the landfill surface as a result of gas pressure

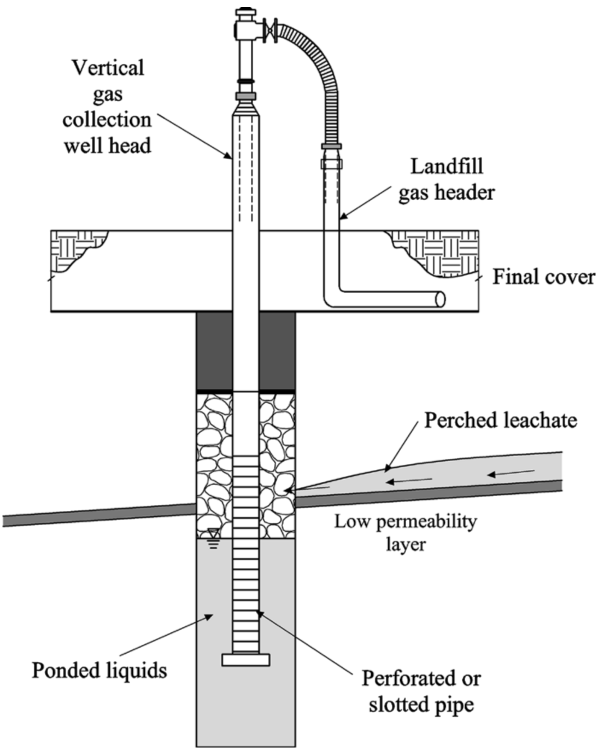

Fig. 13.12 Illustration of perched liquids impacts on leachate levels in vertical LFG wells

soils and the formation of explosive gas conditions in adjacent structures and beyond the property boundary. Some rule programs may also be structured around reducing atmospheric emissions, both for air quality in the site vicinity (e.g., odors, harmful chemicals) and to address regional-scale concerns (ozone precursors, global warming). Chapter 3 provided a review of basic landfill regulatory requirements, including aspects related to planning of sustainable landfill practices.

Some regulatory requirements have been developed to address the potentially greater amounts of LFG produced at landfill sites that add liquids. In the US, LFG collection and control are addressed as part of the National Emissions Standards for Hazardous Air Pollutants (NESHAP): MSW landfills (Code of Federal Regulations 2003). Under the US NESHAP rules, a "bioreactor" landfill is defined as an MSW landfill or a portion of a MSW landfill where any liquid other than leachate (including LFG condensate) is added in a controlled fashion into the waste mass (often in combination with recirculating leachate) to reach a minimum average moisture content of at least 40 % by weight to accelerate or enhance anaerobic biodegradation of the waste. Attaining a 40 % moisture content triggers the LFG collection and control system requirements, not simply the addition of liquids other than leachate or gas condensate. Table 13.3 presents rules specific to bioreactor landfills in the US.

Internationally, specific regulations defining sustainable landfills are somewhat limited, although cases have been reported whereby sustainable landfilling technologies are used to meet specific regulatory requirements. For example, Woelders et al. (2007) discussed a bioreactor test cell that was operated to meet the EU Landfill Directive's definition of an inert waste landfill through examination of leachate chemical quality following recirculation. Additional international experiences are discussed in Chap. 4.

13.5 Design and Operation Strategies

Several design elements must be considered to address the challenges associated with LFG generation and collection at sustainable landfills. The design engineer must consider supplementing traditional GCCS designs or alternatives to effectively collect LFG—both with respect to individual device efficiency (e.g., designing collectors to handle the additional liquids that may be present) and overall system efficiency (designing GCCS components to be installed early enough to capture the greater volumes of gas that can be produced from sustainable landfilling operations). The design elements discussed herein include the use of horizontal and vertical gas collectors, integration of the leachate collection system into the GCCS, the use of alternative LFG collection devices, the use of landfill covers and exposed geomembrane caps, and landfill operational strategies to maximize gas collection.

Table 13.3 Decision points and timelines related to LFG collection system requirements for bioreactor landfills under the US NESHAP rules

LFG-related requirement	Milestone time	Comment
Installation of GCCS	Prior to initiation of liquids addition for bioreactors constructed after November 7, 2000	The 50 $Mg\text{-}year^{-1}$ non-methane organic compounds (NMOC) threshold for conventional landfills does not apply in the case of bioreactor landfills
		Collection and control requirements must be in accordance with the specifications provided in 40 CFR 60.759 or an alternate collection and control design plan submitted for approval
Operation of GCCS	Within 180 days after the landfill initiates liquids addition or 180 days after the bioreactor has reached 40 % moisture content (by weight), whichever is later	Moisture content is evaluated based on in-place waste, initial moisture content, and amount of moisture added
		The calculation of moisture content must be conducted in accordance with the procedures listed in 40 CFR 63.1980 (g) and (h) section 63.1980 (g) and (h) to determine when the 40 % moisture content is reached

13.5.1 Impacts on GCCS Infrastructure

The techniques in the previous section provide the engineer with the ability to predict the enhanced gas generation rate at landfills practicing accelerated waste stabilization techniques. Flow measurement devices at wellheads may need to be larger (larger openings in orifice plates, large flow straightener pipe diameters with pitot tubes) to accommodate greater than normal flow rates. Pipes that route the collected LFG from individual collection devices (the manifolds and headers) to control points must be sized to handle the maximum LFG generation rate. The design and sizing of the control devices (i.e., blower systems and destruction devices) must consider a potentially greater maximum LFG generation rate so that the collection system can handle the maximum quantity of gas expected.

The designer should incorporate infrastructure to handle the added volume of gases and liquids likely to be encountered in the GCCS to allow the GCCS to efficiently collect the gas that is produced. In addition to more condensate as a result of enhanced gas flow, the gas pressures in some gas collection devices will be sufficiently large that leachate is expelled from the landfill into the collection gas collection header; this liquid may have a much greater suspended solids content compared to condensate. Slopes and pipe sizes should be sufficient to handle the added GCCS liquid volumes; the piping system must be properly designed to ensure that liquids do not cause a blockage in the GCCS piping. Additional condensate knockout and drainage locations may be required to handle the added liquid volumes. Additional drainage features such as toe drains may be required, which can be integrated into the GCCS (they also serve to assist in seepage management, see Chap. 11).

13.5.2 Design Considerations for Vertical Wells

As discussed previously, a borehole must be drilled into the waste to install vertical wells. This procedure usually entails placing a PVC well in the borehole, backfilling the annulus with a permeable material, and then sealing it near the surface. By virtue of the installation method, liquids within the landfill (e.g., condensation resulting from collecting the LFG, leachate within the waste matrix) tend to migrate to the boreholes during and after well installation. Consequently, the well's perforated or slotted portion can become filled with liquid, thus blocking some or all of the screened portion intended for LFG collection. Pumps that are specifically designed to remove liquids may be used (see Fig. 13.13), which necessitates increased operation and maintenance and overall costs. Again, this is often an issue at conventional landfills and the problem is exacerbated at sustainable landfills.

Experience with vertical wells used for liquids recirculation has shown that it is unlikely that these wells could be used as the primary LFG collectors. Normally, recirculated liquids saturate the zone surrounding the well and may also fill up part or all of the screened area. Often, this standing liquid slowly decreases over time

Fig. 13.13 Leachate pumps in gas collection wells

and only a limited amount of screened interval is available later for LFG collection. Thus, facilities that employ vertical wells for leachate recirculation must have additional devices that will be used to collect LFG.

13.5.3 Design Strategies Using Horizontal Collectors

As with vertical wells, the challenge with collecting gas from horizontal trenches at landfills practicing liquids addition or with inherently high liquids levels is the high moisture content of the surrounding waste. As detailed in Chap. 9, a horizontal collection is constructed as waste is deposited in the landfill as trenches are excavated in the waste. These trenches are filled with highly permeable backfill material and a perforated or slotted pipe is embedded within the fill material. For horizontal systems, the pipe can either act as a LFG collection device or as a device to deliver liquids to the permeable filler material, which then distributes the liquids to the surrounding waste. If the purpose is gas extraction, the presence of liquids can cover perforations of the LFG collector, thus impeding the ability to capture gas, just as with vertical wells. This can ultimately result in additional and potentially costly operation and maintenance.

Many attempts to collect gas from horizontal trenches used for liquids addition have not been successful; once sufficient liquids have been added to the device, gas collection becomes problematic (Townsend et al. 1994). This results from the saturated conditions surrounding the trench; although gas generation is enhanced and gas pressures are often quite large, gas migration through the saturated waste to the trench for extraction is not the path of least resistance, and thus gas migrates away from the device to other parts of the landfill. Alternatively, operation of horizontal devices first as LFG collectors followed by liquids addition devices may allow a given device to serve two purposes.

Figure 13.14 shows an operational scenario that involves installing a series of horizontal trenches in each lift of waste. The initial horizontal devices that are depicted in Fig. 13.14a are part of the LCRS (the gravity drain lines; gas collection with the LCRS is discussed in greater detail in an upcoming section). Throughout the operating life of the landfill, the LCRS trenches collect both leachate and LFG; gas collection begins when sufficient waste has been placed above the LCRS. Once the landfill is active and the first lift of waste is completed, a set of horizontal trenches will be constructed, as shown in Fig. 13.14b (following same techniques as described in Chap. 9). Initially, the horizontal trenches will not be used for gas extraction, or for leachate recirculation. Once a layer of waste has been placed and compacted on top of the trenches above the first lift of waste (to prevent air intrusion), the pipes within these horizontal trenches will extract LFG.

Upon completion of the second lift of waste (Fig. 13.14c) another series of horizontal trenches will be constructed. When the horizontal trenches above the second lift of waste are completed and covered with a layer of compacted waste (Fig. 13.14d) the function of the trenches in the first lift of waste will transition to adding liquids, while the trenches in the second lift of waste will collect gas. Ultimately, the gas collection will always take place in the upper-most horizontal trenches to decrease the issues posed by excess liquids in the landfill. Accordingly, as indicated in Fig. 13.14e, when the third lift of waste is filled and the horizontal trenches are complete (and sufficiently covered with compacted waste), they will function as gas collectors, while the trenches within the second and first lifts of waste will serve as liquids addition devices.

Once the horizontal trenches are used for liquids addition, they are typically no longer effective for LFG collection. As depicted in Fig. 13.14, as a landfill is built, newly-installed pipes near the surface are used for LFG extraction while previously-installed trenches are used for liquids addition. Eventually, LFG is collected only from the LCRS and the uppermost horizontal trenches. The operator may still desire to occasionally draw gas from wetted trenches, but they should be prepared for greater than usual liquids extraction and possibly very limited gas removal.

13.5.4 Integrating LCRS Into GCCS Design

Gas will migrate from the landfill under pressure. If a well or a trench is present, especially if it has been placed under vacuum, gas will migrate to these locations. One region of the landfill where some gas will typically always migrate to is the LCRS. Plumbing the LCRS for LFG collection is critical at landfills where liquids are added because of the aforementioned difficulty in collecting LFG with traditional GCCS devices in deeper sections of waste that are dense and wet. The nature of the LCRS (which is intended to quickly drain liquids across the entire landfill

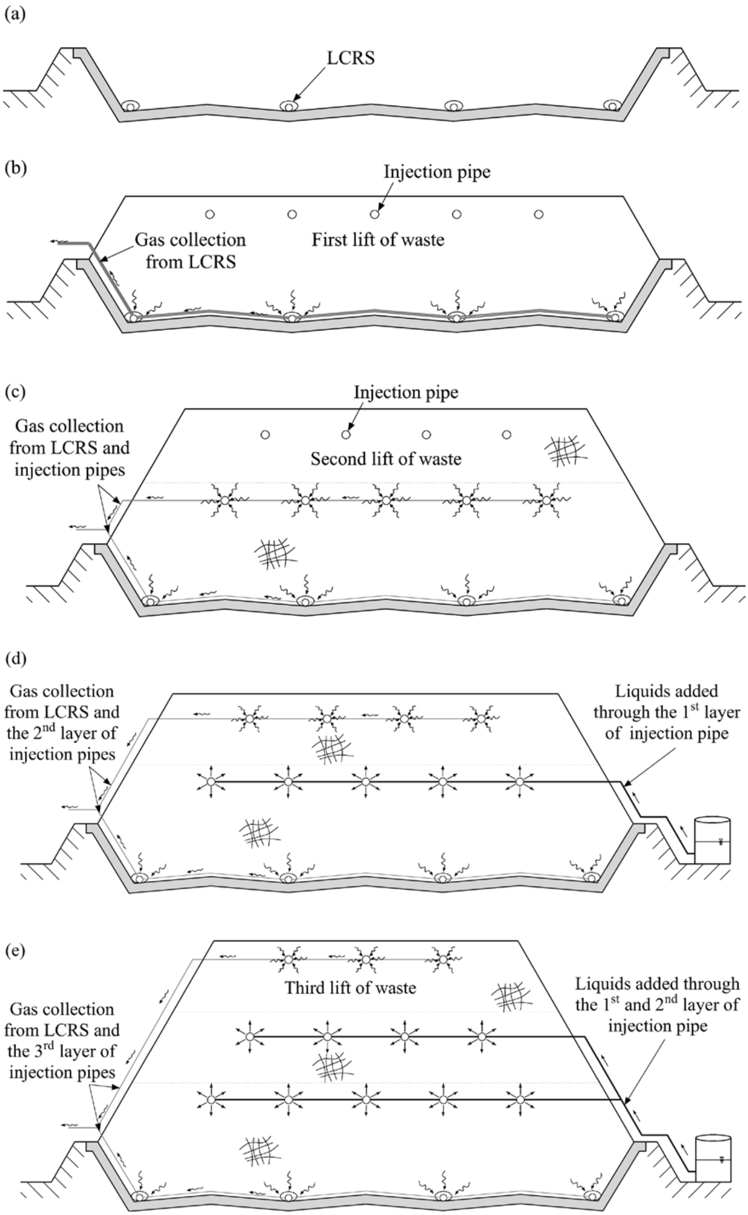

Fig. 13.14 Illustration of staged use of horizontal trenches for liquids addition and gas collection (**a**) Initial landfill LCRS; (**b**) after first lift placement, collection of gas from LCRS (continues throughout) and construction of horizontal trench layer 1; (**c**) liquids addition into layer 1, construction of layer 2; (**d**) extraction of gas from layer 2; (**e**) liquids addition into layers 1 and 2, gas collection from layer 3

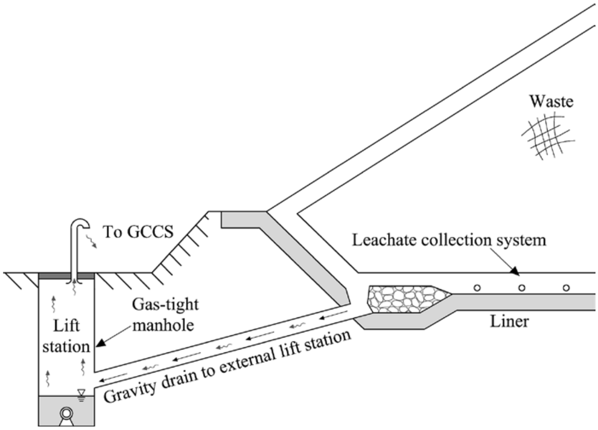

Fig. 13.15 Example of gas escape from LCRS through manholes or pump stations

Fig. 13.16 Manhole of LCRS sealed with HDPE geomembrane and plumbed for gas collection

footprint via gravity) lends itself well to LFG collection, especially if dedicated piping is designed with the intent of LFG collection from the beginning (Townsend and Miller 1997).

Figure 13.16 illustrates the use of a conventional external leachate collection pumping system for LFG collection. It is common for landfill operators to notice gas buildup in the pumping stations and manholes. As portrayed in Fig. 13.15, gas migrates through the primary leachate drain into the manhole. If the manhole is appropriately designed from the beginning for gas collection (e.g., gas-tight covers,

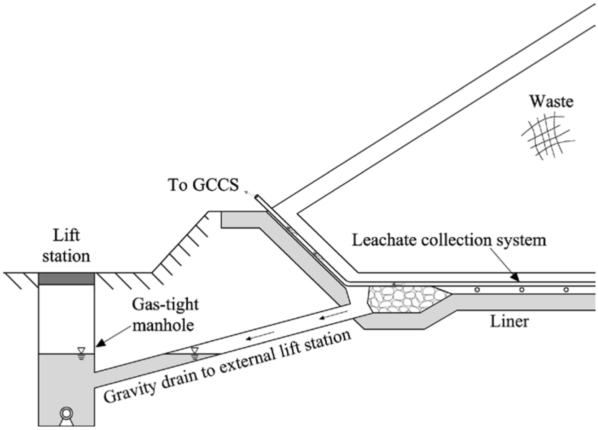

Fig. 13.17 Maintaining leachate levels in external manholes to promote gas collection from extraction points within the landfill

gas extraction vents), each manhole can serve as a gas extraction point. It is quite common; however, that such systems are not designed from the beginning with such practice in mind, and the challenges in retrofitting these locations to be gas-tight have prompted some owners and operators to find other solutions. For example, Fig. 13.16 shows a manhole that was completely encased in a geomembrane to facilitate gas collection. Retrofitting manholes for gas extraction can be accomplished, but consideration for this function should be explored in the initial LCRS design.

Figure 13.17 illustrates an alternative approach. The liquid levels in an external manhole (or pumpstation) are raised so that the migration pathway for LFG into the manhole is cut off. Pump stations will normally be equipped with on/off switches that are triggered by the depth of water in the manhole, and these can be adjusted to effectively isolate the headspace of the manhole from the interior of the landfill. A gas vent at some location connected to the LCRS inside the landfill must be provided as an extraction point for the gas. Retrofitting LCRS cleanout is a common practice, though again, design this function from the beginning would be most efficient.

Chapter 11 discussed the use of toe drains to help control seeps at the bottom of the exterior slopes of above-grade landfills, and described how these devices can also provide an effective extraction point for the collection of LFG. Toe drains will typically be connected to the LCRS to provide necessary drainage. Design and construction of a toe drain as an element in the GCCS provides another promising method for LFG collection; once sufficient waste is placed, a low vacuum can be created on the toe drain to collect gas that accumulates at the landfill perimeter and that which may be exiting the landfill from the LCRS. It is also possible for the toe drain GCCS element to be integrated into the overall LCRS gas collection infrastructure. Figure 13.18 illustrates gas collection from a landfill toe drain that is integrated with the facility's LCRS.

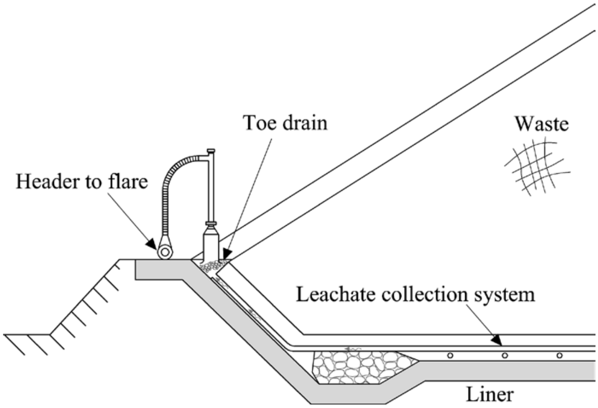

Fig. 13.18 Gas extraction from a leachate toe drain connected to the LCRS

Fig. 13.19 Horizontal gas collection trench (perforated pipe bedded in stone) installed on top of the LCRS drainage layer (Photo courtesy of Jones Edmunds)

Even without considering gas collection, most LCRS will still facilitate gas collection. For many sites, a better approach, especially for wet landfills, is to integrate gas collection into the original design of the LCRS as a separate component. This can be accomplished in several ways. Figure 13.19 shows a site where a horizontal gas collector was installed on top of the LCRS sand drainage blanket. A perforated HDPE pipe was installed in a shallow trench in the LCRS sand; permeable stone

Fig. 13.20 Horizontal gas collector (perforated pipe blanketed in a geocomposite) placed on top of the LCRS drainage blanket

was then mounded around the pipe and covered with more sand. These gas collection pipes were then routed to the side of the landfill and connected to wellheads for later gas extraction. Figure 13.20 shows another approach, where perforated pipes were wrapped in a geocomposite placed on top of the sand drainage blanket of the landfill's LCRS. Similarly, these pipes were routed to the side of the landfill for eventual connection to the site's GCCS.

13.5.5 Surface Gas Collection Systems

Another approach to LFG collection at landfills implementing sustainable practices is the use of an exposed geomembrane cap (EGC) top cover underlain by horizontally-oriented surface collectors. Figure 13.21 shows such a series of gas collection trenches installed on the side slope of a landfill where liquids addition is practiced with a goal of augmenting waste stabilization. There are several benefits to integrating an EGC into the GCCS, whether as part of a final closure or simply a temporary practice. First, the ECG can act as a visual indicator to alert the operator whether or not sufficient vacuum is being induced in a given area of the GCCS; traditional vegetative covers may provide some indication (e.g., dead or distressed vegetation) but this often occurs later than when GCCS inefficiency can be identified at a site with an EGC, where billowing or bubbling of the cap can occur fairly quickly. When placed on areas that are at interim grades, an EGC allows a greater

Fig. 13.21 Construction of surface trenches for gas collection to be placed under an exposed geomembrane cap

vacuum to be induced on devices within the waste mass. The EGC can also assist in managing liquids on side slopes by mitigating liquid or leachate seeps that occur and allowing the seeps to be routed to a toe drain system (see Chap. 11). Chapter 17 discusses the pros and cons of using an EGC as a sustainable landfill practice.

Care during construction, operation, and maintenance is required with this type of system (just as with a traditional LFG collection system). Several specific design and construction issues must be considered at landfills that employ a temporary geomembrane. The temporary EGC should be constructed over all areas with LFG collection and subject to quality control procedures to check integrity of seams for signs of protrusions through the cap. Wellheads connected to extraction points should include seals or gaskets that reduce air intrusion; in fact, wellhead connections should be minimized. Checks for tears in the cap or at seams must be rigorously conducted.

13.5.6 Downward Collection Systems

As described earlier, a major operational issue with gas collection systems (at landfills in general and potentially more so at landfills implementing sustainable practices) involves additional liquids impeding LFG collection; LFG collection devices can become flooded, significantly reducing the efficiency of the GCCS.

Another problem with modern LFG collection is that the waste surface settles after a landfill is filled, which can cause the GCCS wells to shift, ultimately resulting in surface seeps and breaks in the GCCS. This can cause the vacuum system to intake ambient air, and these problems require frequent maintenance by landfill operators.

An alternative LFG collection system may be used in which extraction pipes are installed before the waste is placed and plumbed in a way that LFG collection may commence during the early stages of landfill development and so that LFG can be collected concurrent to liquids removal. As the landfill is filled up, the pipes that were installed originally will be continually extended upward until the landfill has reached its final grade or elevation. A similar technique has been practiced at some landfills with traditional GCCS, where the wells start after the first lift of waste has been placed (not connected to the LCRS). Figure 13.22 shows the progress of construction of a downward draining gas collection system. In Fig. 13.22a, combination gas collectors/leachate drains are installed with construction of the LCRS; these devices are plumbed so that leachate drains to the LCRS while gas can ultimately be extracted as part of the GCCS. Figures 13.23b–d illustrate the progress of extending the collectors/drains upward as the landfill is filled. If a gas-tight seal is maintained at the top, gas collection can occur even as waste operation continues. Upon final waste filling, the devices can possibly be buried beneath the final cover. This approach thus has the potential to provide a less operationally intensive GCCS after completion; the engineer should consider differential waste settlement around the devices as part of the design and operations plan development.

This method should significantly reduce the issue of LFG collection wells filling with liquid since both gas and liquids will be collected and extracted through the bottom of the landfill. Furthermore, as a landfill is filled, the gas collection wells can be extended vertically to continue collecting gas from new layers of waste. The engineer would need to provide a design that allows continued extension of the collectors/drains while minimizing interaction with the atmosphere once sealed (preventing future air intrusion). This approach also offers strong promise to alleviate excess pore water pressures that can lead to slope stability issues in landfills with added liquids (see Chap. 12).

Figure 13.23 shows a landfill site employing vertical gas collection wells that begin in the LCRS and that are raised as waste filling progresses; these wells, however, are equipped with collection devices at the top of the well. A primary drawback of where wells are constructed as the waste is deposited is the compatibility with landfilling operations—the site operators would need to ensure LFG wells are protected from incoming waste trucks and landfill equipment. Furthermore, operational difficulty may be experienced through the progressive enabling and disabling of gas collectors as vertical extensions are installed.

13.5.7 Delayed Liquids Addition

Delaying liquids addition is an approach that allows the landfill cell to be filled first before the addition of liquids. The landfill would then be covered by a low-permeability cap (EGC, traditional multi-layered cap, or a temporary earthen cover such as clay).

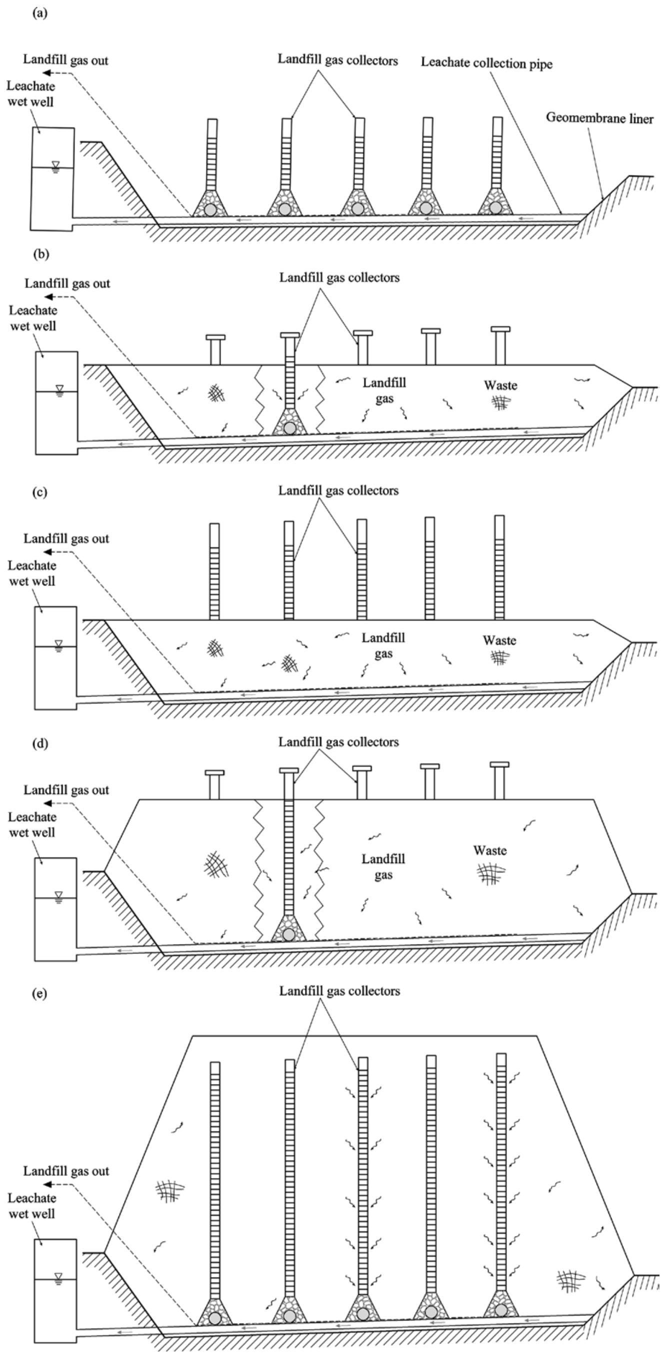

Fig. 13.22 Construction sequence for a downward draining GCCS. (**a**) Combination gas collectors and leachate drains are installed as part of liner and LCRS construction; (**b**) waste filling commences; (**c**) devices are raised as needed; (**d**) waste filling continues; (**e**) the devices are buried under the cover systems and gas collection occurs through the LCRS

Fig. 13.23 Example of vertical gas well constructed from the LCRS and extended upward as waste depth increases

The cap construction would allow for more effective gas collection as well as assist in liquids management. The primary disadvantage for delaying liquids addition is that the operator misses out on the LFG generation/recovery from the early years of operation. Also, as discussed in Chap. 6, since the total volume of liquids targeted for addition may be large, and since the greatest volume of liquids available for addition occurs during the operational years of the landfill, delay of liquids addition may have some other operational consequences. The gas forecasting methods described earlier in this chapter can be used to estimate the overall fraction of gas that will be collected under different liquids addition and start time scenarios.

13.5.8 Methane Oxidation

At some point in a landfill's life, the volume of gas may not be sufficient to warrant collection for energy recovery, and flaring may require an additional source of gas. At this point, several other approaches may be required to most effectively reduce CH_4 emissions to the atmosphere. Landfill aeration for older landfills has been utilized frequently in Europe as a means of reducing CH_4 emissions; aerobic conversion of remaining organic matter, along with oxidation of remaining methane, results in CO_2 being the primary exit gas. This process is discussed in detail in Chap. 14.

Another approach allows the remaining gas to vent through an adequately thick and vegetated cover soil layer to promote biological methane oxidation. Such activity has been widely documented at landfill sites (Visvanathan et al. 1999; Christophersen et al. 2001; Barlaz et al. 2004). Design of landfill covers to maximize their methane oxidation potential has been proposed as a strategy for mitigation of CH_4 emissions, particularly at older landfill sites (He et al. 2007; Rachor et al. 2011).

CH_4 oxidation has been reported to be influenced by soil properties such as particle size distribution, moisture content, soil texture, mineralogy, and porosity, as well as environmental factors such as barometric pressure, temperature, the pressure gradient, oxygen availability, microbial population, and vegetation (Visvanathan et al. 1999; Streese and Stegmann 2003; Borjesson et al. 2004; Barlaz et al. 2004; Spokas and Bogner 2011). He et al. (2007) reported significant increase in methanotrophic bacteria population over time in a methane-rich environment and proposed use of a soil with previous exposure to a methane-rich environment such as soil reclaimed from old landfill for soil cap. Rachor et al. (2011) used a column study to evaluate the CH_4 oxidation capacity of soils available to site owner for landfill cover construction. In addition to the soil properties, the type of vegetative cover has also been reported to influence the methane oxidation rate (Reichenauera et al. 2011). Bohna et al. (2011) attributed increase in methane oxidation with vegetation cover to factors such as improved oxygen diffusivity in soils via roots and enrichment of soils with plant cover. When assessing methane emissions to the environment, some modeling techniques include a specific term or factor to account for methane oxidation (IPCC 2006).

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Chapter 14
Landfill Air Addition

Abstract Although less well-developed compared to anaerobic sustainable landfilling technologies, the addition of air as an extensive or just a portion of sustainable landfilling operations provides a series of distinct potential benefits compared to anaerobic systems. The fundamental system configuration and design approaches for aerobic systems are provided, along with operation, monitoring, and control techniques. Given the unique nature and relatively limited experience with full-scale aerobic systems (compared to anaerobic), a special series of case studies from Asia, Europe, and North America are provided to provide examples of how aerobic technologies can be incorporated into sustainable landfilling operations.

Keywords Landfill • Air addition • Aerobic • Temperature • Fire • Stabilization

14.1 The Role of Air Addition in Landfill Operation

Under normal waste disposal conditions at landfills, an anaerobic environment and biological stabilization process dominates. Aerobic microbial processes are present when waste is first disposed as oxygen exists in the pore spaces within the waste, but the oxygen is quickly consumed at a rate greater than it can be replenished from the outside environment. Thus, an anaerobic environment is maintained throughout the majority of the active phase of waste decomposition. As illustrated in Chap. 2, aerobic phases are limited to a short initial phase, and given time, a final phase after waste stabilization reaches completion.

The anaerobic pathway of waste stabilization, and the resulting landfill gas and leachate conditions, is the default environment encountered at disposal facilities integrating sustainable landfill practices. Efforts to create and maintain an environment of aerobic waste stabilization for some, and even a majority, of a landfill's operating life have been attempted. Aerobic composting of solid waste, whether for the bulk waste stream or an organic-rich fraction (e.g., source segregated food waste), is a commonly-employed method of biological waste treatment around the world (Haug 1993). Operators of composting systems promote aerobic conditions within the waste so that biological decomposition can occur in a relatively short time period (typically a matter of several months) compared to the lengthy process

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of anaerobic decomposition. Ideally, this process results in an end-product that can be beneficially used as a soil amendment to provide nutrients for agricultural lands. The operation of landfills akin to large composting facilities has also been explored as a waste treatment technology.

In considering the potential benefits offered by adding air to landfills, it is useful to first assess the relative differences between aerobic and anaerobic biological treatment processes (see Table 14.1 for a summary of this assessment). Since aerobic respiration of the biodegradable waste more completely oxidizes organic matter (producing CO_2 and H_2O), more energy is released in the reaction, resulting in more rapid reaction rates and higher temperatures (Haug 1993; Palmisano and Barlaz 1996). While the anaerobic degradation pathway is also exothermic and energy is released, part of the organic matter's energy is conserved in the form of CH_4, which in turn can be collected and harvested for energy (see Chap. 19). Creating environments favorable for aerobic stabilization are theoretically easier to achieve and control, as the primary requirements are providing sufficient air and moisture. Because of the interdependence of microorganisms in anaerobic systems (see Chap. 2), it may take longer to reach a state of active CH_4 production and these systems may be susceptible to imbalance and upset (e.g., acid buildup and suppression of methanogenesis).

Because of these differences, aerobic operation provides conceptual advantages with respect to waste and leachate treatment compared to the anaerobic pathway, and since the amount of CH_4 produced will be reduced, aerobic operation offers benefits with respect to greenhouse gas (GHG) emissions in cases where landfill gas emissions are inefficiently controlled. The trade-off, however, is that aerobic operation is more expensive because of the need to mechanically add air to the waste (via either forced air injection or application of vacuum pressure to pull air into the waste mass). Anaerobic landfills take longer to stabilize but do not require mechanical energy other than that needed to add liquids and extract the gas, which itself can be converted to energy. Aerobic landfills also require a higher degree of monitoring to avoid potential issues with smoldering or fires and the formation of explosive gas mixtures.

In this chapter, we summarize and examine practices for employing air addition as part of sustainable landfill management. A review of existing experience finds that landfill researchers and operators have attempted to realize several of the benefits that can result from aerobic waste treatment, including providing better leachate treatment, conditioning the waste for further anaerobic treatment, providing rapid waste stabilization, and "curing" landfills near the end of their active life. Following a discussion of these different beneficial aspects, design and operational considerations, as well as challenges, are presented. The chapter ends with a description of air addition practices implemented at landfills around the world.

14.2 Achieving Benefits from Air Addition

In some aerobic landfill applications, the operator introduces air only during targeted periods of a landfill's operation as a means to meet specific objectives. In other applications, the operator attempts to maintain aerobic conditions throughout the

Table 14.1 Comparison of aerobic and anaerobic biological conditions

Feature	Comparison
Biological reaction	Biology in aerobic operations is thought to be more diverse, including bacteria and fungi. Anaerobic biology consists of a more defined set of microbial groups that are dependent on one another. The aerobic reaction pathway is generally viewed as more rapid and robust. Anaerobic pathway is sensitive to environmental conditions and may take time to become established
Energy released and temperature	Both reactions are exothermic, but the aerobic reaction releases more energy, due to the more favorable thermodynamics of micro-organism use of O_2 as an electron acceptor. Landfilled waste often reaches temperatures of 60 °C, while temperatures as high 70 °C or greater are often reached in aerobic composting processes. Greater temperatures result in more rapid reaction rates and pathogen destruction. High aerobic temperatures can contribute to smoldering, combustion, and fire issues at composting facilities and landfills
Exhaust gas	In anaerobic systems, the prime end-product gases are CH_4 and CO_2. In aerobic systems, the primary product gases are N_2, CO_2, and O_2, depending on the degree of oxygen utilization. Mixed systems may generate some quantities of all listed gases
Trace gases and odor	Chemicals found as byproducts in both systems may be malodorous, but the anaerobic environment tends to produce chemicals with strong, pronounced odors. These include volatile fatty acids, reduced sulfur compounds (e.g., H_2S), and ammonia. Presence of trace compounds that are either decomposition products or products of volatilization will depend on the initial waste composition
Final material product quality	At the end of waste stabilization, a mature product from either process will be of similar quality. The fate of some chemical species may differ (e.g., Nitrogen will be conserved in anaerobic systems as ammonia). Because of its more complete stabilization, aerobic treatment is often used as a post-treatment step for anaerobically produced products
Energy	Aerobic systems are net energy consumers (because of energy needed to introduce air). While some energy is required in anaerobic systems, the opportunity exists to harvest energy through CH_4 recovery and conversion

landfill's operational life. As a result of more rapid reaction rates and the ability to more completely transform some chemical constituents, landfill operators can utilize controlled air addition to meet a number of desired sustainable operation targets; see Table 14.2 for several of these potential applications.

Some landfill researchers and operators have attempted landfill air addition to utilize aerobic biological activity as the dominant waste stabilization mechanism, replacing the anaerobic pathway. Instead of CH_4 and CO_2 being the dominant gas-phase decomposition products, an aerobic landfill would have a gas composition consisting primarily of N_2, CO_2, and possibly O_2. Leachate quality differs in the rate at which organic strength (BOD, COD) is reduced, as well as other differences such as pH, nitrogen, and heavy metals.

Several researchers have compared performance and outputs of aerobic and anaerobic landfill operation in the laboratory and at pilot scale. Stessel and Murphy (1992) demonstrated in a set of laboratory lysimeter experiments that recirculating leachate through simulated landfilled waste while simultaneously adding air resulted in reduced leachate concentrations of organic compounds and more rapid waste degradation rates, measured by means of waste settlement. Optimal degradation (maximum waste settlement) was observed under the minimum moisture content, moisture addition rate, and air addition rates of 75 %, 0.09 m^3/m^2-day, and 40,000 m^3/m^3 water applied, respectively (Stessel and Murphy 1992). Similarly, Matsufuji et al. (2004) compared solid waste stabilization in semi-aerobic (often referred to as the "Fukuoka method"; discussed more later in this chapter) and anaerobic landfill cells at the laboratory scale, and found that leachate BOD concentrations decreased much faster in the simulated aerobic landfill cells, along with decreased BOD to COD ratios (<0.05 after 3 years of experimentation) and low NH_3–N levels as compared to anaerobic landfill cells. Using data gathered from large scale lysimeters where semi-aerobic, recirculatory semi-aerobic, and aerobic conditions were tested, Matsufuji et al. (1993) reported that aerobic landfill conditions metabolized 72.4 % of the organic waste mass within 10 years as compared with 56.7 % under anaerobic landfill conditions.

Bilgili et al. (2007) utilized four laboratory-scale systems to investigate the effect of leachate recirculation on aerobic and anaerobic waste degradation and leachate quality, and observed that conductivity, TDS, and chloride concentrations were greater under aerobic conditions due to the higher pH values; pH in the aerobic treatment remained between 8 and 9 after study day 100, in contrast to anaerobic cells where pH rose steadily from roughly 6 at day 100 to 7.5 on day 500. Air addition effectively reduced organic matter and ammonia leachate content (Bilgili et al. 2007). In laboratory columns containing a waste stream designed to represent the composition of fresh MSW, Sartaj et al. (2010) found that aerobic conditions were effective in reducing the concentration of heavy metals, attributing this to the adsorption of metals on waste materials and precipitation of metal oxides due to the increased pH. Kim et al. (2011) operated four waste-packed laboratory columns, two each under aerobic and anaerobic conditions for a period of 1,650 days, and observed differences in leachate heavy metal concentrations; some elements were greater in concentration under the aerobic environment, while others were greater under anaerobic conditions. Cr(VI) accounted for approximately 45 % of the Cr in

Table 14.2 Potential beneficial applications of air addition to landfills

Application	Description
Improving leachate quality	Introduction of air into the bottom layers of a landfill (the pipes and drainage stone of a LCRS) stimulates a leachate treatment zone, particularly for the organic matter
Primary waste treatment	Similar to an aerobic waste composting operation, adding sufficient air to landfilled waste will result in the bulk of waste decomposition to occur via the aerobic biological pathway
Waste conditioning	A brief period of air addition to newly-deposited waste may better prepare waste for subsequent anaerobic decomposition in that waste temperatures are increased (particularly beneficial in colder climates) and rapidly degradable organic matter can be stabilized to avoid uncontrolled acid production by anaerobic decomposition conditions
Waste curing	The addition of air following anaerobic waste treatment serves to stabilize the residual waste
Nutrient management	Air addition is used to biologically transform recalcitrant ammonia nitrogen to nitrate, which can be further denitrified in other anoxic areas of the landfill

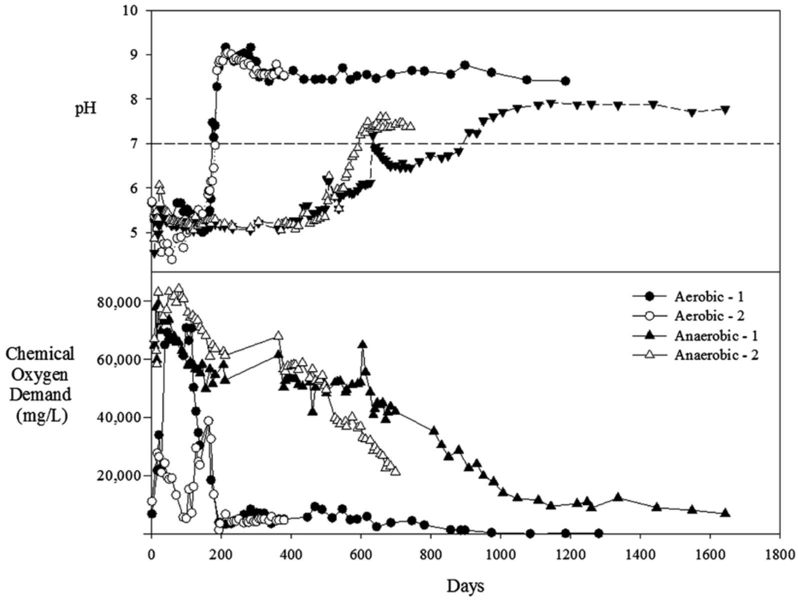

Fig. 14.1 Differences in pH and COD in landfill leachate from simulated bioreactor landfills (Kim et al. 2011). One pair was operated aerobically and the other was operated anaerobically

aerobic lysimeter leachate while chromium in the anaerobic lysimeter leachate was below the detection limit. Kim et al. (2011) found that metal leachate concentrations decreased significantly in leachate from the aerobic lysimeters as waste stabilized, while concentrations in the anaerobic columns remained stable. Figure 14.1 provides the pH and COD for this experiment and illustrates the difference between these two environmental extremes.

While most biodegradable organic matter can be equally treated through aerobic and anaerobic pathways (although reaction rates may differ), for some chemical constituents, aerobic treatment offers treatment capabilities not possible with anaerobic systems. For example, the dominant form of N in anaerobic landfill leachate is ammonia nitrogen (as discussed in Chaps. 2 and 11), and this constituent tends to be conserved in the landfill over time, and thus increases in concentration, presenting a treatment challenge (Berge et al. 2005). Using aerobic treatment, ammonia can be nitrified to nitrate, which denitrifies to N_2 gas in a subsequent anoxic step, thereby removing it from the system (Berge et al. 2006, 2007). This approach has been examined in several different configurations as illustrated in Fig. 14.2.

Some landfill operators practice external nitrification in tanks, and then recirculate the nitrified leachate back into the landfill to promote the anaerobic conversion of nitrate to nitrogen gas. This approach has been described by some as a hybrid bioreactor landfill. Other researchers have investigated the potential for adding air to specific regions within a landfill so that the nitrification step can occur within the landfill itself (i.e., in situ). Leachate treatment (including ammonia transformation)

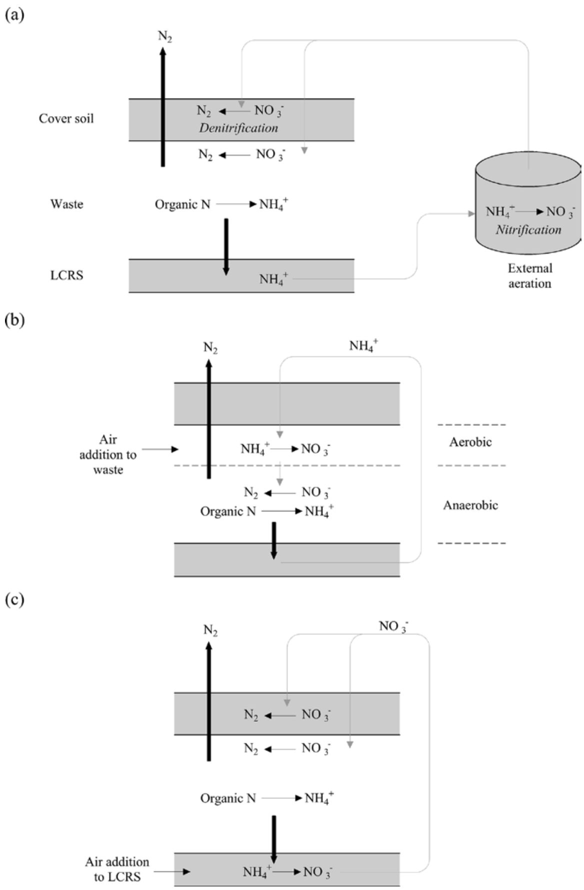

Fig. 14.2 Alternative strategies for promoting leachate nitrogen removal by using air addition (**a**) external aeration (**b**) air addition into the waste mass (**c**) air addition into the LCRS

represents a major motivating factor in the decision to employ the semi-aerobic landfill approach, a technique where air is introduced into the LCRS using large diameter pipes to promote ventilation, thus creating an aerobic treatment layer at the base of the landfill; the semi-aerobic landfill approach is discussed in greater detail later in this chapter. Onay and Pohland (1998) conducted laboratory-scale experiments that demonstrated the ability for reactors (operated as either aerobic or anoxic) working in series with internal leachate recycle to achieve 95 % nitrogen conversion (nitrification and denitrification) to the end-product of N_2 gas. An investigation into the kinetics of in situ ammonia (NH_3–N) removal from landfill leachate showed the feasibility of simultaneous nitrification/denitrification in an aerobic landfill environment, with total N removal rates of 0.196 and 0.117 mg/day-g dry waste for acclimated and non-acclimated waste (acclimated waste had an established nitrifying microbial population), respectively (Berge et al. 2006).

Some landfill operators practice the addition of air early in the active life of the landfill for a limited period, allowing the bulk of biological treatment to occur through anaerobic conversion (Rich et al. 2008). Early air addition has been utilized as a method for increasing the temperature of the waste (a particularly valuable function of aerobic operation in colder climates), thereby conditioning the waste for subsequent conversion to an anaerobic environment, and as a means to provide treatment of readily degradable organic compounds that otherwise might result in rapid acid formation in anaerobic environments. An additional early-phase air addition strategy has included the induction of air into surficial regions of landfill (specifically, recently-added waste lifts) as a means to control CH_4 emissions to the atmosphere prior to LFG collection device installation (Hansen et al. 2002; Jung et al. 2011). In this system, LFG is extracted into a horizontal collection layer at the base of the targeted waste lift with the goal of inducing air from the surface of the landfill into the waste, thus minimizing anaerobic CH_4 production. Later, when additional waste is placed on top of this area, the devices are repurposed as horizontal collectors for anaerobic biogas; air addition piping can also serve a later purpose as liquids introduction devices for bioreactor landfills.

A common practice, especially in Europe, has been the addition of air to landfills toward the end of their active life as a method of promoting near-complete stabilization of waste that has already undergone anaerobic decomposition. In some cases, infrastructure for LFG extraction is reconfigured so airflow into the landfill can be induced. In other cases, wells are added to older landfills for the specific purpose of air addition. Low-pressure aeration projects have been undertaken extensively in Germany. The Milmersdorf landfill represents one such case where >90 % of biodegradable organic carbon was stabilized via oxidation with active aeration and active off-gas extraction through wells installed in the waste (i.e., the AEROflott® technique) (Ritzkowski and Stegmann 2012).

14.3 Air Addition System Configuration and Design

The design of an air addition system includes estimating the volume of air that must be added (or extracted in an induced system) to meet design objectives, selection of the type of air addition system (vertical wells and/or horizontal pipes), detailed specifications on sizing and configuration of the air addition devices, setting spacing between individual devices, and selection of materials for air piping. Finally, the design should include specification of other control and monitoring devices such as pressure and temperature measurement gauges and automated controls (e.g., emergency shut-off valves that engage at a high pressure threshold) as desired. This section reviews design objectives, methods for estimating air addition volume requirements and rates, and air addition system infrastructure.

14.3.1 Design Objectives

The engineer will consider multiple objectives in the design of a landfill air addition system. A primary objective will be the conveyance of air to the targeted area of the landfill. Infrastructure will be required to actively deliver (an active system) or passively encourage (a passive system) air to the landfill region of interest. In the case of active systems, mechanical blowers, fans, or compressors must be connected to a piping network capable of accommodating the desired flow rates to the targeted addition points. In the case of passive systems, infrastructure (e.g., vents, drains) must be located and appropriately sized to promote air entry into the landfill based on temperature gradients.

Integral to the design of the air conveyance system will be the identification of the target air volume and addition rate so that the infrastructure can be sized appropriately. This determination will depend on overall project objectives such as the purpose of air addition (e.g., primary waste treatment versus targeted waste heating or curing) and needed performance requirements. In addition to air volumes and flow rates, appropriate air addition pressures that promote necessary distribution of air into the waste mass must be considered.

As a result of concerns such as explosive gases and excessive waste heating, it is critical that the engineer maintain the objective of designing a system that can be monitored and appropriately controlled during operation. Important monitoring parameters include gas composition, gas temperature, and waste temperature. Coupled with monitoring must be a plan and equipment specification for addressing concerns that may be revealed as an outcome of monitoring. For example, if elevated temperatures create excessive waste temperatures, the monitoring and operations plan must include contingency procedures to slow or mitigate the high temperature conditions.

14.3.2 Air Addition Rate

In a similar manner as discussed in earlier chapters for liquids addition, a multitude of factors must be considered when calculating the amount of air that should be added to a landfill to meet a given design objective. The total amount of air added per volume or mass of waste will reflect the degree of aerobic treatment targeted; complete stabilization will require much more air than systems where the objective is to heat the waste prior to anaerobic stabilization or to cure the waste after anaerobic degradation has reached practical completion. The rate of air addition depends upon several factors, including the ability of the landfill to accept air, the number and size of the addition devices available, the ability of the blower system to deliver air, and the ability to add air while minimizing the potential to create excessive heat generation, explosive conditions, and related issues.

In a similar manner as the CH_4 potential (L_o) for waste undergoing anaerobic decomposition (see Chap. 13), an O_2 consumption potential for waste undergoing aerobic decomposition can be estimated. This may be measured in the laboratory or estimated using assumptions regarding waste composition and the fraction of waste potentially subject to aerobic decay. The following equation is commonly cited in design texts for solid waste and represents the O_2 demand as a function of a generic stoichiometric representation of waste's chemical composition (Haug 1993).

$$C_aH_bO_c + \left(\frac{4a+b-2c}{4}\right)O_2 \rightarrow aCO_2 + \left(\frac{b}{2}\right)H_2O \tag{14.1}$$

When this equation is simplified to the aerobic degradation of cellulose ($C_6H_{10}O_5$), we arrive at:

$$C_6H_{10}O_5 + 6O_2 \rightarrow 6CO_2 + 5H_2O \tag{14.2}$$

A similar equation for the anaerobic decomposition of cellulose was presented in Chap. 13. Upon comparison of these two equations, the anaerobic decomposition of one molecule of cellulose results in three molecules of CH_4, while the aerobic respiration of one molecule of cellulose requires six molecules of O_2. Thus, as an approximation, the O_2 consumption potential for a cellulosic waste would be approximately twice as much as L_o, and given the composition of air (approximately 79 % N_2 and 21 % O_2), the air consumption potential (A_o) would be 9.5 times as much an L_o.

If the design target was 100 % aerobic stabilization, the volume of air needed would be large. Figure 14.3 provides an assessment of the magnitude of air that would be required by showing the amount of air needed (volume per time at steady state) to keep up with an incoming waste disposal rate (mass per time). The values presented assume a waste with a L_o of 100 m^3 of CH_4 per Mg (A_o = 950 m^3/Mg) where waste could be theoretically stabilized as effectively aerobically as anaerobically. In addition to a line representing 100 % aerobic target activity, lines corresponding to a 50 % aerobic treatment target (50 % anaerobic) and a 10 % aerobic treatment target (90 % anaerobic) are presented. As this figure illustrates, the large amount of air needed for complete aerobic treatment is one of the limitations of aerobic biostabilization as a primary waste treatment technique, particularly at larger landfills.

Calculating the design air addition rate depends on several other considerations beyond the desired addition rate. The desired rate must be achievable within the constraints of the system provided. For systems where air is injected under pressure, the flow rate achievable into a device (e.g., a vertical well) depends on the dimensions and construction of the device (e.g., the length and diameter of well, perforation or slot size and configuration) and the hydraulic properties of the waste (e.g., permeability, porosity). Jain et al. (2005) conducted a series of air pump tests using small (5 cm diameter) vertical wells at a landfill designed in part for aerobic operation

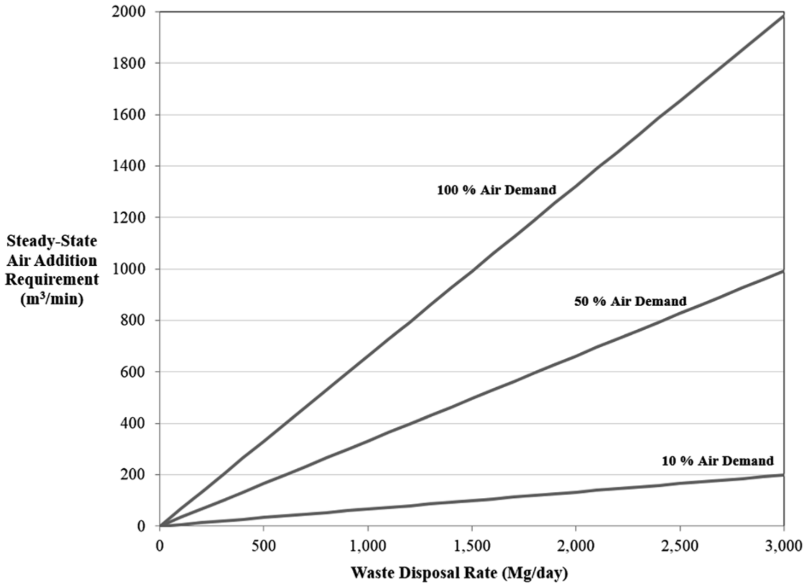

Fig. 14.3 Air addition requirement for complete aerobic waste stabilization as function of waste disposal rate

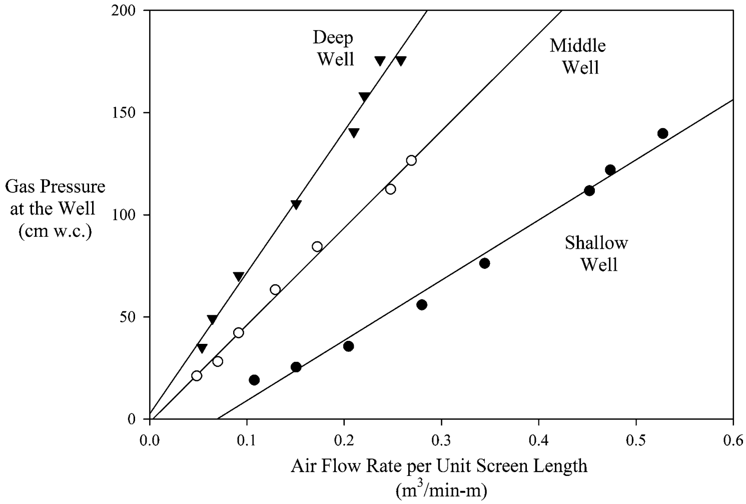

Fig. 14.4 Results of aeration pump tests at a MSW landfill: backpressure as a function of added flow rate (Jain et al. 2005)

(New River Regional Landfill, Florida, USA). Figure 14.4 shows a representative graph of pump test results, where the flow rate was measured as a function of injection pressure in wells installed at varying depths within the waste. Greater injection pressures resulted in greater air addition rates, and the achievable rates declined as the well construction depth increased, which was attributed to the greater overburden pressures in deeper sections, larger amount of moisture present, and increased gas pressures present from anaerobic decomposition.

Since pressurized air addition in landfills has not been practiced to a large extent, methodologies for the design and placement of air addition devices lag similar efforts for liquids addition and LFG extraction. Some basic concepts from modeling gas extraction in landfills, however, may be applied (e.g., the concept of radius of influence). Additionally, the large body of design information available for air addition and vapor extraction for soil/groundwater remediation systems can be consulted and adapted. Air injection system design (blowers, manifold, and injection wells) methodology takes into account the necessary air volume, air flow rate, air entry pressure for the surrounding media, constituent mass to be degraded, friction and minor pressure losses, and a factor of safety to decrease the potential for air flow backup due to high pressures within the media. In the case of a landfill, leachate surrounding an injection well may cause a need for increased injection pressure (Marley et al. 1995; Hudak 2000; Leeson et al. 2002). Air addition systems may also be designed with the intent of pulsed or periodic air injection, possibly necessitating a higher air addition rate while blowers are operating to achieve the overall air addition volume over a fixed time period. The unique challenge for designing these systems for landfills is the heterogeneity of the waste material and the potential for elevated temperatures and subsurface heat-generating reactions. When air is added to an injection well, aerobic decomposition activity will occur to the greatest extent in the area immediately surrounding the well. The rapid reaction rates associated with aerobic activity may result in large amounts of heat generation, and it has been observed that temperatures within the waste can increase beyond the upper range where aerobic microorganisms thrive (discussed in next section) (Stone and Gupta 1970; Powell 2005).

The selection of a blower depends on the volume of air required, desired flow rate, and anticipated pressures required to add the amount of desired air. There are several factors that can influence the effectiveness of the air addition system. Due to the heterogeneous nature of the solid waste placed in the landfill, a wide variation of achievable addition rates should be expected. Another consideration is the presence of higher moisture contents in the landfill waste; moisture acts as a physical barrier to air flow and can reduce the flow significantly (observed by Jain et al. 2005). In practice, it may be impossible to have a completely aerobic landfill, because waste in deeper sections of the landfill is dense and well compacted, and thus air permeability is very low (see Chap. 5). For aerobic landfills, the balance of air and water addition is critical. Sufficient water must be available to provide a suitable environment for microorganisms to thrive. If sufficient water is not available, excessive heat production can result in the combustion of the waste. However, if an excessive amount of water is present, hydraulic limitations make it difficult to add sufficient amounts of air evenly to the waste, resulting in short-circuiting and uneven treatment of the waste mass. Finally, with respect to heating of the waste, sufficient infrastructure must be in place to allow generated heat to escape, as discussed in the following section.

14.3.3 Air Addition System Infrastructure

The three primary components of air addition system infrastructure include a mechanical blower or fan, a conveyance system, and a network of air injection and gas handling piping. The conveyance system delivers air from the blower to the landfilled waste, and the air injection and gas handling network is used to distribute air to the landfilled waste mass (and, where applicable, remove gas from the landfill). The air injection network can be installed in different ways, depending on the site-specific conditions and design goals.

Landfills that have an LCRS can incorporate the LCRS infrastructure to add air to the waste mass. In this system, air is allowed to move passively through the headspace of the LCRS piping that is open to the atmosphere. The temperature differential between the interior of the landfill (high temperature) and the ambient temperature (generally lower) produces a "chimney effect" in which air is drawn into the pipes and brought into the waste mass (Leikam and Keyer 1997).

For landfills with no LCRS or when the LCRS is not chosen as the means for air introduction to the landfill, wells dedicated to air introduction are used. Air can be injected via retrofitted vertical injection wells that are drilled down into the waste from the landfill surface and connected to necessary piping infrastructure. This type of a system is more commonly employed at closed or abandoned landfills that have been targeted for enhanced stabilization or remediation for a variety of goals, including CH_4 mitigation, improvement of leachate quality, or perhaps as part of preparation for another land use (Heyer et al. 2005; Ritzkowski et al. 2006). Alternatively, for sites where air addition infrastructure is constructed as landfilling progresses to achieve aerobic decomposition of organic wastes earlier in the landfill's life cycle, horizontal wells, typically situated in trenches filled with permeable media, may be used (Hansen et al. 2002).

Air introduction to waste may be accomplished through an assortment of methods utilizing vertical wells. Ritzkowski and Stegmann (2012) detail four major vertical well aeration strategies, and these are summarized in Fig. 14.5. One method involves high pressure (i.e., compressed air forcing $\geq$30 kPa) aeration where positive pressure forces air deep into the waste mass, and where suction is applied to other wells which pulls injected air through the waste (Fig. 14.5a). Another method utilizes low-pressure aeration with parallel off-gas extraction via applied suction at additional injection wells (Fig. 14.5b). Low pressure aeration can also be applied without off-gas extraction (injected air migrates through waste eventually to the atmosphere; Fig. 14.5c) and with simple atmospheric venting (vents are drilled into waste to allow for low resistance pathways; Fig. 14.5d).

Pumping and extraction systems for aerobic landfilling operations are similar to those used in a GCCS in some respects. Both utilize blowers to move gases (see Fig. 14.6 for a picture of a blower used for air injection to landfilled waste), particularly in cases where air entry is achieved through induced vapor extraction.

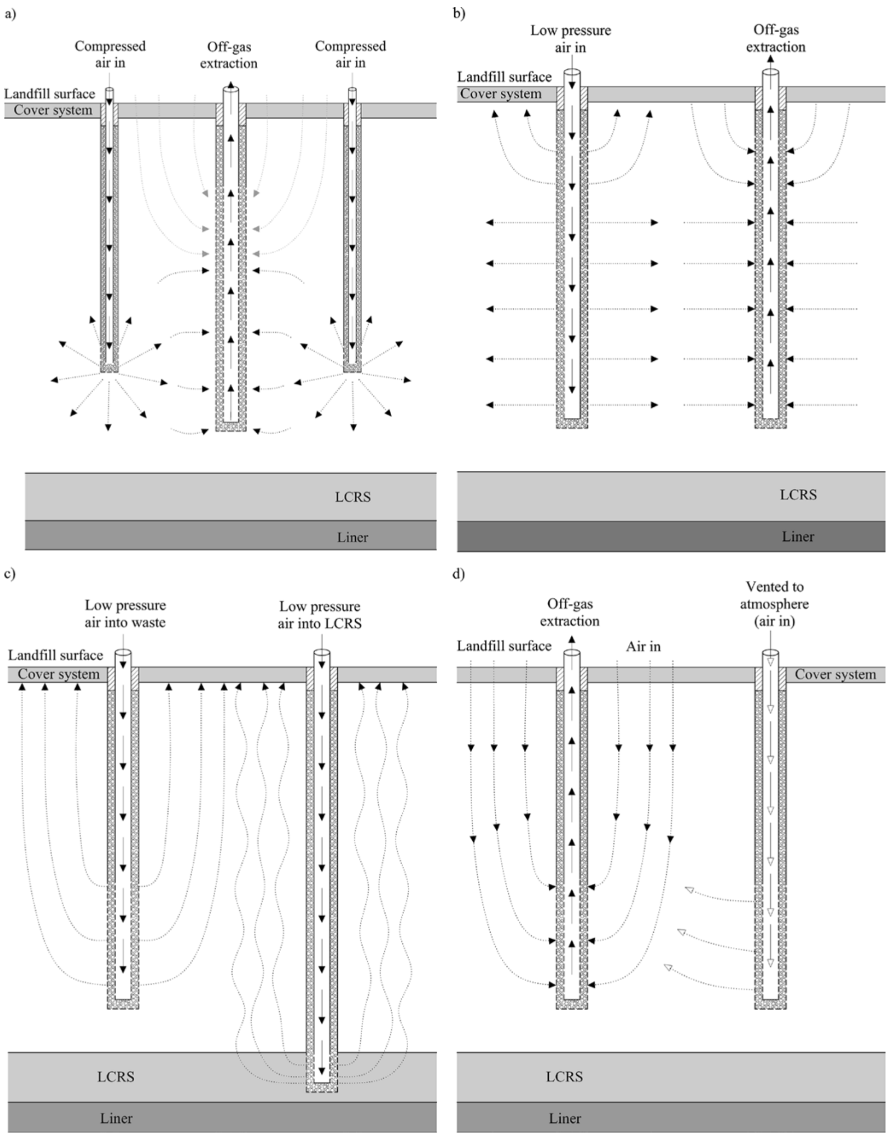

Fig. 14.5 Vertical well air addition strategies (**a**) (modified from Ritzkowski and Stegmann 2012) (**a**) addition of pressurized air (**b**) combined extraction-aeration system inducing low-pressure aeration (**c**) aeration into the LCRS and waste mass (**d**) extraction system allowing air introduction to a vent open to the atmosphere

Since the volume of air required to stabilize a unit mass of waste is greater than the volume of LFG produced under anaerobic conditions, the sizing of system infrastructure (blowers, pipes) will necessarily be larger. Aerobic systems may also be operated following a pulsed period so more effective oxidation for a larger radius of influence is achieved (Boersma et al. 1995; Bass et al. 2000; Yang et al. 2005).

Fig. 14.6 Variable speed positive displacement blower used for air addition at New River Regional Landfill (Ko et al. 2013)

14.4 Operation, Monitoring and Control

Because of the uncertainties related to air addition and the potentially dramatic consequences that might result from improper operation (e.g., excessive waste heating or smoldering conditions), proper operation, monitoring and control are critical. This section reviews these issues, including a focus on explosive gas control and fire prevention.

14.4.1 Operation

Aerobic waste degradation results in the release of more heat than anaerobic activity, thus leading to an increase in landfill temperature relative to typical anaerobic landfill environments. The rapid release of heat can increase the waste temperature and result in combustion or combustion-like conditions, referred to as landfill fires, subsurface oxidation events, subsurface exothermic reactions, or hot landfills. This must be controlled by careful monitoring of temperature and by installing a system to add water if needed. The explosivity range of CH_4 is from 5 to 15 % (volume) in air, thus the potential to create explosive conditions may exist when air is added. Furthermore, landfills (particularly larger facilities) are typically well-insulated, thus rapid heat increases within the landfill are often difficult to dissipate.

The primary operating constraints for an air addition system will include pressure, air or gas flow rate, gas composition, and temperature (gas or waste). The operating pressure (or the required injection pressure) will be based on limits or ranges established at the design stage. The design pressures are typically calculated using literature-reported values for waste properties (e.g., intrinsic permeability), possibly coupled with fluid flow modeling (see Chap. 5) and may be supported through limited field pump tests to establish site-specific constraints or conditions (see Fig. 14.4). In addition to the pressure considerations related to injecting air into the waste mass, another factor to consider is the backpressure experienced within the piping infrastructure—blower and compressor systems have an upper limit of backpressure that can be experienced before mechanical shutdown. Again, in this case it is useful to establish pressure profiles as part of pump testing prior to specification of mechanical blower equipment so that under- or over-design can be avoided. Given that pulsed or periodic air injection has been shown to be advantageous over continuous injection for aeration (Boersma et al. 1995; Yang et al. 2005), these techniques should be considered for landfill aeration systems and design flow rates should account for the possibility of operation as a pulsed system. Air channels (i.e., preferential airflow pathways) form within the surrounding media and pulsed operation increases mixing of aerated pore space with landfill gas or leachate through formation and collapse of these flow paths (Johnson et al. 1993; Yang et al. 2005).

Temperature monitoring and control are among the most critical factors in the operation of aerobic landfills. Landfills that are in a regulatory environment that requires extraction and monitoring of LFG [e.g., US landfills that are subject to the US EPA Emission Guidelines or New Source Performance Standards under the Clean Air Act (Code of Federal Regulations 1996)] may be required to monitor gas temperature. However, in aerobic environments, additional temperature measurement and monitoring is often warranted for multiple reasons, including within the waste mass itself. First, extracted gas temperatures can include the temperature of gas produced radially outward from a given gas extraction point, thus the measured gas temperature represents a combination of gases produced in all directions from the given extraction well. Second, gas temperatures are often lower than actual waste temperatures, thus the measurement of a given gas temperature may not accurately reflect the temperature conditions of the waste itself, particularly near areas where air is added. Finally, the frequency of gas temperature measurement in regulatory environments like those in the US EPA regulations is limited (monthly), which does not provide the operator sufficient data to understand whether air addition is effective or if excessive temperatures are occurring within the waste.

Gas composition is another key operating parameter that must be measured during air addition operations. Similar to waste temperatures, measuring gas composition provides an opportunity to understand the degree of effectiveness of air addition. The number of gas composition monitoring points must be balanced with cost; ideally, a larger number of monitoring points allows for more information on the landfill environment, but too many monitoring points (which could consist of piping comprised of stainless steel, carbon steel, PVC, or CPVC probes drilled vertically into the waste) could be cost prohibitive. Table 14.3 summarizes these key

Table 14.3 Summary of key aerobic landfill operating parameters and associated monitoring devices or approaches

Operating parameter	Monitoring devices or approaches
Pressure	Pressure should be measured at individual air addition devices, at the blower or compressor station, and possibly within header pipes. Dial pressure gauges may be appropriate, with the pressure range spanning the design pressures at a minimum. The injection pressures may be adjusted manually and monitored visually or they may be tracked and adjusted using a supervisory control and data acquisition (SCADA) system
Flow rate	Total system flow rate (at the blower station) and flow rate into individual wells should be monitored at a minimum. Rotameters have been shown to be effective devices to track flow rate and should be specified to include the range of anticipated design flow rates at a minimum. Similar to pressure measurement, flow rates may be adjusted manually and monitored through visual inspection, or flow may be controlled through a SCADA system
Temperature	Temperatures may be monitored by installing thermocouples within the waste (extension-grade Type T thermocouple wire has been successfully used in MSW landfill environments), either placed directly in waste or housed in a sheathing such as a small-diameter PVC pipe. The density of thermocouple placement depends on the number of air addition points and the design objectives, but a prudent approach would include providing thermocouples around air addition points and at different depths. At sites where a large number of thermocouples is desired, routing all thermocouple wiring to one or more central locations for data logging is preferred to reduce labor and provide a more robust dataset. Temperature can be read from thermocouples via manual readout devices or connected to a multiplexer and data logger for frequent, automatic measurements
Gas composition	Gas composition monitoring can occur at dedicated monitoring points, at LFG extraction wells, or within LFG extraction header pipes. A specialized meter designed to analyze LFG is recommended to reduce potential interference. These meters typically analyze CH_4, CO_2, O_2, and calculate a balance gas. LFG meters can provide frequent measurements. In some cases, the monitoring of certain trace gases may be required (e.g., CO or H_2), particularly in cases where high temperatures are observed. Order-of-magnitude measurement of CO in the field can be accomplished by collecting samples in non-reactive gas sample bags (e.g., Tedlar) and sampling the gas using a colorimetric detector tube (Powell et al. 2006). Confirmatory laboratory sampling may be achieved by collecting gas samples from monitoring points of interest in a Tedlar bag or a passivated stainless steel canister

operating parameters and provides information on monitoring devices or approaches that can be taken. More specific information on gas composition and temperature monitoring techniques are presented in Chap. 16.

The operation of the liquids addition system will require integrated planning with respect to air addition system operation. Moisture may be added prior to or during air addition, and liquids addition could occur concurrently or alternately with air addition events. Ultimately, the selection of these operating conditions must be incorporated into the landfill's overall design and operating plan so that the system can meet design goals.

14.4.2 Explosive Gas Control

A concern at all landfills is the formation of explosive gas mixtures, as CH_4 is flammable when mixed in a certain proportion with O_2. Locations at a landfill where LFG has the potential to mix with air, and thus CH_4 to mix with O_2 (such as pump stations, valve vaults, buildings near the landfill, and GCCS infrastructure) require periodic monitoring to assess whether potentially explosive conditions have formed (a spark or ignition source must be present for an explosion to occur when an explosive gas mixture is present). Landfill operators attempt to avoid explosions by minimizing locations where explosive gas conditions exist, and where they might exist, avoiding potential ignition sources (e.g., explosive proof switches at pumping stations, prohibiting smoking in or around active or closed landfill areas). Clearly, landfill operators that purposely promote air entry into the landfill must be extra vigilant with regard to avoiding explosive conditions.

When evaluating landfill gas for flammability, the most typically cited values are a 5 % lower explosive limit and a 15 % upper explosive limit, by volume (ATSDR 2001). These values refer to the percentage of CH_4 present in air. When the CH_4 content is less than 5 %, not enough fuel is present to sustain a flame (the mixture is too lean), whereas when the CH_4 is greater than 15 %, the mixture is too rich. These values, however, refer to the occurrence of CH_4 in air. In reality, CH_4 would almost always be accompanied by another gas such as CO_2, and other non-flammable gases act to dilute the CH_4. The presence of "diluent" gases therefore reduces the range over which CH_4 is flammable.

Given the impact of diluent gases, it is more helpful to describe CH_4 flammability in the form of a flammability chart, as opposed to a fixed set of CH_4 concentrations. Figure 14.7 presents a flammability chart, with O_2 shown as a function of CH_4, and zones delineated that express whether the mixture is flammable or not (following the procedure of Coward and Jones 1952). The relative concentration of the primary diluent gases expected, N_2 and CO_2, will vary depending on specific site conditions, thus the chart presents the flammability zone with N_2 treated as the diluent gas, as it provides a larger (more conservative) range.

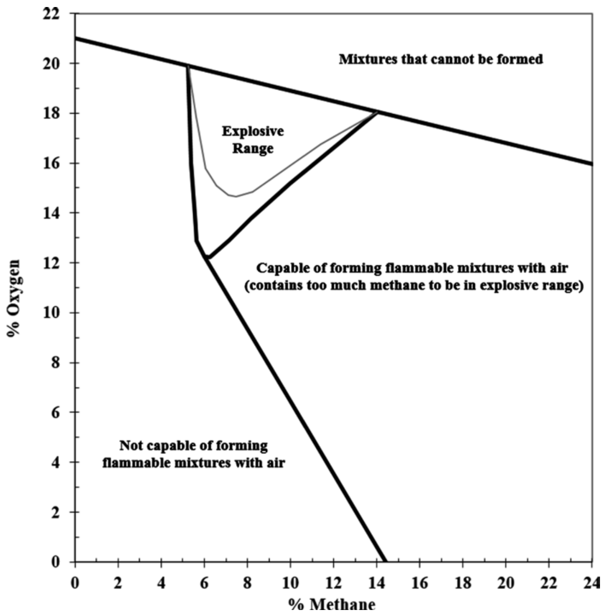

Fig. 14.7 Flammability chart (Ko et al. 2013)

14.4.3 Fire Prevention and Control

Heating events within the waste mass, which are also referred to as subsurface fires, subsurface oxidation events, subsurface exothermic events, or hot landfills, among other terms, are a concern at all landfills. Landfill fires on the surface are fairly common in the US and internationally, and the causes can vary widely (FEMA 2002). Generally, heating events can be caused by external factors (such as hot or smoldering materials delivered to the landfill) or caused by reactions within the waste itself (such as intrusion of atmospheric air that results in aerobic reactions). In anaerobic systems, temperatures as high as 55–60 °C are sometimes reached in the landfill interior, and this temperature becomes self-regulating since higher temperatures will limit the activity of the anaerobic organisms. With aerobic systems, however, temperatures can reach 70 °C or more; Powell (2005) reported waste temperatures increasing approximately 20 °C to more than 70 °C within 1 week of initiating air addition at an MSW landfill in the US. While the aerobic process may be self-regulating to a degree, the well-insulated conditions within a landfill may prevent the heat produced from aerobic reactions from exiting the waste. For example, waste temperatures following cessation of air addition as reported by Powell (2005) showed very slow temperature declines, which is in contrast to the rapid temperature increases brought about by aerobic operation. At this point, heating reactions may create smoldering or pyrolysis-like conditions within the waste (with temperatures ranging from 80 to 100 °C or more), which is supported by work reported by Moqbel (2009).

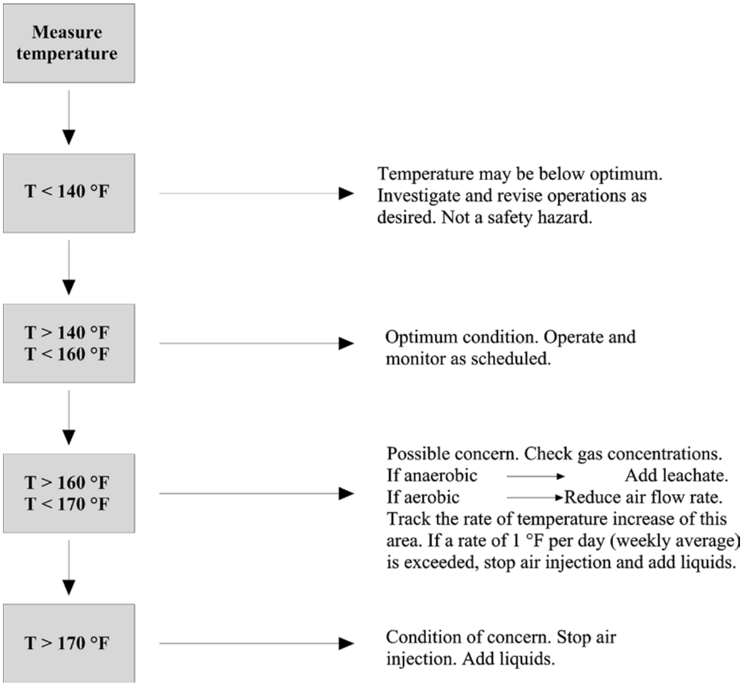

Fig. 14.8 Temperature control chart used as part of the NRRL Aerobic Bioreactor Research (Ko et al. 2013)

Given the complexities inherent with landfilled solid waste (and accompanying cover material), adding sufficient air to a full-scale landfill operation at a rate that meets air addition objectives but does not promote excessive waste heating, combustion, or pyrolysis conditions may be challenging. Landfill operators who add air must have monitoring points to measure in-situ temperature of the waste to understand subsurface conditions and to regulate air addition rates; methods for monitoring temperatures within landfills are summarized in Chap. 16. The engineer who develops a site's operations plan must establish monitoring equipment, methods, frequencies, and operating thresholds to maximize control over the system. Figure 14.8 presents the temperature threshold regime utilized as the New River Regional Landfill described in Chap. 4 (air addition was practical at this site as summarized by Ko et al. (2013).

When monitored temperatures reach a level of concern, the typical first course of action is to reduce or stop air addition. Given the insulating environment present within landfills, cessation or reduction of air addition may slow or stop the increase in temperatures within the waste, but that may not always occur, at which point other measures such as addition of liquids in the area of concern may be needed. The amount of liquid added must be balanced with the goal of future air addition, since hydraulic limitations to air addition will occur with excessive liquids addition.

14.4.4 Control of Fugitive Emissions

CH_4 and other gas-phase compounds produced in anaerobic landfills necessitate the installation of recovery and treatment systems, both to meet regulatory and environmental considerations, and for energy recovery. As stated earlier, one of the cited goals of some practitioners of air addition to landfills is the suppression of CH_4 generation. This raises the fundamental question of whether aerobic landfill exhaust requires collection and treatment. Even if a landfill were designed, constructed, and operated to be completely aerobic, because of hydraulic and other constraints already discussed, it is likely that CH_4 generation could not be completely suppressed. Thus, in a regulatory environment it is not likely that avoidance of active LFG collection would be possible. In this case, the addition of air would need to be balanced with the need to actively collect LFG produced anaerobically in the landfill. This leads to a complex situation where the goals of operating a landfill aerobically would need to be consistent with the requirements typical of active LFG collection systems. For example, US EPA Clean Air Act requirements for active LFG collection systems place a limit on the amount of O_2 (5 % by volume) or N_2 (20 % by volume) that may be present at LFG collection wells or devices. The obvious conflict can be seen when considering the composition of air that would be introduced into a landfill during aerobic operation. These regulatory considerations must be examined at the design stage and the approach to aerobic operation would need to be discussed with the appropriate regulatory officials to ensure the aerobic operation would be consistent with existing regulatory operating constraints.

14.5 Air Addition Experience

In recent years, aerobic bioreactor landfill technology has received increased attention due to the cited potential benefits (Matsufuji et al. 1993; Rich et al. 2008; Ritzkowski and Stegmann 2010). The concept of the aerobic bioreactor landfill has been applied—although with varying practices and techniques—in several countries, including Japan, Germany, and the US. These experiences and approaches are summarized in the following sections.

14.5.1 Asia

The semi-aerobic method of landfill operation was developed at Fukuoka University in Japan, and thus is frequently described as the "Fukuoka method" and has been used in Japan, China, Korea, and to some degree, in Malaysia (Matsufuji et al. 2004; Ritzkowski and Stegmann 2012). Developed in 1965, this approach has been presented as a technique well-suited for developing countries and has been implemented

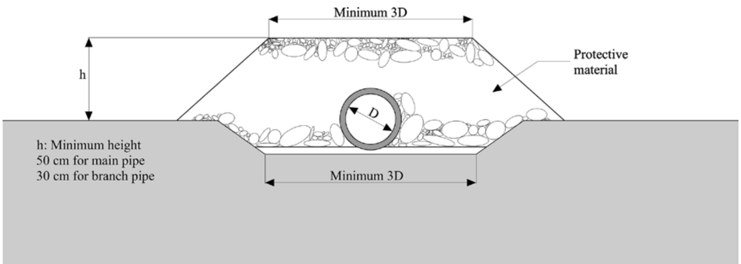

Fig. 14.9 Configuration of large diameter LCRS drain for the semi-aerobic landfill

Fig. 14.10 LCRS of semi-aerobic landfill after construction and before waste placement; connected rock drains are shown (Photo courtesy of Yasushi Matsufuji)

in several regions, particularly in Asia (Chong et al. 2005). The core fundamental of the Fukuoka method is to create as much of an aerobic zone as possible within the landfill by building an air introduction system in a manner that promotes natural ventilation into the waste. The method does not require the use of mechanical extraction systems (e.g., air pumps or blowers) and allows for locally-available and less expensive materials to be used.

Air entry into the semi-aerobic landfill is achieved through two means. First, a large leachate collection pipe, typically at least 0.45 m diameter and as large as 0.6 m, serves as the primary leachate drainage port for the landfill and extends outward to the point of discharge and open to the environment (Figs. 14.9 and 14.10). This pipe should be bedded in drainage rock and at least two-thirds of the pipe diameter should remain open to provide for passive air inflow to the bottom of the landfill. Deep aeration was observed in lysimeter experiments to provide the quickest degradation of organic carbon as well as enhanced nitrification compared to injection of air at shallower waste depths (Wu et al. 2014).

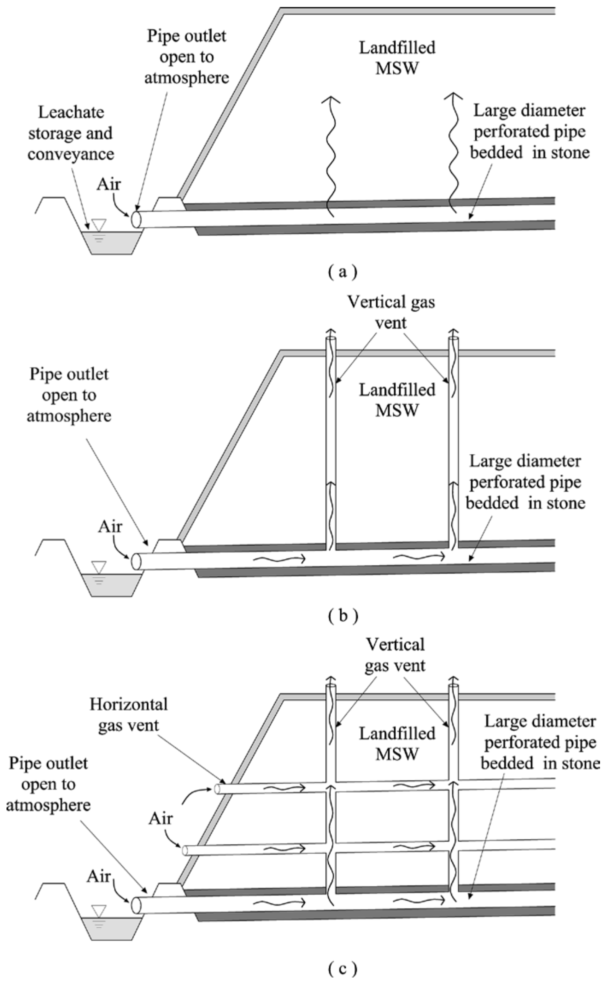

Fig. 14.11 Illustration of the semi-aerobic landfill concept (**a**) LCRS vents, (**b**) LCRS and vertical well vents, and (**c**) LCRS, vertical well, and horizontal vents

Figure 14.11a illustrates air entry into the semi-aerobic bioreactor from the LCRS. The second means of promoting air entry is the connection of vertical pipes to the leachate drainage pipes (Fig. 14.11b). The Fukuoka method recommends a spacing of the vertical pipes of 20–40 m, with closer spacing recommended for deeper landfills. These pipes (sometimes referred to as vents) serve as a means for heated vapor within the landfill to rise to the surface and thus draw air into the waste from the bottom. The vents can be constructed in a similar manner as LFG collection wells placed during waste filling (see Chap. 13), but the method encourages innovative use of construction techniques and less expensive construction materials (Matsufuji et al. 1993, 2004; Chong et al. 2005). Figure 14.12 shows a vent constructed for a semi-aerobic landfill in Thailand. The Fukuoka Method developers

Fig. 14.12 Vertical vent of a semi aerobic landfill after construction and before waste filling

describe the ability of the vents to draw air into the landfill as critical to the success of the technology, and if site-specific reasons preclude close spacing of vents, additional horizontal vents exiting the side of the landfill should be constructed (Matsufuji et al. 2004). The horizontal vents should be connected to the vertical risers and should slope downward toward the vertical wells to promote gravity drainage of liquids (Fig. 14.10c, Matsufuji et al. 2004).

14.5.2 Europe

Under current European Union directives, landfilling of unprocessed waste is discouraged or prohibited, and thus investigations and application of sustainable landfill technologies have not focused on landfills as a primary means of stabilizing solid waste (Ritzkowski and Stegmann 2012). The presence of old landfills in countries such as Germany, Italy, Austria, and the Netherlands, coupled with the desire to reduce CH_4 emissions from old waste, has led to active pursuit of sustainable landfill practices through landfill aeration, given the decreased potential for GHG release via aerobic landfills (Matsufuji et al. 1993; Rich et al. 2008). In this approach, landfills where the bulk of stabilization has occurred through anaerobic processes, and where biogas volumes are sufficiently small such that gas to energy is no longer feasible, are operated to encourage aerobic stabilization of the remaining biodegradable organic matter to reduce GHG emissions and environmental impact by replacing CH_4 emissions with CO_2 emissions (Ritzkowski et al. 2006).

Fig. 14.13 Inlet point for air addition and gas extraction at a closed landfill undergoing aerobic treatment (Photo courtesy of Marco Ritzkowski)

Several landfill aeration techniques, using a variety of well configurations, have been pioneered and patented in Europe, most notably in Germany, as profiled by Ritzkowski and Stegmann (2012). Many of these systems include the pressurized addition of air into vertical wells in the landfill combined with active extraction of off-gas (vapor) from other wells. Figure 14.13 shows the inlet of an air injection and gas extraction landfill at a German landfill. Some systems utilize filtration of off-gas (collected gas) through landfill soil cover or other filtration media (e.g., biofilters comprised of wood chips or compost) (Ritzkowski and Stegmann 2012), while others utilize passive aeration. Figure 14.14 gives an example of an aeration system at a closed landfill included the contained blower structures and the air treatment system. Figure 14.15 shows a passive aeration vent installed at a similar site. Many facilities repurpose formerly operated LFG collection systems such that much of the required infrastructure to operate aerobically is present. An additional beneficial effect of these aerobic treatment systems is odor minimization (Ritzkowski and Stegmann 2012), as it promotes oxidation of reduced compounds which tend to comprise the variety of malodorous compounds (e.g., mercaptans, volatile fatty acids).

14.5.3 North America

Air addition into landfills has received limited application in North America. In the 1960s, air addition was explored at a large landfill in California, where Merz and Stone (1966) added air through an access well in the center of a 20-ft deep landfill

Fig. 14.14 Blower housing and exhaust gas treatment system at a closed landfill (Photo courtesy of Marco Ritzkowski)

Fig. 14.15 Wind-powered air vent at a closed landfill undergoing aerobic treatment (Photo courtesy of Marco Ritzkowski)

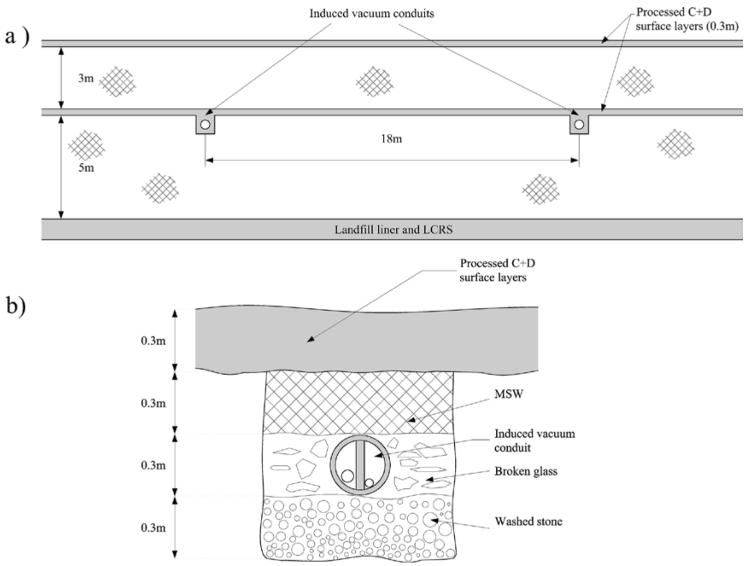

Fig. 14.16 Cross section illustrating construction of the VSA biostabilization technique

test cell using a mechanical blower. Aerobic conditions dominated within the test cell (as characterized by exhaust gas composition) and waste settlement in the first year was four times greater than a corresponding anaerobic control cell. Waste temperatures as high as 190 °F were measured, and at times the exhaust gas exhibited smoke and signs of fire, although the issue was reportedly remedied by blower shut down for a period of 50 days (Merz and Stone 1966).

At some large landfills where leachate recirculation is practiced, air is first added to the horizontal leachate addition lines as a means of increasing temperature and stimulating biological activity, especially in colder climates. For example, at the Outer Loop landfill (Kentucky, USA), air was added to a horizontal piping network [4-in. pipes spaced 60 ft apart (10 cm diameter pipes spaced 18.3 m apart)] approximately 30 days after one lift of waste was placed over the pipes to accelerate decomposition. Air addition, via compressed air injection, proceeded for periods of 30–90 days (at a flow rate of 57 m^3/min), until one of three set points were reached: (1) waste temperature reaches 71 °C, (2) temperature change of 6.7 °C (12 °F) in a 24-h period, or (3) air addition duration of 90 days.

At the Sullivan County Landfill in Monticello, New York, a technique described as vacuum-induced semi-aerobic (VSA) biostabilization was explored (Hansen et al. 2002). In this process, horizontal trenches containing 30-cm perforated conduits were placed on the landfill surface (Figs. 14.16 and 14.7). After wetting the waste with leachate and placing a synthetic daily cover, a vacuum was placed on the pipes using the site's existing LFG collection system, causing atmospheric air to be drawn through the surface of the landfill. The objective was to provide rapid

Fig. 14.17 VSA trench under construction (Photo courtesy of David Hansen)

waste stabilization to newly-placed waste while simultaneously reducing CH_4 emissions to the atmosphere. CH_4 flux to the atmosphere from VSA areas was found to be reduced on average by greater than 90 % (up to 17 m away) when compared to wetted areas with no vacuum applied. CH_4 fluxes were greater than non-wetted control areas, demonstrating that waste biostabilization was enhanced. Without application of vacuum, CH_4 flux to the atmosphere from the VSA stabilization area was approximately 30 times greater than the control cell.

In the late 1990s, aerobic bioreactor technology was marketed in the US as a method of producing rapid waste stabilization, reducing CH_4 emissions and eliminating the need for LFG collection, and providing leachate volume reduction (thus reduced need for treatment) through evaporation and stripping (Read et al. 2001). Several demonstration projects in the southeast US were initiated using small diameter vertical wells for the addition of air (via mechanical blower systems) and liquids (Hudgins and Harper 1999; Ritzkowski and Stegmann 2012). Some preliminary results were presented suggesting accelerated waste decomposition compared to anaerobic areas, reduced CH_4 emissions, improved leachate quality, and enhanced leachate evaporation. Figure 14.18 shows an air addition well used for a landfill facility in the Southeast US.

In response to the proposed aerobic bioreactor technology, several intensive research projects were conducted to examine the viability of full-scale aerobic treatment of landfilled waste and to gather needed design and operational data. At the New River Regional Landfill in Florida (see Chap. 4 for more details), air was mechanically pumped into small diameter (5-cm) clustered wells (three different depths) installed in a grid pattern at 16-m center-on-center spacing (Ko et al. 2013). While liquids were added to all of the wells, air was added only to a subset of the wells. Maintenance of aerobic regions through injection of ambient air was found to

Fig. 14.18 Distribution manifold and air addition well for an aerobic landfill in the Southeast US

be very challenging, primarily due to the inability of many wells to accept air. At the Yolo County Landfill in California (also discussed in Chap. 4 for more details), a vacuum was placed on horizontal gas collection pipes (1–15 cm) placed in shredded tire-filled trenches to draw air through the permeable surface of the landfill (Yazdani et al. 2010). This study reported challenges with respect to suppressing anaerobic activity and maintaining an aerobic state. Even in areas with substantial air injection, anaerobic pockets still persisted, and the presence of anaerobic pockets was more prevalent in areas where moisture content was greatest (Yazdani et al. 2010).

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Chapter 15
Operations

Abstract This chapter builds on concepts that were previously presented in the more design-oriented chapters by highlighting the importance of establishing a crosswalk between design and operation. The duties of landfill operation staff for sustainable landfills are presented, including a comparison with typical duties of operations staff at traditional landfills. Elements that a landfill operations plans should contain to accommodate sustainable landfilling procedures are presented; important operator responsibilities include monitoring and data collection (e.g., tracking the liquids balance), infrastructure inspections and record keeping. Recommendations for using effective system performance monitoring metrics are presented at the end of the chapter.

Keywords Landfill • Bioreactor • Operation • Monitoring • Construction • Inspection

15.1 Importance of Operations

Although much of this book focuses on technical information regarding the science and engineering of processes related to landfills undergoing rapid waste stabilization to promote long-term environmental protection, we cannot escape the fact that even the best planned and designed system can fail without careful and dedicated operation. For example, an engineer may design a LCRS that provides necessary drainage for leachate from the landfill, but if the removal pumps are not properly maintained, inspected and operated, liquid levels can build up within the landfill and result in consequences ranging from poor gas collection to side slope failure. Even if the designer provides robust plans for a pumping and piping system that promotes even distribution of liquids throughout the landfill, successful installation of the infrastructure depends on coordinating construction with routine waste disposal operations and appropriate recordkeeping.

While many facets of other chapters relate to operational issues, the role of the operator is so critical with regard to environmental safety and successful outcomes of sustainable landfill processes, a separate chapter highlighting the role of operation is warranted. In addition, this chapter, coupled with the monitoring technologies in

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the chapter that follows, should provide operators of advanced landfill systems a strong foundation for the efforts required beyond traditional landfill operation. This chapter, in concert with the other more science and engineering-oriented chapters of this book, should provide the design engineer helpful insight on how best to prepare a system design and operations plan that maximize the operator's chances for success.

15.2 Operator Duties and Expectations

The landfill operator must comply with all requirements of the governing regulations and the facility's permit. Beyond this, the landfill operator should be responsible for operating and maintaining the facility in a manner that is protective of the facility's other employees, site visitors, nearby residents, and the environment in general; such expectations apply not only to the current operational time frame, but to every extent possible, the future. These duties and expectations, along with the fiscal responsibility of operating a facility within the constraints of the provided operating budget, pose a challenge for the operator of any landfill.

Best practices for operation of sanitary landfills are described in several different documents developed by the professional and regulating community (Bolton 1995; IRL EPA 1997; EuropeAid 2010), and some resources include information of operation of landfills operated as bioreactors (Reinhart and Townsend 1997; ITRC 2005). Routine duties of landfill operators include weighing and inspecting waste loads and directing vehicles to designated unloading areas, moving waste to appropriate disposal areas after unloading, compacting the waste, and placement of required cover material at the necessary frequency and amount (see the general discussion of landfill operation in Chap. 2). Standard site maintenance activities include mowing grass, maintaining roads, and repairing erosion damage. A common regulatory-required operator duty is the examination of incoming and deposited waste loads to identify and remove prohibited material (waste screening).

Some operational duties may be performed with facility staff, but the operator may elect for an outside contractor to provide such services. Examples include operation and maintenance of the leachate and gas management systems, monitoring groundwater and soil vapor, conducting topographic surveys to track landfill elevation and topography, and vehicle maintenance. Record keeping and reporting are also major operator responsibilities, and likewise these duties may be handled with facility personnel, with outside consultants, or some combination of the two.

At facilities employing sustainable landfill technologies, operators will be charged with additional responsibilities beyond routine landfill operation. Some of the responsibilities result from added operational requirements (e.g., installing additional infrastructure, adding liquids and air), while others come about because of an increased degree of required monitoring (e.g., liquid levels, degree of waste stabilization). Similar to many of the routine landfill operator tasks, some facilities perform these responsibilities in-house while others contract with outside parties.

15.3 The Operations Plan

In addition to construction drawings, a major deliverable of the design engineer should be a detailed written plan for the operation of the landfill, including those added features of sustainable landfill operations. An operations plan will often be a requirement of the regulatory agency as part of the permitting process and will be integrated into the operating permit for the site. The operations plan and permit serve as the operating manual and rulebook for the facility. Often, the most effective operations plans are those developed under a coordinated effort between the operator and the engineer. Table 15.1 summarizes typical elements of a landfill operations plan, along with specific comments on issues pertaining to sustainable landfill operations.

Several of the operation plan elements listed in Table 15.1 will be heavily influenced by the implementation of sustainable technologies. The filling sequence and waste placement plan provide the operator with direction on compacted waste lift location, lift sequence, slope, and elevation. Infrastructure such as pipes, trenches, wells, or monitoring devices will in many cases need to be installed at specific times during waste filling, so these locations must be appropriately noted and described on the filling sequence. Detailed advance planning of infrastructure placement can facilitate resource planning (time, cost, and equipment), though it is acknowledged that infrastructure locations identified in operations plans should be considered a guideline and that operators and engineers should make field adjustments at the time of construction to ensure optimal performance.

As described in Chaps. 11 and 13, the sequence and topography in which the landfill is filled may be dictated by strategies for gas collection and liquids addition and control. The construction, operation, and monitoring of the liquids addition system will be a major addition to the site's operational plan. Similarly, installation and operation of a GCCS may occur much earlier than in conventional landfills (and progressive expansions likewise added more quickly) and involve more devices and a greater level of planning and field execution (construction and operation). The following sections provide in-depth discussion of operator issues with respect to construction, liquids management, gas and air management, and monitoring.

15.4 Construction, Oversight, and Recordkeeping

The construction of infrastructure for liquids and air addition to landfilled waste and the installation of monitoring equipment and instrumentation fall outside the typical duties of routine landfill operation, and the operator must determine to what extent landfill personnel will perform these duties. Some operators take an active role in the construction of pipes and trenches for delivering liquids to the landfill, while others rely solely on outside contractors for such installations. Regardless of the level of involvement the operator plays in actual construction, it is important that

Table 15.1 Typical elements of a landfill operation plan and additional considerations for sustainable landfills

Landfill operation plan element	Broad definition and additional considerations for landfills using sustainable technologies
Waste screening and inspection	A plan for inspecting and removing prohibited wastes. Materials that promote or inhibit waste stabilization may be targeted for placement in designated areas
Filling sequence and waste placement	A plan for waste filling includes site drawings indicating the placement location and dimensions of waste cells and lifts within the landfill unit, providing directions to the operator from beginning of waste placement to final landfill build-out. Infrastructure for liquids and air addition, gas extraction, liquids drainage, and monitoring instrumentation, can be included as part of fill sequencing
Soil cover application	Directions describing placement areas and/or characteristics of daily, intermediate and final cover soil (or other waste covering activities). Landfills with liquids addition may specify additional requirements for as cover removal and stricter controls on the types of cover materials to be used. The plan may also designate alternative cover materials that are more compatible with liquids addition operations
Leachate management	A description of techniques and protocols to manage the expected quantity and characteristics of leachate from the cell or group of cells at the site. Additional leachate pumping and distribution to the waste may be required, along with expanded duties with respect to construction, operation, maintenance, and monitoring of leachate systems
Storm water management	A plan to route and manage water from rainfall that does not contact solid waste. In sustainable landfills, stormwater may be managed differently to promote liquids retention in the landfill. Stormwater management infrastructure may be integrated into seep and gas control systems
Gas management	A plan to manage an active GCCS—this plan may be part of the larger operations plan or a stand-alone document. GCCS operation and monitoring may be practiced earlier and at an enhanced level at sustainable landfills. The presence of more liquids in the landfill may result in more maintenance and monitoring of the GCCS
Record keeping and reporting	Directions outlining the type and frequency of data collected as part of regulatory requirements, permit requirements, or simply for good landfill management practice. Additional site records and reporting are typically required at landfills using sustainable technologies

Fig. 15.1 Operator inspecting and observing construction of a liquids addition device

they provide strong oversight and recordkeeping of construction activities and resulting infrastructure, because of both short-term implications on routine landfill operation, and the long-term impacts on the successful operation of the system (Fig. 15.1).

Landfill operators utilize heavy equipment as part of routine disposal operations (or with ancillary activities), and thus may have the equipment and trained personnel needed for the construction of many sustainable landfill components without the need for outside contractors. The construction of bedded horizontal liquids addition or gas extraction lines requires an excavator to construct a trench in the waste, a loader to bring materials (excavated waste, drainage media) to and from the construction area, and laborers to move the pipe into place. It is common for many operators to perform these activities themselves, as they have the training and equipment, and since installation must be so closely coordinated with routine waste disposal operations. The construction of vertical wells, however, relies on specialized drilling equipment and most landfill operators will need to contract third parties for these services.

Even if equipment and trained personnel are available as part of the facility's permanent staff, the operator may still find use of an outside contractor a better choice. At some sites, existing, demands of routine waste disposal operation (waste filling, compaction, cover soil placement) do not leave sufficient additional time and resources for operators to commit to other construction activities. Operators may also simply prefer to use services of entities that have previous experience in the construction of such systems as a way of mitigating risk, particularly at sites that have not employed sustainable landfill operations in the past. Even under these circumstances, it is imperative for the operator of the systems being constructed to understand the design, observe the construction, and require appropriate recordkeeping.

Some components of the constructed system may not be connected until a later time (e.g., a buried injection trench that will be routed to a distribution manifold), and very likely will not be operated immediately, so it is very important for the locations and elevations of all buried pipes, trenches, or related devices be surveyed and recorded. This should be a requirement of the permitted operations plan.

The operator must coordinate construction activities with routine landfill operations. Considerations include the location of the construction area with respect to the area of active waste disposal; the location of access roads, storm water drainage features, and structures; and the location of buried pipes for gas and liquids management. In addition to the devices themselves, sufficient area will be required for storing scraped soil, excavated waste, bedding materials, and pipe. For some designs, excavated waste will be pushed back over the construction area and compacted in place, but in other cases, the excavated waste will require loading and transport to the active disposal area (see Chaps. 9 and 10). Some landfill operators construct the piping on their own using thermal polyethylene (PE) or chemical (PVC) welding.

15.5 Liquids Addition Operation and Monitoring

The site's liquids addition operations plan, which is a component of the overall site operations plan or a separate document, provides a framework under which liquids operations should proceed. The liquids addition operator (or operators) carries out the tasks in the operations plan and uses judgment based on knowledge of the system's specifications, system response, and other relevant training to ensure effective operations. The operation of a liquids addition system has the potential to impact other facets of typical sanitary landfill operation. As such, the operator must be aware of other permit-related and operational requirements that may be impacted and coordinate closely with other site personnel responsible for such duties.

15.5.1 Liquids Addition Operation

Operational tasks or performance metrics that are likely the responsibility of the liquids addition system operator include those necessary to achieve and monitor liquids addition rate, inclusive of flow rate (overall system flow rate and/or flow rate to specific devices) and cumulative volume added. Liquids addition monitoring is one of the critical elements of an operations plan since system performance can be closely tied to the liquids addition data and observations. Similar to the liquids addition rate, the liquids addition pressure is also a critical component. Design pressures are established using empirical data and engineering assumptions to avoid the creation of excessive pore pressures within the waste mass (Chaps. 8 and 9), which could in turn impact waste mass stability (see Chap. 12). Liquids addition pressure should be checked by the operator routinely (either manually or through data-logged components).

Table 15.2 Example operational sequence for a liquids addition system

Step 1	Visual inspection of liquids addition infrastructure, including pumping system, pipe manifolds, meters and valves, well-heads or entry points into the landfill, and the landfill side slopes
Step 2	Record initial volume readings on meter(s)
Step 3	Adjust valves to targeted liquids addition zones in accordance with operations plan
Step 4	Turn on liquids addition pumps and verify flow meters and pressure gauges are working correctly
Step 5	Inspect liquids addition well-head or landfill entry points. Record injection pressures as appropriate. Depending on the system, check liquid levels in vertical well systems
Step 6	Visually inspect the system periodically, record meter readings and gauges as required, and adjust operation as necessary
Step 7	At a specified time, shut down pumps
Step 8	Close valves as required by the operations plan
Step 9	Perform final inspection of the system
Step 10	Record final meter readings and enter into record-keeping system as appropriate

The liquids addition system should be designed so that the pumping, piping, metering, and control system supports liquids addition rates, volumes and pressures required for operation. In some cases, the engineer might include automated controls (e.g., through a supervisory control and data acquisition (SCADA) system) that maintains flow rates and pressures in the desired range and opens and closes pumps and switches valves at designated intervals; SCADA systems could be controlled via devices connected to the internet or a mobile network. Other systems may require predominantly manual involvement of the operator as described in Chaps. 7–9; while liquids addition have the potential to be practiced over extended periods, it is most common to limit addition to times when a trained operator of the system is on site. Table 15.2 presents an example operational sequence for a liquids addition system associated with intensive manual operation.

For some types of liquids addition systems, maintaining the liquid level below the surface of the landfill can be challenging. This normally requires extensive operator inspection and adjustment to make sure that specified liquid levels are not exceeded. Given that achievable liquid addition rates will normally decrease with time in a given area, operator interaction and evaluation is critical. While technologies exist that can automate such liquids addition (water level sensors and piezometers controlled by actuated valves), the expense associated with such techniques may limit widespread application. The viability of enhanced control systems should be evaluated at the design stage and periodically after commencing operation to assess new technological capabilities or changing cost conditions.

Operators of buried systems are often less concerned with maintaining liquid levels below a specified level as these systems have the flexibility of being operated under pressure. Normal operational routine for buried horizontal trenches or blankets

Fig. 15.2 Adjusting valves as part of liquids addition system operation

includes operating the pumping system, adjusting valves to accommodate the desired operation strategy [i.e., which trenches will be utilized in a given liquids addition cycle (Fig. 15.2)], monitoring flow rate and pressure, and inspecting for seeps. In the operations plan, the operating pressure guidelines must be provided so that appropriate system constraints are clearly identified for the operator. Incidences of high pressure in a liquids addition line may be the result of a pipe or trench failure (e.g., crushing or buckling of the pipe), so when high pressures are observed, the system should normally be shut down (either manually or automatically) in these areas to allow for further exploration of the problem. The operations plan should include troubleshooting guidelines to determine whether an injection line can be salvaged or should be abandoned. Pressures that can still be achieved in functioning systems, but that are greater than desirable slope stability thresholds, should be identified by the operator along with appropriate responsive measures.

15.5.2 Tracking the Liquid Balance

Among the more important sets of data the operator must collect, interpret and maintain are the different components of the liquids balance for the landfill. This includes the elements needed for tracking the landfill's liquids budget, but also distinct volumes and depths of liquids at different points within the landfill and its associated infrastructure (ITRC 2005). An accurately documented liquids balance requires measurements and estimates of major inputs (infiltration from rainfall, added liquids) and major outputs (leachate removal, evapotranspiration from the landfill surface). Infiltration from rainfall will be the difference between rainfall

Fig. 15.3 Operator recording liquid flow meter reading

intercepted by the landfill surface and that running off as storm water. Rainfall is simple to measure and track using rain gauges or weather stations, and indeed many landfills are required to track weather conditions under their permit conditions. Storm water runoff, however, cannot be directly measured, and thus can only be estimated using engineering techniques that factor in slope, soil type, and other site-specific features. Hydrologic models such as HELP (Chap. 5), and the associated engineering methods that serve as the basis for this model, can be used to estimate water balance components such as infiltration and evapotranspiration.

A major responsibility of the operator includes tracking liquid volumes added to the system. Such measurements normally utilize flow meters associated with the pumping systems (Fig. 15.3). Available meter output typically include the flow rate and the cumulative volume passing through the meter. In some cases, the meters are equipped with data logging equipment and the operator's responsibility is to periodically compile recorded data, evaluate results, and organize the information for proper recordkeeping and possibly regulatory submission. In other cases, the operator is required to manually record meter readings. Flow rate readings provide an assessment of system performance and changes over time. Cumulative readings provide volumes added over specific time intervals. Daily measurements of liquids addition (rate and volume) are typical. Where possible, flow meter readings should be collected from as distinct of a landfill area as possible (i.e., knowing flow rates from multiple different collection points or landfill cell is more useful to understanding system performance than a single combined measurement).

Liquids removed from the landfill in the form of leachate is normally measured using flow meters attached to pumping systems. As a backup, pump run times can be recorded to provide an estimate of pumped volumes. In cases where all leachate removal is through gravity drainage, alternative meters (e.g., weirs with water level detectors) can be utilized. The volume of leachate discharged off site, even if in batches, should be tracked, and together with liquids addition volumes, should be compared to leachate removed from the landfill cell. All of the water budget data can be used to calculate changes in moisture storage with the landfill system, and if an initial estimate of moisture content is known, average moisture content for the landfill cell can be estimated. Under some regulatory jurisdictions, tracking the landfill's water balance is critical to determining when regulating thresholds become active (see discussion of US EPA bioreactor rules for landfill gas in Chap. 13).

15.5.3 Inspection

Inspecting, identifying, and managing seeps is one of the major responsibilities of the operator (see the discussion of seep management strategies in Chap. 11). Seeps can be addressed as part of the design and through operation by adjusting flow rates and pressures to minimize the risk of seeps. The pressure and flow threshold should be identified in the operations plan along with appropriate response measures. Nonetheless, seeps should be expected regardless of the operation, and contingencies for managing these seeps should be incorporated into the operations plan (Fig. 15.4).

Fig. 15.4 Inspecting a landfill slope for side seeps

In addition to seep inspection, other components of the liquids management system and other potentially impacted areas of the facility should be routinely examined. Conditions of pipes, valves, and meters should be noted and required maintenance scheduled. Beyond obvious signs of liquid seepage, the operator should note any changes in surface topography (e.g., excess differential settlement) cracks in the landfill cover soil or cap, and alteration in appearance of vegetation. The engineer should include in the operations plan provisions for the operator to act upon when such observations are noted.

15.6 Gas and Air System Operation and Monitoring

Chapters 13 and 14 describe the roles of landfill gas collection and control, as well as air addition, in sustainable landfill operation. Thorough and careful operations are critical to successful implementation of both these elements. A key component of assessing the performance of landfills operated to enhance waste stabilization is evaluation of landfill gas quantity and quality. Techniques and frequencies of landfill gas measurement at such facilities are not altogether different when compared to a conventionally operated landfill with a GCCS. Objectives of a landfill gas-monitoring program may vary from conventional landfilling particularly as tracking gas production is an invaluable tool for monitoring waste stabilization and overall system performance (Fig. 15.5).

Landfill GCCS operators must be provided with appropriate training; several professional training courses have been developed by different organizations and GCCS operation instructional documents are available (e.g., ISWA WG-Landfill 2005).

Fig. 15.5 Collecting gas data as part of GCCS operation

The GCCS operator must coordinate with the design engineers regarding future planning of liquids addition devices and gas collection system components to assess the required vertical and horizontal offsets to help avoid issues with watering out of gas collection components. The operator must evaluate gas well liquid level measurements (for vertical well systems) to assess potential operational changes to the liquids addition system that may be warranted. Alternatively, gas collection performance data from individual wells may be used to evaluate whether watering out is occurring—in cases where frequent watering out occurs, remedial actions such as installation of a dedicated pump may be warranted.

Addition of air requires elements similar to both the liquids addition system operation and GCCS operation. As outlined in Chap. 14, the motivation for air addition may differ among sites, and it is important for the operator to possess a clear understanding of site-specific objectives and designed outcomes. An overriding objective in operating a landfill aeration system would be to provide sufficient oversight and monitoring to avoid formation of fires or explosive gas conditions.

15.7 Monitoring System Performance

Integrated into previous chapters on fundamentals and design approaches related to sustainable landfill activities were discussions of many different parameters related to system performance (e.g., flow rate and pressure of liquids addition; pressure, temperature and composition of gas extraction and air addition; leachate chemistry changes through the progression of waste stabilization). In the design process, the engineer will make assumptions regarding the magnitude of the different parameters needed or expected to be observed for successful operation. The system design and operations plan will therefore include infrastructure for achieving necessary conditions (e.g., pumps sized to deliver appropriate liquid flow rates) and operational constraints that the operator must meet (e.g., appropriate extracted gas composition), along with the controls necessary to adjust operation to meet constraints (e.g., a wellhead for adjusting gas flow rate and pressure).

Depending on the objectives of site operations and requirements of the operations plan, a variety of measurements and readings may either need to be collected by the operator, or contracted to a third party by the operator. Table 15.3 provides a summary of typical monitoring parameters that the landfill operator may be responsible for, particularly for those sites where sustainable practices are implemented. Some degree of system monitoring will be necessary for all landfill sites, but for those locations where liquids and/or air are added, and in general at those facilities, at those facilities where waste stabilization is an objective, additional monitoring will be necessary. Interpretation of monitoring results with respect to system performance, and steps to alter or adjust operations based on these results, should follow requirements of the site permit and operations plan (for routine operation). Where needed, qualified professionals and regulatory officials should be consulted (e.g., for unexpected results or those that might result in dramatic

Table 15.3 Typical monitoring parameters for landfill operation

Monitoring parameter	Typical units	Description
Liquid addition flow rate	Volume per time (gpm, lpm)	A permissible range of flow rates into an addition device or a series of devices will be specified in the operations plan. The operator will adjust the flow rate as required by adjusting control valves, the pumping system, or altering the devices used for addition
Cumulative liquids added	Volume (gal., L)	For some devices or landfill areas, a maximum allowable volume of added liquids may be specific for a given time period (e.g., daily maximum allowable). The operator will need to track the volume and stop addition once reached
Liquid pressure	Pressure (psi, in. w.c.)	The pressure of added liquids may be limited to avoid concerns with seeps and slope stability. Operator will need to monitor pressure and adjust or cease operation if thresholds are exceeded
Liquid depth	Depth (in., m)	The depth of liquid may be limited, such as depth of leachate on liner system or in a vertical well. The operator will need to monitor depth and adjust or cease operation if thresholds are exceeded
Leachate composition	Concentration (mg/L)	Leachate samples will be periodically analyzed. In the short-term, some changes may indicate that operations require adjustment (e.g., rapid decrease in specific conductance may indicate too much stormwater is entering leachate collection system; sudden decrease in pH and increase in BOD may indicate portions of system are stuck in acid-forming phase). In long-term, leachate composition can be used to help assess the progression of landfill stability
Air and gas flow rate	Volume per time (cfm, lpm)	Air flow rates added to or extracted from the landfill will be periodically measured for individual devices. For air addition, flow rate limits will be specific in the operation plan. For gas extraction, for wells with large flow rates (especially at small vacuums) may suggest that additional extraction points are warranted. Flow rate can be directly measured or calculated (e.g., based on differential pressure across an orifice plate)

(continued)

Table 15.3 (continued)

Monitoring parameter	Typical units	Description
Gas pressure	Pressure (psi, in. H_2O)	Gas pressures at well heads, points in the GCCS network, or points within landfill are measured
Gas composition	Concentration (percent, part per million)	Portable or fixed meters will be used to determine composition of major gas components to assess performance of gas extraction and air addition systems. Portable sampling containers may be used to analyze major or trace gases
Temperature	Degrees (°C, °F)	Measurement of internal landfill temperature provides an assessment of waste biological activity. Temperature is a critical parameter for monitoring landfill fire occurrence. Temperature of landfill gas may be measured using a portable meter (often the same meter used to measure composition)
Moisture content	% Wet weight	Internal moisture sensors may be used to assess the efficiency of moisture distribution systems

changes in site operation). Specific details pertaining to monitoring techniques and devices, and common practices for sustainable landfill monitoring (e.g., collection frequency), are presented in Chap. 16.

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Chapter 16
Tools and Techniques for Landfill Monitoring

Abstract Specific tools and techniques that can be used for landfill monitoring, with particular focus on methods that enhance monitoring and maintenance procedures at landfills practicing sustainable technologies. Key monitoring parameters and methodologies covered include liquids (e.g., volume, depth, pressure, chemical composition), landfill gas (e.g., flow rate, pressure chemical composition), and properties of the waste solids themselves (e.g., moisture content, methane potential). The use of instrumentation placed within the landfill to measure temperature, moisture content, and pressures are described.

Keywords Landfill • Bioreactor • Monitoring • Leachate • Gas • Instrument • Pressure • Analysis

16.1 Monitoring Locations and Parameters

A variety of methods, devices, and techniques provide the operator an ability to monitor landfill performance, both for assessing site-specific goals (e.g., airspace consumption) and to meet regulatory requirements for environmental protection (e.g., monitoring of groundwater). Operators using sustainable landfilling technologies will likely employ a larger suite of monitoring tools to assess performance and promote environmental safety. The aim of this chapter is to provide an overview of the many monitoring opportunities that may be utilized at landfills, especially those where sustainable practices are implemented. Readers are also referred to other documents that address monitoring of landfills practicing sustainable technologies (specifically bioreactor landfills) such as Tolaymat et al. (2004) and ITRC (2005).

The various monitoring technologies available to the operator have the potential to be utilized at multiple facility locations (illustrated conceptually in Fig. 16.1). In some cases, monitoring objectives target emissions leaving the landfill (e.g., leachate, gas), while other objectives involve tracking data within the landfilled waste itself (e.g., temperature, pressure). Monitoring locations might include existing landfill infrastructure (e.g., pumps, pipes), specifically-added monitoring points (e.g., buried instruments), or the landfill surface. Table 16.1 summarizes these locations, along with examples of the types of parameters that could be assessed. The

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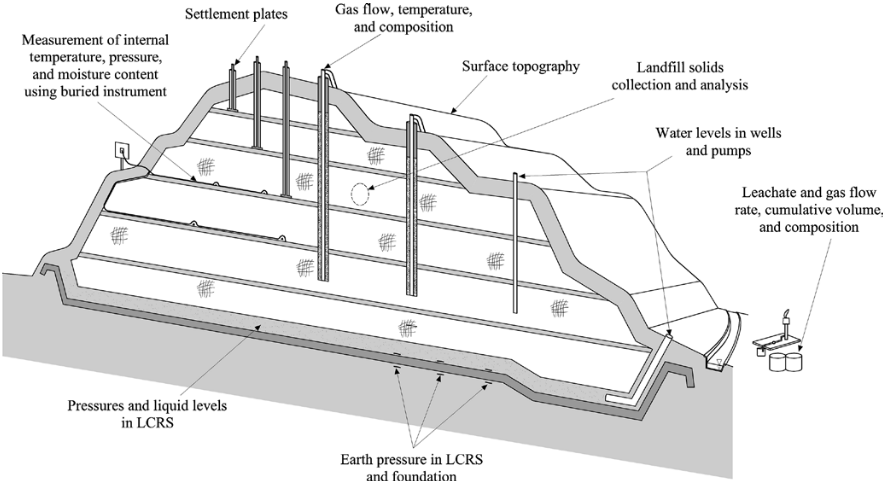

Fig. 16.1 Conceptual illustration of landfill monitoring locations

Table 16.1 Summary of potential monitoring locations and parameters

Monitoring location	Parameter
Liquid collection manholes, pump stations, and storage systems	Liquid depth or pumping rate (or volume)
	Liquid pumping rate or cumulative volume
	Leachate chemical composition (field-measured and laboratory-measured)
Wells and trenches within the waste mass	Liquid depth
	Liquid addition rate or total volume
	Liquid pressure
	Leachate chemical quality
	Gas composition (field-measured and laboratory-measured)
	Gas pressure
	Gas temperature
Gas blowers, wellheads and piping systems	Gas composition (field-measured and laboratory-measured)
	Gas pressure
	Gas flow rate or cumulative volume
	Gas temperature
Within the landfill	Waste temperature
	Moisture content
	Leachate ionic strength
	Pressure
	Elevation
Landfill surface	Gas flux
	Elevation
	Settlement

remainder of the chapter provides description of common monitoring parameters and available methodologies with a particular focus on application to landfills implementing sustainable practices.

16.2 Liquid Volume, Depth, and Pressure

Chapter 15 described the operator's frequent requirements for measuring liquid levels at various locations within a landfill site. Target monitoring points may be locations within the existing infrastructure, or they may be added features included for the specific purpose of monitoring. Whenever liquids are conveyed by pumping through pipes, flow meters can be used to measure flow rate. When measuring leachate flow, because of the potential for high-suspended solids content and mineral precipitation, conventional water flow meters that use turbines or paddle wheels should be used with caution. Ultrasonic or magnetic flow meters are a better choice because clogging concerns are alleviated. In addition to flow rate, most flow meters allow for measurement of cumulative flow volume. Flow meters can be coupled with an electronic data logger or a chart recorder for continuous data collection, or the operator can manually record instantaneous and cumulative liquid volume at designated intervals following the operations plan.

Liquid pressures are measured in a variety of ways. In the case of pipes or tanks, standard dial-pressure gauges or graduated transparent pipes allow for visual measurements. Other instruments are often used when a visible reading is not possible or feasible, such as liquid levels in sumps, pump stations, or wells. Water level sounders consist of water sensors mounted on the tip of a measuring tape and reel, and are designed to be lowered into wells or similar locations until an audio or visual signal indicates the water surface has been reached. The corresponding depth on the measuring tape is recorded and referenced to a fixed object (e.g., top of well casing) or benchmark elevation point near the surface. Depending on the type of sensor employed, these devices may have trouble assessing liquid levels in gas or leachate wells where foam is present, a problem which often results when landfill gas bubbles through leachate.

Submersible electronic pressure transducers, sometimes referred to as piezometers (not to be confused with boreholes or wells used to measure water level), are attached to cables that provide power and transmit a signal, and provide a measurement of the pressure at the tip of the sensor (Fig. 16.2). This device can be lowered into a well, and the point where pressure begins to increase indicates the water surface. Such devices can also be mounted at a fixed point (such as the outside of a tank or at a point in the LCRS) and used to measure the depth of water above the tip of the transducer. The target depth of water to be measured, the surrounding environment, cost, labor, data quality objectives, and the frequency of exposure should be considered when selecting an instrument.

Sensors that are installed permanently inside the landfill environment should take into account possible corrosion, high overlying waste pressures, elevated temperatures, or other conditions that may damage the sensor. Sensors that are buried within soil or waste, as well as the attached cable, must be able to accommodate much

Fig. 16.2 Pressure transducer used for measuring the location of liquids surface with a landfill well

larger physical pressures on the device (not necessarily the pressure being measured) relative to those sensors only used for measurement of liquid depth. For devices buried in the landfill, it is important to consider that the pressure reading measured represents a combination of both liquid and gas pressure (Kadambala et al. 2011); for some applications, this could confound the results. The application of in-situ pressure sensors will be discussed in greater detail in Sect. 16.8 of this chapter.

16.3 Leachate Chemical Composition

Landfill operators commonly monitor leachate on a routine basis as part of regulatory permit conditions, or to meet pretreatment or treatment requirements. The majority of the parameters useful for describing the chemical conditions of landfill leachate require laboratory analytical methods. Simple techniques may be performed at the landfill site if the facility is equipped with the appropriate field measurement equipment. Some of the laboratory analyses target specific components or elements (e.g., chloride, toluene), while other methods provide a measure of an overall characteristic (e.g., BOD). Typical leachate monitoring parameters are described in the following sections, and are organized into measurements made in the field and classes of constituents measured in laboratory (organic strength measurements, inorganic strength measurement, nutrients, and trace chemicals; Table 16.2 summarizes these classes and major associated water quality indicators). Specific laboratory analytical methods are not presented, and readers are referred to

Table 16.2 Classes of leachate monitoring constituents

Leachate constituent class	Description	Examples of specific parameters monitored
Field parameters	Measurements made immediately after collecting samples using portable probes and meters	pH
		Temperature
		Specific conductance
		Oxidation reduction potential
		Dissolved oxygen
Organic strength measurement	Organic chemicals are created from biological decay of the waste and leaching from waste components themselves. Some organic matter (OM) parameters represent biodegradable OM, while others characterize total OM. The concentration and type of organic matter determines treatment requirements and provides an indication of the waste stabilization environment inside the landfill	BOD
		Chemical Oxygen demand (COD)
		Total organic carbon (TOC)
Inorganic strength measurements	Depending on waste composition, leachate contains substantial amounts of dissolved inorganic ions. There may be measured in bulk (TDS) or individually (anions, cations)	TDS
		Anions (chloride, potassium)
		Cations (sodium, calcium, magnesium)
Nutrients	Several nitrogen and phosphorous chemicals are present in leachate, though nitrogen is more prominent. Ammonia-nitrogen content often strongly controls treatment options, although dissolved organic nitrogen can be limiting when a treatment facility discharges to nutrient-limited water bodies	Ammonia
		Total Kjeldahl Nitrogen
		Nitrate/nitrite
		Total phosphorus
Trace constituents	A variety of trace constituents, both organic and inorganic, leach from waste components in the landfill	Heavy metals and metalloids
		Organic pollutants

standard water and wastewater analytical method compendia (Rice et al. 2012; US EPA 2013). Leachate quality can vary tremendously from site to site (and within a single site) as a function of waste type, age, climate and operating conditions. Numerous publications describe leachate quality (Chu et al. 1994; Kjeldsen et al. 2002); example ranges of several major constituent concentrations are presented for landfills practicing sustainable technologies to provide likely magnitudes and trends.

16.3.1 Sample Collection and Field Parameter Measurement

Leachate samples can be collected from multiple locations, including wells or similar boreholes within the landfill, leachate sumps or pumping stations, pressurized pipes, and external storage areas (tanks, ponds). Since leachate originates from multiple locations within a landfill unit or from different landfill cells are often combined as part of the collection and conveyance system, the sample collection location should be appropriately noted and considered when interpreting results. In some cases, leachate samples can be obtained directly from a sampling port or accessible leachate surface, but certain locations will require sampling pumps or manual bailers. Sample agitation may impact analytical results. Exposure to air can alter some water quality parameters (e.g., dissolved oxygen, oxidation reduction potential, volatile organic compound concentrations) and excessive stirring of sediments from sampling locations may result in elevated suspended solids content (which can in turn increase the concentration of other parameters if included in the measurement).

The pH of a leachate sample is a measurement of the hydrogen ion (H^+) concentration in the leachate and describes how “acidic” or “basic” the solution is. The pH is reported as a numerical value in the range of 0–14. Acid solutions have a low pH, while basic solutions have a high pH; a pH value in the range of 6–8 is considered neutral. Most MSW leachates are relatively neutral, though as discussed in Chap. 2, a pH outside of the neutral range may occur, which would be reflective of a distinct stage of waste decomposition in the landfill. Figure 16.3 provides pH data for two landfills over a 20–25 year period; both landfills practiced technologies to enhance waste stabilization (described in Chap. 4). The vast majority of all pH data for these two sites fall in the 6–8 range.

The specific conductance (also referred to as electrical conductance or conductivity) provides a measure of the ionic strength of a solution by measuring the degree that a sample conducts an electrical current. Both positively-charged dissolved ions (cations) and negatively-charged ions (anions) contribute to the overall ionic strength. A greater concentration of dissolved ions in a liquid sample results in a larger specific conductance. All leachates contain dissolved ions, but landfills co-disposing ash will typically have higher conductivity because of the greater mass of inorganic ions leaching from the ash. Conductivity provides a quick, simple means of estimating the total dissolved solids (TDS) content of leachate, and measurements are typically reported in units of μmho/cm or mS/cm; example data are presented in Fig. 16.3.

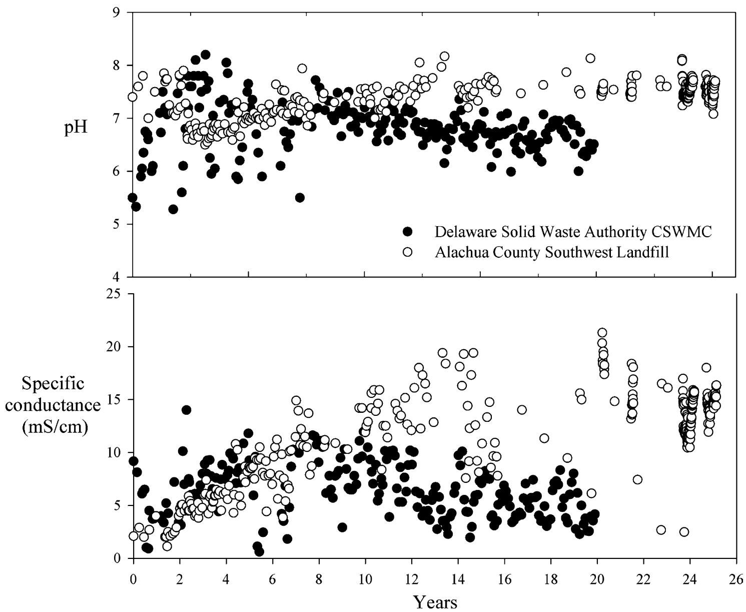

Fig. 16.3 pH and specific conductance at two landfills practicing liquids addition

An oxidation-reduction potential (ORP) probe provides an indication of how oxidizing or reducing the landfill environment is. Biologically active anaerobic landfills are by nature reducing. The units of ORP are mV and most landfill leachates will have negative ORP values. The dissolved oxygen (DO) content of leachate can be measured using a probe connected to portable meter portable meter; units are mg DO/L. Landfill leachate in most cases have a low DO, although this will depend on sample location and the level of atmospheric exposure during sampling.

16.3.2 Organic Strength Measurements

As described in Chap. 2, the type of OM present in landfill leachate varies with the dominant landfill environment and stabilization stage. Looking at several different organic strength measurements thus provides useful information. Because so many different kinds of organic chemicals may be present in landfill leachate, it is not practical to measure them individually. However, since organic chemicals have the potential to be oxidized, laboratory measurements of oxygen demand provides a useful means of measuring organic strength. BOD consists of biologically degradable dissolved organics in the leachate, while COD is a measure of chemically oxidizable components and reflects the combined oxygen demand represented by BOD and other oxidizable non-biodegradable components (large molecular weight OM and some oxidizable inorganic chemicals). As indicated in Chaps. 2 and 11, the ratio of BOD to COD provides a means to assess the relative biodegradability of the leachate OM. Leachate from landfills in the acid phase of waste of decomposition is usually dominated by biodegradable OM, and the ratio of BOD to COD is approximately 1. Some authors suggest BOD to COD ratio of less than 0.1 to be an indicator of mature, stable leachate (Kjeldsen et al. 2002; Tolaymat et al. 2004). Figure 16.4 provides BOD and COD measurements for two landfills including the BOD:COD ratios; both landfills practiced liquids addition to stabilize the waste. In the case of the DSWA landfill, BOD initially was high and decreased over time, while at ACSWL, BOD concentration were relatively low throughout. Both landfills possessed a BOD:COD of approximately 0.1 or less in the later years.

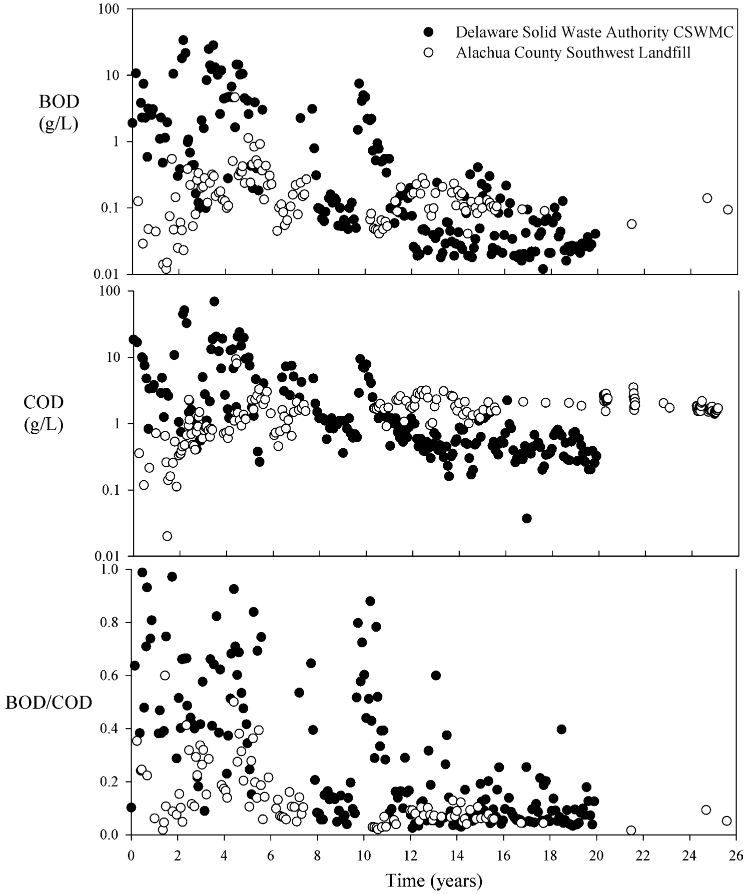

Fig. 16.4 BOD, COD and BOD:COD at two landfills practicing liquids addition

Another measurement of bulk OM of a liquid is total organic carbon (TOC); TOC provides the magnitude of all organic compounds present, but does not independently allow assessment of the stabilization phase. Although it is not feasible to measure all individual organic chemicals, in some cases, measurement of specific dominant species, namely volatile fatty acids (VFA) can prove helpful. As VFAs are present at greater concentration in the acid-forming phase of waste stabilization, VFA measurement (either individual compounds or a combined) provides similar helpful information as the BOD:COD ratio.

16.3.3 Inorganic Strength Measurements

Inorganic chemicals also make up a considerable fraction of the dissolved mass of constituents in landfill leachate. Dissolved inorganic ions (anions and cations) make up the bulk of the dissolved inorganic strength. Primary anions include chloride, bicarbonate, and sulfate. Primary cations include sodium, potassium, ammonium, calcium and magnesium. Most of the ions result from the disposed waste as the direct source (e.g. chloride and sodium from food waste). Bicarbonate (HCO_3^-) primarily results from CO_2 produced during the biological waste decomposition process and its subsequent dissolution into leachate.

Concentrations of individual ions can be measured with a variety of techniques. Ion chromatography can be applied to both anions (Cl^-, SO_4^{2-}, HCO_3^-) and cations (Na^+, K^+, Ca^{2+}, Mg^{2+}), although cations can also be measured using the same techniques used for measuring trace heavy metals. Together, these ions along with dissolved organic matter constitute the bulk of the TDS in leachate. TDS measurements involve filtration to remove suspended solids followed by evaporation of water and measurement of remaining mass. Measurement of dissolved inorganic ions, either in bulk or as part of TDS, provides information regarding the overall strength of the leachate. Often, levels of dissolved organic ions can dictate treatment options for the leachate. Dissolved ions tend to increase over time in closed landfills practicing leachate recirculation, attributable at least partly to the reduction in dilution of leachate that occurs since rainwater percolation is limited. If clean water is continually added to the landfill over time, as would be the strategy with a flushing bioreactor, ion concentrations would decrease. Inorganic strength measurements are not very useful in assessing internal landfill environment (i.e., the degree of biological activity) because they tend to be conservative (resist biological or chemical transformation). Figure 16.5 presents TDS and chloride measurements for the two landfills previously described. In the case of the DSWA landfill, TDS dramatically decreases over the first 5 years and then begins to decrease slowly; ACSWL TDS concentrations increase with time. The initially high DSWA TDS corresponds to the large OM content (as seen in Fig. 16.4). The slow decrease in TDS over time compared to the slow increase with ACSWL corresponds to differences in liquids management after closure. The DSWA site discontinued recirculating leachate and any new liquids addition was from rainfall, while ACWSL continued the practice of leachate recirculation.

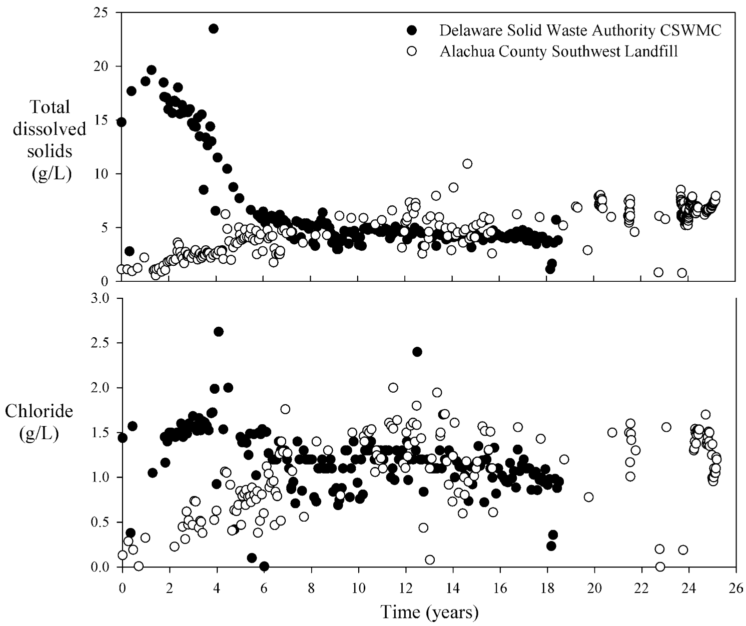

Fig. 16.5 TDS and chloride concentrations at two landfills practicing liquids addition

16.3.4 Nutrient Analysis

While many chemicals may be considered a nutrient, in the context discussed here, the term nutrient refers to nitrogen and phosphorous compounds in a wastewater such as leachate. Ammonia nitrogen is the most abundant nutrient in landfill leachate, and as nitrogen is released into leachate as a result of biological decay of waste components, ammonia nitrogen concentration increases. The form of ammonia nitrogen, either NH_4^+ (ammonium) or NH_3 (dissolved or ammonia gas) depends on pH; under neutral and acidic conditions, the majority will exist as NH_4^+. Ammonia is conserved in the anaerobic environment of a landfill and thus it builds up in leachate over time similar to ions such as chloride and sodium. Figure 16.6 present the total ammonia leachate concentrations for the DSWA and ACSWL facilities; the concentration trends are similar to that of chloride (for similar reasons). Total Kjeldahl Nitrogen (TKN) is also a commonly used nitrogen parameter measured in wastewater; it represents the sum of the ammonia nitrogen and organic nitrogen species (the majority in leachate will be ammonium N). Nitrate (NO_3^-) and nitrite (NO_2^-) are other inorganic nitrogen species, and while the concentration of these ions should be relatively small compared to the total nitrogen content (because of the anaerobic nature of most landfills), these ions may be important in systems where air addition is employed. Phosphorous occurs at low concentrations compared to nitrogen. Phosphorous analyses frequently performed include the inorganic form as well as total phosphorous (TP).

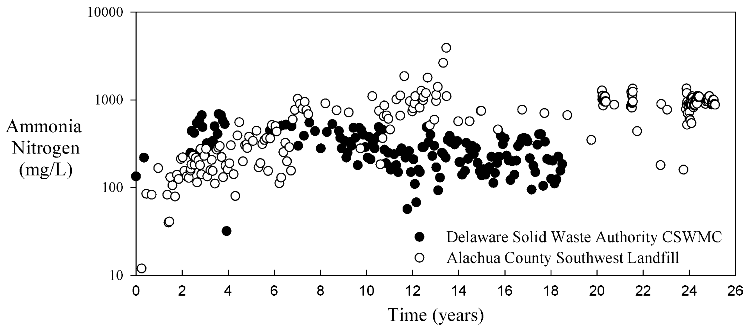

Fig. 16.6 Ammonia concentrations at two landfills practicing liquids addition

16.3.5 Trace Constituent Analysis

The bulk organic and inorganic strength of leachate (along with ammonia-N, which will principally be present as one of the major ions) dominate treatment considerations. The trace pollutants, however, which occur in much lower concentration, often dictate regulatory concerns because of their potentially adverse health effects. These parameters are necessary measurements when determining how a leachate may be managed outside of the landfill. Examples of trace heavy metals include arsenic, cadmium, mercury, lead, and zinc, while examples of trace organic compounds include benzene, vinyl chloride, acetone, and anthracene. While the concentrations of these chemicals are relatively low compared to the other leachate parameters discussed, their presence may be important when assessing treatment options and long-term leachate management options, and when evaluating potential groundwater impacts.

In general, one would expect trace chemical constituents to decrease with time. Since most of these chemicals are not routinely detected, however, they may not exhibit trends in the pronounced manner that the bulk constituents do. The fate of organic trace chemicals will be highly dependent on the specific chemical compound and properties such as volatility, absorption potential, and biodegradability (Reinhart and Pohland 1991). Some trace metals will be bound within the waste, but concentrations will be highly dependent on species, pH, and ORP (Kim et al. 2011).

16.4 Gas Volume, Pressure, and Flux

As described in Chap. 13, appropriate management of LFG is one of the most important objectives of sustainable landfill practice. The monitoring of LFG, both as part of GCCS operation and to assess and control emissions to the environment, is very important. Table 16.3 summarizes the various monitoring parameters utilized to characterize LFG and their associated measurement techniques.

Table 16.3 Monitoring parameters for landfill gas

Parameter	Techniques
Composition	Handheld meters are typically used at the landfill site for bulk gas concentration measurement
Bulk gases:	Field techniques such as colorimetric detector tubes can be used to measure some trace gases. Trace component analysis is often performed by collecting a sample and analyzing individual components in the laboratory
• CH_4	
• CO_2	
• O_2	
Trace gases	
• H_2S	
• CO	
• NMOC	
Flow rate	Flow rate can be measured using a field meter and well-heads on a manual basis. Extraction pipes can be equipped with dedicated flow meters. Flow can be measured directly or can be calculated after measuring a differential pressure
Well head	
Extraction manifold	
Blower/flare station	
Pressure	Pressure can be measured using field meters and monitoring points at the well-head or in the pipe manually. Dedicated pressure gauges can be installed at desired points. Instruments can be placed within the landfill to measure in-situ gas pressure
Well head	
Extraction manifold	
Within the waste	
Surface emission	A variety of techniques can be used to measure the concentration or flux of gas from the landfill surface, including dedicated flux chambers, optical scanning (open-path FTIR), and portable equipment such as photoionization detectors (PIDs) or flame ionization detectors (FIDs)
Flux chamber	
Optical scanning	
FID/PID	

16.4.1 Flow Rate and Pressure

Gas flow at a landfill will be measured at multiple locations, including individual collection wells, as well as centralized regulation stations and extraction points (see Chap. 13 for more details). Gas flow rate is normally measured at individual LFG extraction points that are equipped with a well head. A valve is used to control applied vacuum to the well, with ports on either side of the valve allowing measurement of system pressure and well pressure. The well-head includes a device for flow measurement, typically either a pitot tube or an orifice plate. Pressure measurement devices, most often in the form of a differential pressure transducer included as part of a mobile gas-monitoring meter, are used to measure pressure drop across the device, which can in turn be used to calculate flow rate (see Fig. 16.7). A port for temperature monitoring or an in-line temperature gauge is provided, as temperature is one of the parameters used in the flow rate calculation.

At sites using one or more regulating stations for gas control, measurement of multiple wells occurs on an automatic basis at user-specified intervals using a mass

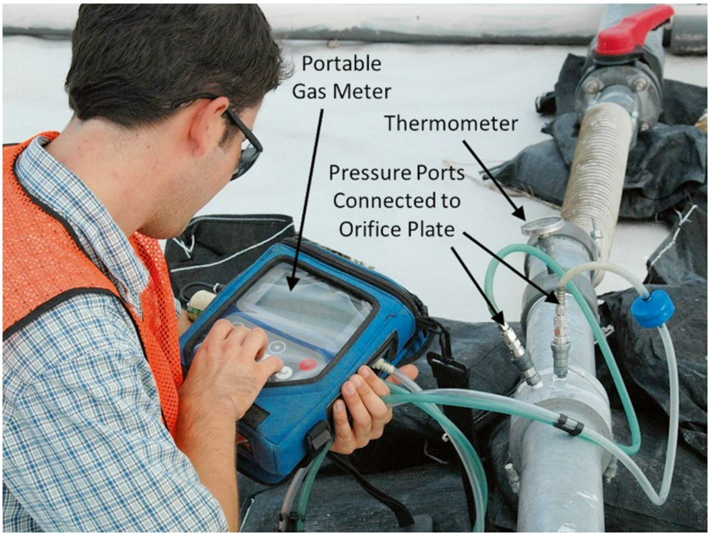

Fig. 16.7 Measurement of landfill gas flow rate as a wellhead using a portable meter

flow measurement device. These systems will normally include instrumentation for gas composition measurement. The station utilizes a programmable logic controller that allows establishment of set points to adjust applied vacuum, typically in response to low CH_4 and/or elevated O_2 concentrations. These measurements will typically be data logged. At blower/flare stations or gas-to-energy systems (where present), combined gas flow rate from the entire collection system is measured using mass flow meters, with flow rates and cumulative volume continuously recorded at specified intervals. Figure 16.8 provides an example of such data, showing both total volume of methane collected over time and the percentage of methane for a landfill practicing liquids.

16.4.2 Surface Emissions

Several methods are available for monitoring gases at the landfill surface. Some regulatory programs require surface CH_4 emissions monitoring on a routine basis (typically four times per year) in areas where gas is being actively extracted. The instrument used for this monitoring normally consists of an flame ionization detector (FID) or a photoionization detector PID and the concentrations of interest are much lower than that produced within the landfill (e.g., 500 ppm is the US-specified surface concentration limit). This monitoring approach can provide insight regarding areas where high gas production rates are occurring and/or poor GCCS performance.

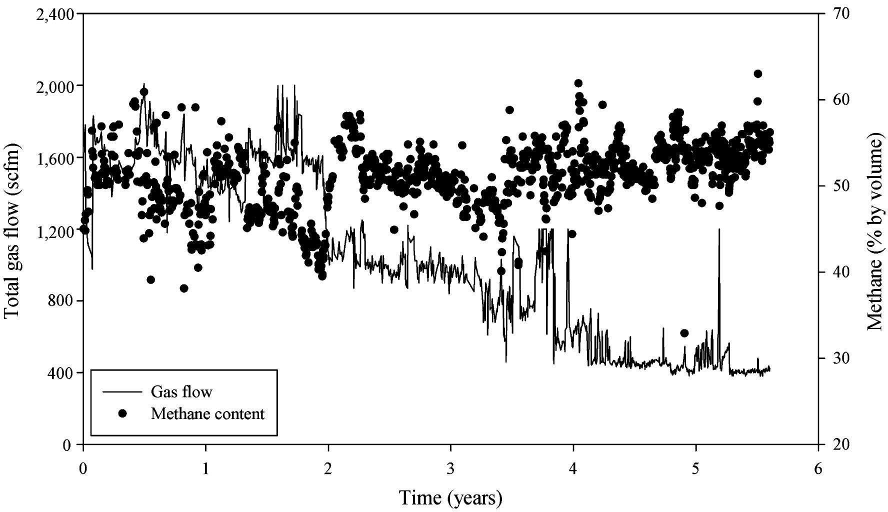

Fig. 16.8 Gas flow rate and percentage methane measured over time at the gas collection station of a landfill practicing liquids addition

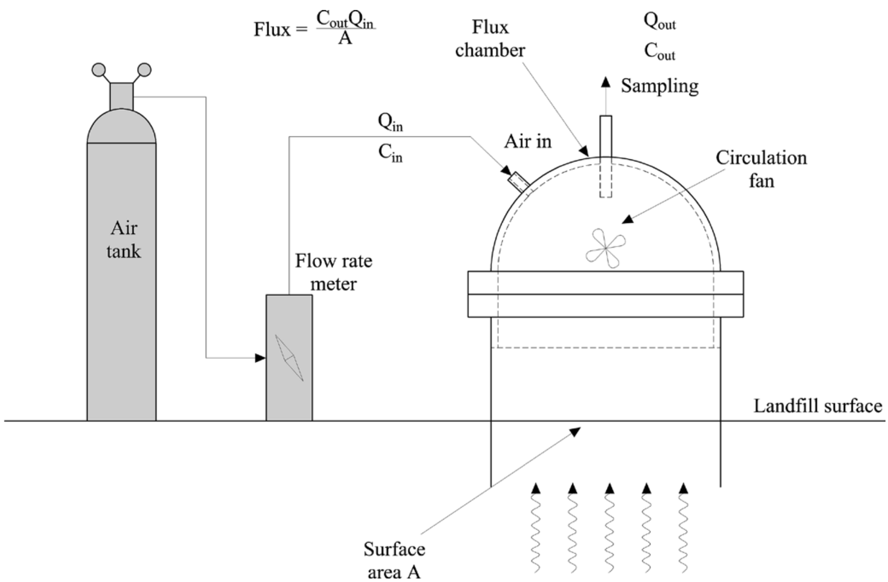

Fig. 16.9 Basic setup of flux chamber use for measuring landfill surface emissions

Flux chambers (sometimes referred to as flux boxes) have been used at several landfills to assess surface emissions (Reinhart et al. 1992); these devices measure the flux of gas emitted through the surface area into the chamber (Fig. 16.9). These instruments are typically used for research purposes and can provide more robust data in a specific area when compared to surface monitoring using an FID or a PID;

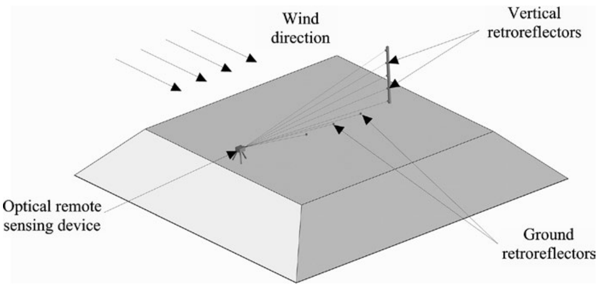

Fig. 16.10 Illustration of open path technique for measuring surface emissions at a landfill

however, high spatial variability across the landfill surface has been observed when using flux chambers (Borjesson et al. 2000; Spokas et al. 2003).

Other techniques have been developed to measure the surface emissions flux from large landfill surfaces. The open-path FTIR technique involves sending a series of energy waves over the surface of landfill, reflecting them back, and measuring a resulting change in the wave that corresponds to the amount of a particular gas in the air above the landfill (Fig. 16.10; US EPA 2006b; Thoma et al. 2010). These measurements can be converted to an emission rate or flux. This technique is somewhat expensive, but may provide a better estimate of emissions over a large area compared to single-point flux box measurements. This technique has been most commonly applied for measuring landfill CH_4 surface emissions.

16.5 Chemical Composition of Gas

Measurement of CH_4 and CO_2 produced from biological decomposition, coupled with N_2 and O_2 to assess the occurrence of atmospheric air in an active GCCS, provides necessary data on conditions within the landfill and performance of the GCCS. Thus, measurement of the concentration of LFG constituents is performed routinely. Since most LFG sources are assumed to be saturated with moisture, the water vapor content is not routinely measured. Trace chemicals of importance are also measured on occasion to address regulatory needs or site-specific issues.

16.5.1 Bulk LFG Constituents

Measurement of gas composition involves analysis of the major components (CH_4, CO_2, O_2) in the field, measurement of trace components in the field, or collection of a sample that is subsequently sent to a laboratory for analysis. Field devices are equipped with an infrared sensor with frequency calibrated to detect CH_4 and CO_2.

These field devices typically are also equipped with sensors to measure pressure, flow, and/or temperature at GCCS well heads. N_2 concentration is not directly measured in the field, but is often assumed as comprising the "balance" after subtracting the concentration of CH_4, CO_2, and O_2, which are normally measured directly. Samples for laboratory analysis are collected in non-reactive sampling bags (e.g., Tedlar) or passivated stainless steel canisters. Both CH_4 and CO_2 are typically analyzed in the lab using a gas chromatograph (GC) equipped with a (FID), while O_2 is typically measured with a device equipped with an electrochemical sensor.

16.5.2 Trace Constituents

A number of trace chemicals are present in landfill gas and Table 16.4 provides a summary of many trace chemical classes. Trace gases may be of concern for a variety of reasons. Hydrogen sulfide (H_2S) is a problematic gas because of strong odor and public health issues when emitted to the atmosphere, and when collected high levels of H_2S can create problems with energy production equipment and other mechanical gas moving devices because the gas can transform to sulfuric acid and prematurely wear these components. Siloxanes are a group of chemicals that are of concern at landfills with energy production equipment, as these chemicals can build up on gas moving equipment and their oxidation product, silicate, can cause premature wear, similar to H_2S.

Another group of chemicals that may be measured is non-methane organic compounds (NMOCs). This is a group of compounds that have the potential to cause a variety of human health and environmental impacts. These compounds cause the formation of acid rain, contribute to global warming, and lead to other adverse effects. The amount of NMOC emissions is one of the factors that dictate whether an MSW landfill is required to collect actively LFG in the US. Another trace constituent that can be measured is carbon monoxide (CO). The presence of CO can suggest that subsurface oxidation or smoldering is occurring; this is a concern of landfills with active GCCS (see Chap. 13) and landfills where air addition is practiced (see Chap. 14). Although researchers have not established CO levels that

Table 16.4 Examples of trace LFG constituents commonly measured and associated measurement techniques

LFG chemical or chemical group	Measurement option(s)
CO	Colorimetric detector tube (field), electrochemical cell (field), also laboratory analysis
H_2S	Colorimetric detector tube, electrochemical cell attachment to LFG analyzer (field), or laboratory technique (e.g., thermal conductivity detector)
NMOCs	Laboratory analysis (sample collection in passivated stainless steel canister)
Siloxanes	Laboratory analysis (different sample collection methods include collection in passivated stainless steel canister and the use of in-line midget impingers)

definitively suggest the presence of smoldering within the waste, concentrations on the order of several hundred ppmv could indicate potential issues.

Field measurement of H_2S can be conducted using commonly used landfill gas analyzers equipped with an electrochemical cell or pod that measures H_2S. The cell requires periodic re-charging. Colorimetric detector tubes are a simple method, and are commonly used for the measurement of H_2S or CO concentrations. Once a LFG sample is collected in a non-reactive sample bag, the sample is pumped through a glass tube containing a reactive medium that changes color when exposed to a specific gas. The concentration is subsequently read directly on the tube. Laboratory measurements of trace gases may also be used as some lab techniques provide a more robust or accurate measurement technique.

16.6 Landfill Volume, Density, and Topography

16.6.1 Surface Topography

Professional surveyors use a variety of techniques to measure the surface elevation of landfills and surrounding property and infrastructure. These include manual measurements using a transit and staff along with measuring tapes. More common today is GPS-enabled survey equipment that uses satellite data to measure elevation and location (Fig. 16.11). In all cases, an appropriate benchmark of known elevation must be established and referenced. This benchmark should be a stable area not

Fig. 16.11 Use of GPS technology to measure surface elevation and location

prone to change. Areal surveying technologies (e.g., photogrammetry using a light aircraft) are now also commonly employed at landfill sites. Recently, the use of unmanned air vehicles (also referred to as drones) have been proposed as a novel, low-cost approach to obtaining photogrammetric survey information at landfills, but regulatory questions regarding civil applications of drone use are still in development, thus more widespread use of this technique may not occur for some time.

16.6.2 Density (Specific Weight) Estimation

Density relates the mass of a media to the volume it occupies; specific weight relates the weight of a medium to volume (see Chap. 5 for a description of the relationship between the terms). Specific weight is an important parameter to track at landfills as it reflects the efficiency of airspace utilization for a landfill unit. Most commonly, the specific weight is estimated by measuring the weight of incoming waste loads deposited in the landfill and estimating the volume of utilized airspace capacity in that same time frame based upon surface topography data. This type of measurement, however, is not the true value for the landfilled waste materials as it does not include the weight of the cover soil (which is not normally measured in routine landfilling operations). Another complicating factor is that waste volume changes (settles) through both physical and biological mechanisms (see Chap. 5). As described in Chap. 5, it is common to track the apparent density (or specific weight) at a landfill site—this represents the mass (or weight) of disposed waste per volume of landfill space (waste plus soil) and is commonly used in landfill capacity projections.

Specific weight or density can also be calculated by excavating or augering material from a landfill, weighing the removed material, and applying a measured or estimated volume of the excavation (Zekkos et al. 2006). Borehole measurements using this technique have found, as expected (see Chap. 5), that waste mass (waste plus soil) densities increase with depth within the landfill and increase with decomposition (as the heavier soil becomes more prominent; Jang 2013).

16.6.3 Settlement Measurement Techniques

As biological landfill stabilization proceeds, mass is converted from organic material in the waste and leachate into gaseous products, primarily CH_4 and CO_2. The loss in mass from the landfill system corresponds to a loss in landfill volume, manifested as a decrease in landfill height. Measurements of landfill settlement rate provide an indirect indication of the state of waste stabilization activity, although settlement may not occur linearly with time; furthermore, settlement will continue even after most of the biological stabilization process has occurred (see Chap. 5).

Waste settlement is most commonly monitored by measuring the elevation of the landfill surface using the techniques previously described. This approach works

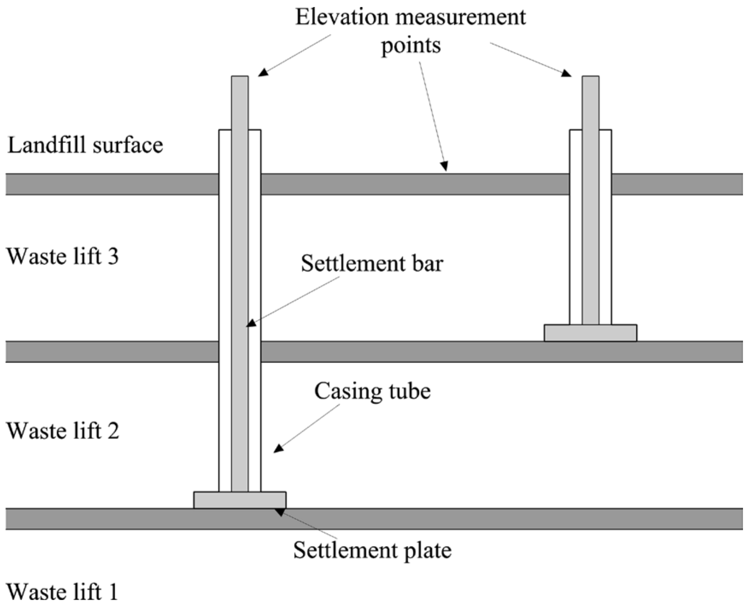

Fig. 16.12 Illustration of settlement plates used for measuring elevation changes of points within a landfill

well for closed or inactive landfills that have reached a point in operation where surface conditions no longer change, or change slowly. At a site where surface topography continues to evolve through waste filling or other changes (e.g., soil placement), routine survey techniques may have limited utility for tracking temporal settlement unless these additional material surcharges are specifically tracked and subtracted from previous measurement points.

Several approaches have been utilized for tracking the elevation of locations buried within a landfill even as waste placement continues. Settlement plates have been used at some sites (e.g., Jang 2013), and consist of flat plates connected to vertical rods (settlement bars) that are placed on the desired location at a point on the landfill surface. Prior to placing waste on top of the plates and around the rods (which must be performed very carefully to avoid damage), a solid pipe (casing tube) is installed over the rod so that the in the future, settlement measurements at the top of the rod correspond directly to that occurring at the top of the plate (Fig. 16.12). When several settlement plates are installed at different depths in the landfill, measurements of elevation at the top of each rod can be used to estimate the settlement of different layers.

Electronic instruments can also be used to measure elevation changes at specific points within a landfill. Some vendors manufacturer transducers designed to be placed in subsurface environments to measure elevation changes. In some cases the device is permanently located in a buried pipe or similarly protected location, while in other cases the devices are periodically inserted into and moved through a length

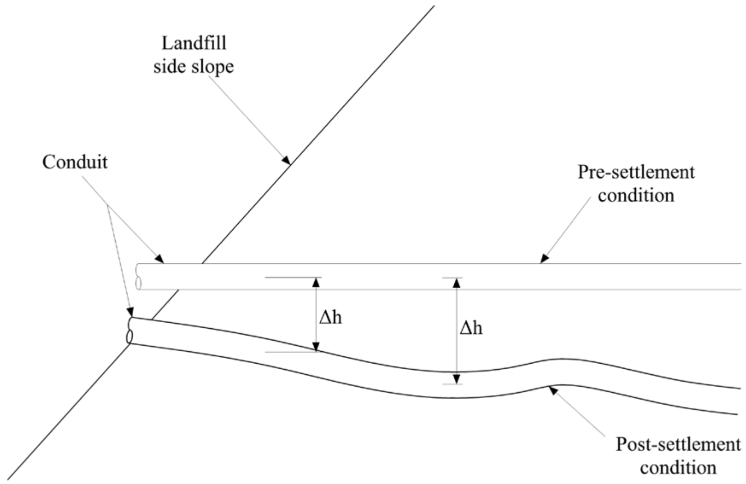

Fig. 16.13 Illustration of buried conduit application for measuring internal elevation changes

of buried pipe. Figure 16.13 illustrates how elevation changes in a buried pipe could be used to measure the settlement of the underlying media (waste and/or soil).

One type of instrument that could be used, either as a permanent device or one that is moved through a buried conduit, is a pressure transducer with a measurement tip connected to an external reservoir of liquid maintained at a known or measured elevation outside the landfill (the reservoir would require refilling as needed). The transducer provides a measurement of the difference in elevation between the transducer location and the reservoir surface (Fig. 16.14a). An inclinometer is another type of instrument useful for measuring elevation changes when passed through a conduit. As the inclinometer is moved through the conduit, the angle of the instrument is recorded as a function of location within the conduit (Fig. 16.14b). When the resulting elevation profile is compared to a previous profile from an earlier time, the settlement occurring over that time increment can be calculated.

16.6.4 Slope Measurements

Slopes are routinely measured as part of surface topography surveying. Other slope measurements might also be used to assess the slopes of pipes that are constructed to provide gravity drainage and to monitor side slopes for potential movement. As described in Chap. 10, both the base grade of a landfill liner and the collection pipes/trenches are sloped to provide gravity drainage of leachate to low points in the landfill (for removal). LCRS pipes are often inspected and cleaned. The slopes of theses pipes can be assessed using instruments such as inclinometers or settlement cells as described in the previous section. In Chap. 12, the importance of slope stability was

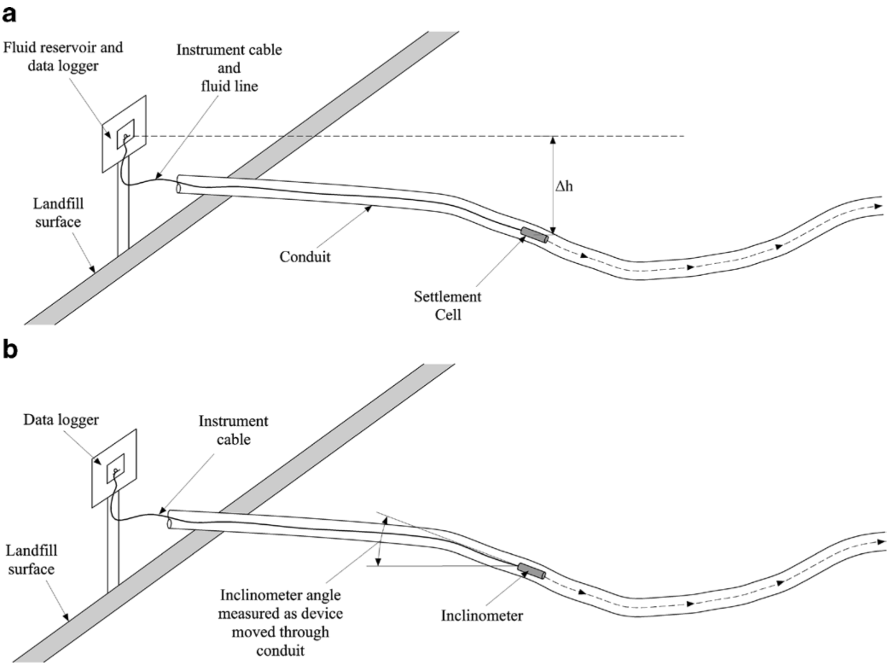

Fig. 16.14 Methods for measuring elevation (and settlement) using a buried conduit. (**a**) Pressure transducer connected to an external fluid reservoir and (**b**) slope inclinometer

described. While no instrumentation replaces routine topographic surveying and physical inspections for deformation and cracks, inclinometers can be installed on slopes to provide a continuous measurement of slope angles and to track slope changes with time. For more rapid measurements at discrete points, a hand-held slope indicator device may be used or an application may be downloaded and used on a smartphone equipped with an accelerometer.

16.7 Excavated Solids Properties

A direct method that can be used to examine the relative state or degree of decomposition of landfilled waste involves the collection and analysis of physical samples. This technique has been utilized at a number of facilities practicing sustainable landfilling (Townsend et al. 1996; Mehta et al. 2002; Kelly et al. 2006; Kim and Townsend 2012). The difficulty with this approach is that waste sample collection is an intrusive, expensive, and time-intensive operation. Most methods for collecting a waste sample involve auguring into the landfill with a mechanical drill rig and retrieving samples from a specific depth; multiple samples from different depths can be collected from the same borehole. Considerations for developing a solids sampling plan include the number of samples desired, the location of the samples, the mass of samples needed for analysis, and cost of the collection procedure. A key issue to consider when developing a sampling plan is determining how best to obtain samples representative of the landfill location targeted and obtaining a statistically significant number so that observations or conclusions drawn from the solids analysis are valid.

16.7.1 Solids Collection Techniques

Traditional soil sample collection techniques, such as split spoon samplers or Shelby tubes, do not work well with waste, unless the waste has a high soil content and/or is mostly degraded. Researchers and practitioners have used several different auguring techniques. Large diameter bucket augers or rotary augers, those used for the excavation of boreholes for constructing gas wells, (typical diameters ranging from 0.5 to 1 m), are often employed; in this case waste samples can be collected as part of LFG well installation. In the case of bucket augers, waste is removed from the auger boring in continuous batches as the gas well is constructed, providing a reliable method for collecting representative samples. Others have collected solid samples using smaller diameter flight augers, with samples collected from the cuttings. Close attention must be paid to ensure that samples represent the area targeted.

Experience with small diameter flight augers (10–15 cm) suggests that prior to collecting a sample, evacuation of the borehole by rotating the auger in place must be performed to remove loose material that may otherwise collapse from upper layers within the borehole (Kim and Townsend 2012). After removing loose material, the auger is rotated into the hole in a manner to minimize solid disturbance, and after reaching the desired depth, the auger flights are pulled up without rotating and samples are collected from the flights after removal from the hole (Fig. 16.15).

Collection using larger diameter augers offers the advantage of greater masses of samples representative of specific locations within the landfill. The biggest disadvantages to this technique are the larger cost and the greater disturbance to the landfill (more excavated waste to manage, large holes remaining that may require filling). Smaller diameter augers are less expensive and can allow for sample collection from more areas because the technique proceeds more quickly, but the sample mass collected from a given area is smaller. Experience and skill are needed to ensure that the samples retrieved are representative of the targeted area. In both cases, the presence of large zones with heavy moisture can make collecting representative sample difficult as liquids and wet soil and waste will flow into the borehole from distances away from the hole where these liquids are present. Boreholes remaining after excavation represent a pathway for future gas and liquids migration unless they are carefully backfilled with a low permeability soil or grouted with cement.

Fig. 16.15 Collection of landfilled solids samples from an open flight auger

16.7.2 Solids Analytical Procedures

A variety of monitoring parameters have been used to characterize solid samples removed from landfills; see Table 16.5 for a summary. The samples typically require processing prior to analysis. A first step is to dry the samples, which if conducted appropriately, can be also used to measure gravimetric moisture content. Most analytical techniques require relatively small sample masses, thus sample homogenization and size reduction is necessary. One approach is to grind the entire sample with the exception of large pieces of rock and metal; in this case, the entire sample (except rocks and gravel) is subjected to analysis (Mehta et al. 2002; Kelly et al. 2006). Another approach is to first process the sample by component and size, carefully measuring the weight contribution of each fraction, and then size reducing targeted fractions for further analyzed. This approach requires that a weighted average be calculated based on the results of each of the individual sample fractions. This approach was employed in waste sampling conducted to assess the effect of liquids addition on waste stabilization by Townsend et al. (1996) and Kim and Townsend (2012).

Table 16.5 Analytical measurements utilized to characterize excavated landfill solids

Parameter	Description
Gravimetric moisture content	Excavated samples are dried in an oven and the difference in weight between initial and dried conditions is used to calculate weight-based moisture content
Composition	The weight of different waste components, as well as cover soil, are measured after physical separation to determine composition. Screens may be required to separate different fractions of soil and degraded waste from other identifiable components
Volatile solids	Dried samples are ashed in a muffle furnace to remove volatile organic matter. This measurement provides a surrogate for the percentage of organic matter present, though plastics will be included in the results
Lignin, cellulose and hemi-cellulose	Major components of paper, wood, and biogenic textile products are comprised of cellulose, hemi-cellulose and lignin molecules. The content of these chemicals in a sample can be determined using several different chemical analytical methods. Since cellulose and hemi-cellulose are more prone to biodegrade than lignin, the relative ratios of the chemicals provide an indication of the degree of stabilization
BMP	Samples, or subsamples processed to remove non-biogenic OM are incubated under anaerobic conditions to measure a methane yield, lower CH_4 yields (normalized to biogenic VS) indicate a greater degree of stabilization

In addition to measuring moisture content, the objective of most excavated landfill sample analysis is to determine the degree to which samples have been degraded or stabilized. Researchers have used several different analytical methodologies to characterize waste samples for this purpose. Volatile solids (VS) content measurement provides an estimate of OM in a matrix. In this method, dried samples are placed in a muffle furnace at 550 °C for several hours, and the weight loss represents the mass of VS. The VS of a waste sample will include not only biodegradable materials, but also non-biodegradable OM (e.g., plastics). Thus, while VS will decrease with stabilization, waste samples that are stabilized may still have a relatively high VS content.

The biochemical methane potential (BMP) assay measures the amount of CH_4 which could be produced from a media under idealized anaerobic microbial conditions (Owen et al. 1979). This test has been used as a means of assessing energy production potential for different wastes subject to anaerobic decomposition (e.g., Owens and Chynoweth 1993), but it can also be used to assess the extent of microbial stabilization (Wang et al. 1994). In the BMP assay, samples are size reduced and placed in serum bottles (or similar containers), mixed with a nutrient solution and microbial seed, flushed with nitrogen to remove air, and incubated at elevated temperatures. Methane volume is measured over time until most of the methane has been produced (60–90 days) and an ultimate methane yield is calculated. Figure 16.16 presents the results of methane yield analysis for landfilled waste excavated before and after liquids addition (Kim and Townsend 2012).

Since most biodegradable organic matter in MSW is plant-based, measuring the relative occurrence of cellulose and hemi-cellulose (which are expected to decompose) compared to lignin (which is not expected to decompose) has also been used

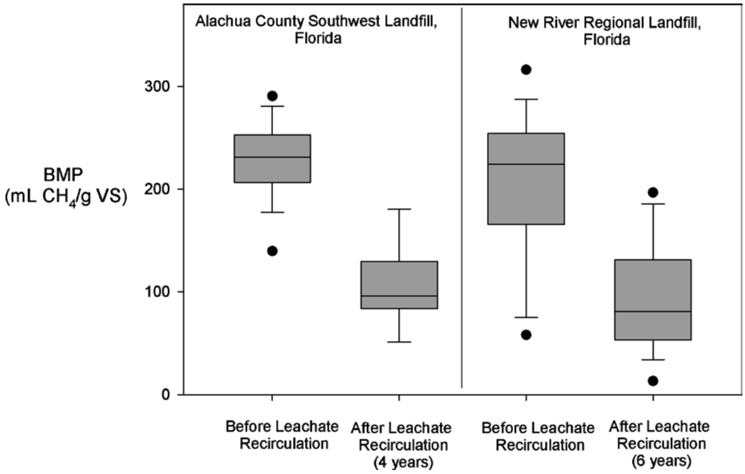

Fig. 16.16 Methane yield results using BMP assay for excavated landfill samples from two facilities

a techniques for assessing landfill waste stabilization. The ratio of cellulose and hemicellulose (C+H) to lignin (L) decreases with time. Analysis of these constituents usually involves contacting the sample with an acid solution to dissolve C+H (Barlaz 2006). The VS content of the remaining solids (once plastics are removed) is considered lignin, and the acid reaction is analyzed for component sugars of C+H. Figure 16.17 presents data from several studies where both BMP and cellulose and/or lignin analyses were performed. Figure 16.17a shows BMP versus cellulose the Yolo County (Mehta et al. 2002) and Outer Loop landfills (US EPA 2006a) (see Chap. 4) and over a dozen landfills studied by Virginia Tech University (Bricker 2009). Figure 16.17b compares BMP versus (C+H)/L for samples from the Yolo County and Outer Loop landfill sites.

16.8 In Situ Moisture, Temperature, and Pressure

16.8.1 Temperature Measurement

The microbial processes responsible for waste decomposition are exothermic; temperatures within a landfill may thus be elevated relative to ambient temperatures, especially when biologically activity is at a maximum. As described in Chaps. 13 and 14, aerobic microbial respiration releases more heat than anaerobic systems, and thus temperature measurement is of critical importance during or at landfills with active gas extraction to prevent subsurface oxidation or fires from forming. Internal landfill temperatures have been reported in a multitude of studies where it can be seen that they can reach as high as 170 °F or more (Townsend et al. 1996; Powell 2005; Yazdani et al. 2010; Hanson et al. 2010).

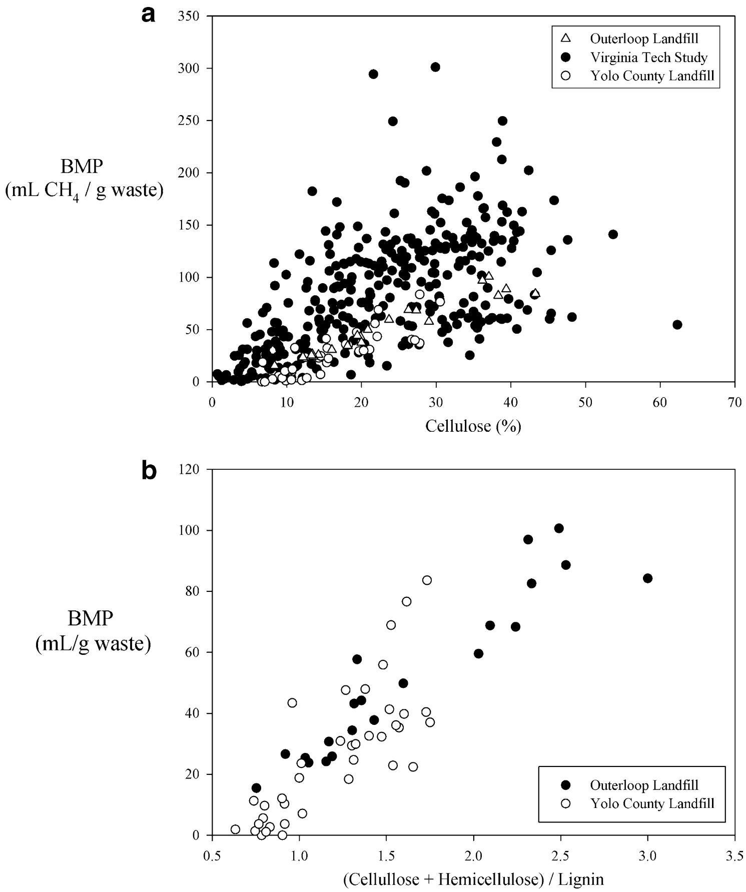

Fig. 16.17 (**a**) BMP methane yield results as a function of cellulose, (**b**) BMP methane yield results as a function of the ratio of cellulose plus hemicellulose to lignin ((C+H)/L)

Measurement of internal temperatures in landfills can be accomplished with several different devices. Many of the devices described in previous sections (e.g., LFG analyzers) include a temperature measurement probe integrated into the device. Additionally, pressure transducers may have temperature measurement capability, thus instruments installed to measure pressure may also provide a reading for temperature. Devices specifically designed to measure temperature can be placed in the landfill, either as it is filled, or in augured boreholes after the landfill is filled.

The most common devices for temperature measurement in landfills are thermistors and thermocouples. Thermistors are resistors with a resistance that is highly dependent on temperature. Thermocouples consist of two shielded wires of different metal composition; if the ends of equal length of these two wires are connected, a voltage is created which can be measured at the connected ends of the wires. Although thermistors and thermocouples are manufactured to measure a wide range of temperatures, temperature measurement devices at landfills must be selected to measure the range of expected temperatures. For example, extension-grade Type T thermocouple wire is commonly used at landfills since it has a range of −60 to 100 °C (−76 to 212 °F).

16.8.2 Moisture Measurement Techniques

Given the considerable importance of moisture in advanced landfill operations, a considerable effort has been devoted to developing techniques that allow the in-situ measurement of moisture inside the landfill. While not common practice, several landfill sites have installed devices to provide the operator an indication of moisture content spatially within the landfill and over time. Soil scientists and agronomists have developed and applied several different types of in-situ moisture instruments for measurement of soil water and movement. Many of these have been extended to measure moisture in landfilled waste. Several approaches have been examined (see Table 16.6), including those that record measurements from the surface of the landfill, measurements determined by tracking the movement of gases through landfilled waste, devices placed into boreholes within the landfill, and instruments buried within in the landfill. Imhoff et al. (2007) reviewed a variety of techniques for measuring moisture content in landfills. A summary of typical techniques is presented in Table 16.6.

Neutron probes have been commonly used to measure the moisture content of soils. In this technique, access tubes are installed in the media of interest and a neutron probe is lowered into the tube. Neutrons emitted from a radioactive source present in the instrument are emitted into the surrounding soil. The neutrons are slowed as a result of collisions with surrounding molecules; water causes a slowdown greater than most media. The cloud of neutrons around the probe can be measured with a radioactive counter (built into the probe), and thus an estimate of surrounding moisture content can be made with an appropriate calibration curve.

Table 16.6 Common techniques for measuring in situ moisture content

Measurement approach	Technique description
Buried instruments	Instruments such as electrical resistance or time domain reflectometry sensors can be buried in the waste, either as the waste is filled or after placement using excavation or drilling, and used to assess in-situ moisture content. Cables connect the buried instruments to a power source and monitoring equipment external to the landfill
Borehole devices	Neutron probes can be lowered into boreholes installed in the landfill to estimate the moisture content of the surrounding waste at different depths
Surface techniques	Geophysical techniques such as electrical resistivity tomography utilize measurements of electrical current passed through the waste to assess locations of zones with different moisture levels
Gas tracers	Gas tracers passed through the landfilled waste will travel at different rates, and since this is heavily influenced by moisture levels, methods such as PGTT can be used to estimate moisture content over large landfill areas

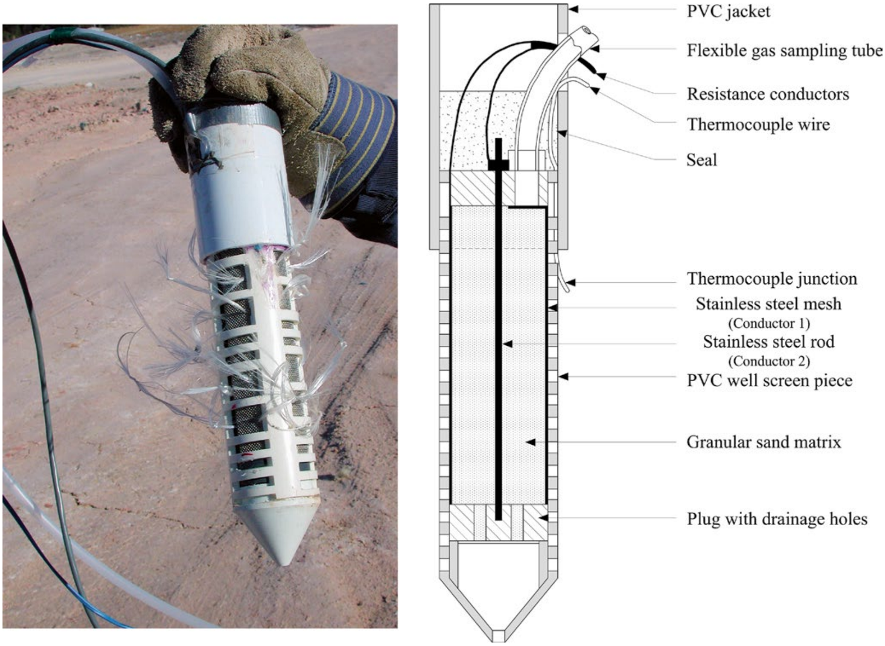

Fig. 16.18 Resistivity-based moisture sensor utilized by Gawande et al. (2003) and Kumar et al. (2009)

Yuen et al. (2000) examined the use of neutron probes at a landfill in Australia practicing leachate recirculation. Seven aluminum access tubes were installed and a neutron probe was used to measure surrounding moisture content using a calibration curve produced using sand. While the technique was found successful at assessing relative moisture levels, the technique did not provide a measurement of actual waste moisture content.

Gawande et al. (2003) reported on an electrical resistance moisture sensor for use in landfills. A stainless steel rod embedded in a granular matrix surrounded by stainless steel mesh was used; electrical resistance across the granular media decreased as moisture content in the media increased (Fig. 16.18); a thermocouple wire was included with the sensor for temperature measurement. Calibration curves (a function of temperature and solution ionic strength) were developed to relate resistance to surrounding moisture content. Kumar et al. (2009) reported the results of the field-scale application of these sensors after 6 years of operation. The sensors provided a reasonable estimate of local moisture content when appropriately calibrated, but did not provide representative estimates of the landfill moisture content as a whole. This was concluded to be a result of preferential channeling of liquids to sensor location, likely a result of the boreholes used to install the sensors.

Time domain reflectometry (TDR) sensors work on the principal that the bulk dielectric permittivity of a medium is related to its moisture content. The dielectric permittivity of water is much greater than MSW; when an appropriate calibration curve is developed, TDR probes installed within landfilled waste can be used to estimate moisture content (Masbruch and Ferre 2003; Li and Li 2011). Li and Zeiss

(2001) used waste from loads of residential garbage to pack columns that included TDR probes; calibration curves were developed by adding incremental volumes of water to increase moisture content. They evaluated the effects of waste properties and leachate ionic strength and concluded TDR to be a viable method for measuring in-situ moisture content in MSW. Jonnalagadda et al. (2010) compared in-situ resistivity and TDR sensors at an operating landfill where liquids addition was practiced. While both technologies were observed to measure transient moisture changes in the landfill, magnitudes of moisture content measured were higher than those predicted using mass balance. The resistivity sensors were found to be less expensive, easier to install, and more reliable.

Several researchers have examined the use of geophysical techniques such as electrical resistivity tomography (ERT) for assessing the presence of moisture in landfills (Gueerin et al. 2004; Clément et al. 2010; Hossain et al. 2011; DeCarlo et al. 2013). In ERT, electrical resistance between electrodes at different spatial locations is measured with results providing information regarding the media in between the electrodes, including the presence of moisture. While ERT can utilize boreholes, where it has been particularly attractive for landfills is as a surface geophysical technique. Surface ERT can provide an image of subsurface conditions and locations of elevated moisture.

The partitioning gas tracer test (PGTT) provides an estimate of moisture content in a region of landfill between two points used for gas tracer injection and gas extraction (Imhoff et al. 2003; Han et al. 2006). In using PGTT, conditions in the landfill are created in which the addition and recovery of two different gas tracers are measured and compared (for example, between two different wells). The difference in travel time of each tracer can yield an estimation of the degree of saturation, and with an estimate of waste density and porosity, can be used to estimate moisture content. Knowledge of temperature in the area of the test is necessary, and while ionic strength of the pore water affects results, this impact have been found to be small for some tracers.

With the exception of geophysical techniques such as surface ERT, a primary challenge in the use of buried moisture sensors is installation in the landfill without damaging the sensors and the associated cables, and without creating conditions around the sensor that would encourage short-circuiting of liquids to the sensor. The two options for installation include placement as the waste is deposited and compacted in the landfill and installation after waste placement by excavating (or drilling) into the waste.

Placement during landfill operation involves excavating a small area of the surface of waste lift, placing the sensor in the excavation, and then backfilling around the waste with an appropriate protective material, and then covering with waste; waste filling would proceed and eventually new waste would be placed on top of the instrumented area. The wires are routed to an appropriate terminal point, normally in trenches excavated on the surface, possibly in protective conduit. Efforts should be considered to minimize any preferential fluid flow along the wires and/or conduits back to the sensor. This approach does not require any specialized equipment for installation and minimizes the potential for preferential channels that might otherwise short-circuit moisture to the instrument. Because this approach occurs throughout the landfill operational period, however, it has a greater potential for interference with routine operations and damage from equipment and vehicles, and thus demands careful planning and coordination.

The second approach involves drilling into the landfill and placing the sensor, or a series of sensors in the borehole. In this case, the instrument cables will be run up to the top of the landfill and then connected to an appropriate monitoring point. This approach minimizes interference with normal landfill operations as it takes place after waste placement has been largely completed. An outside contractor will normally be required as drilling into the landfill will be necessary. One of the biggest challenges of this approach is the natural channel for moisture short-circuiting resulting from the borehole. It is imperative that areas of the borehole not occupied by the sensor be backfilled with a low permeability material such as clay or grout.

16.8.3 In Situ Pressure Measurement

Internal pressures, either pore pressure (the combined liquid and gas pressure in the pore space) or the pressures exerted by the weight of the landfilled mass, have been measured at several landfills. This type of measurement normally utilizes electronic pressure transducers buried within the landfill. These transducers are connected via a cable to an external power source and an output measurement or recording device.

Pore pressure readings from buried transducers can be used to assess moisture (Kadambala et al. 2011) and gas (Ko et al. 2013; Larson et al. 2012) movement and magnitude and thus help assess effectiveness of liquid or air addition and gas extraction systems. Important to recognize in the interpretation of such data is that the measured pressure represents a combination of both liquid and gas pressure. For example, pressure transducers have been proposed as a measurement tool for liquid head on the liner; the resulting pressure, however, constitutes the depth of liquid on the liner plus the gas pressure above the leachate.

Pressure transducers designed to handle burial under applied loads should be specified. Pressure transducers designed for submersion in water may not be able to withstand the forces exerted by the overlying waste mass. Installation can be difficult, both in terms of appropriate burial to prevent damage, securing cables in a manner to avoid damage, and preventing preferential paths for fluid flow that might influence the results. The challenge of short circuiting of liquid and gas flow is similar to that discussed for the installation of buried moisture sensors.

Larson et al. (2012) installed pressure transducers within a leachate recirculation trench and at multiple points away from the trench. Prior to liquids addition, changes in internal gas pressure in response to barometric pressure fluctuations were used to estimate waste permeability. Later, these transducers were used to examine pressure changes as a result of liquids addition. In this case, the transducers were installed during waste filling. The trenches were first excavated, then sensors encased in a sand-filled cloth bag were placed in the excavation and wires were placed in electrical conduits day-lighted out the side of the landfill (see Fig. 16.19). Waste was carefully

Fig. 16.19 Pressure transducers for measuring internal landfill pore pressures installed by burying in sand-filled bags within the waste as filled

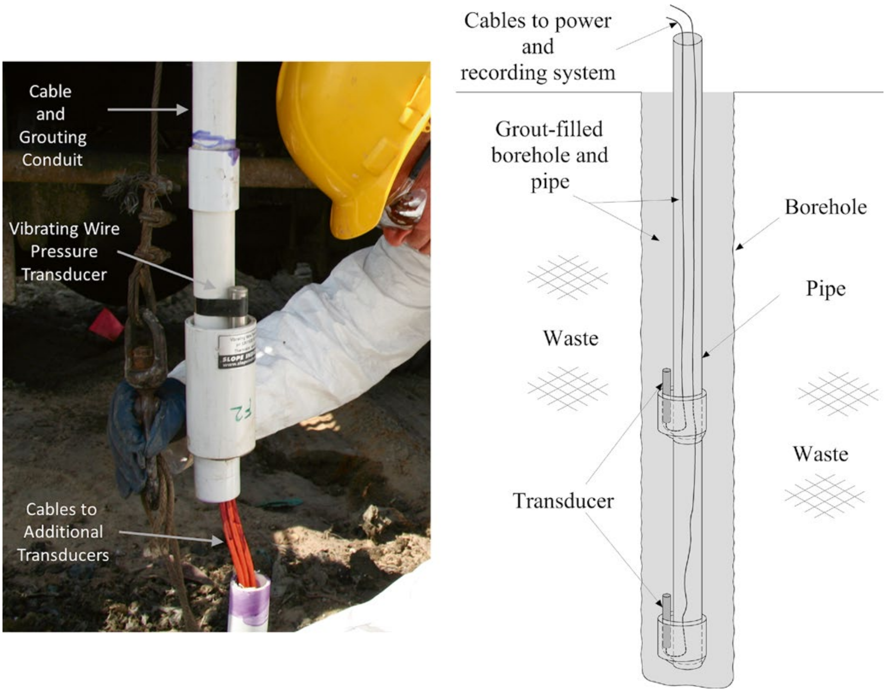

Fig. 16.20 Pressure transducers for measuring internal landfill pore pressures installed by placement in grouted borehole

placed on top of the excavation until enough overburden material was present to avoid crushing of the transducer by heavy equipment.

Kadambala et al. (2011) placed pressure transducers at different elevations radially surrounding a vertical liquids addition well. Results were used to examine moisture and pressure distribution, and provided insight on waste anisotropy (i.e., the degree of directional dependence in terms of permeability). Transducers were placed in existing waste by excavating a borehole and inserting the instrument (Fig. 16.20). In this case, the transducers were attached to the side of a pipe and lowered into an augured hole with the wires exiting the hole through the center of the pipe. To prevent short-circuiting, the hole was then filled with a bentonite-cement slurry.

Pressure transducers can also be configured to measure the total weight resulting from overlying landfill material (overburden pressure). Total earth pressure cells (TEPC) consist of pressure transducers connected to round, flat plates containing a hydraulic fluid. The greater the overlying weight of the material above the plates, the more pressure is exerted on the transducer. Timmons et al. (2012) examined changes in landfill weight (overburden pressure) with time by installing TEPC in the LCRS of a lined landfill. Changes in overburden pressure were observed with the placement of waste lifts.

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Chapter 17
Final Landfill Disposition

Abstract Decisions related to closure and post-closure of a landfill must be made at the design stage to project how the landfill will be configured and used after its disposal capacity is exhausted. This chapter discusses the ways that sustainable landfilling practices impact final disposition, closure, and post-closure planning and how operations throughout the landfill's life can be used in combination with sustainable landfilling technologies to create conditions at closure that are consistent with the site's sustainable landfilling goals. Important considerations such as identifying the termination of the post-closure care period (and how sustainable landfilling can affect the timing of post-closure care), how landfill reclamation and reuse can be incorporated as a viable strategy, and how the final site use and configuration can be impacted by sustainable practices during or after active operations.

Keywords Landfill • Bioreactor • Closure • Post-Closure • After-Care • Mining • Reclamation • Leachate • Gas

17.1 End of Life Considerations

When the disposal capacity of a landfill site, or a specific operational area of a landfill, is reached, several decisions regarding how to manage these areas must be evaluated. The term *closure* designates the process of finalizing waste surface configuration and installing infrastructure designed as the final containment and control system for this area of waste. *Post-closure care* (PCC) refers to activities performed to operate and maintain closed areas so that desired performance and environmental protection are accomplished.

Landfill operators at all facilities must plan for and implement closure and post-closure care, but when implementing sustainable landfill technologies, owners and operators have additional options to consider. This chapter reviews such considerations, starting with a description of typical closure procedures followed by a discussion of specific concerns and opportunities for landfill operators practicing liquids addition and rapid waste stabilization. One major issue is the determination of when landfill operation and activity are considered complete, such that post-closure maintenance and operation can be ceased, or at least reduced in frequency. As described

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in Chap. 3, a primary objective for some facility owners attempting accelerated waste stabilization is early completion of PCC activities. An additional topic is whether a landfill practicing sustainable technologies might not need to be closed in the same fashion as traditional disposal facility, but perhaps instead stabilized materials can be reclaimed at the end of operation and reused either at the landfill or off site.

17.2 Elements of the Closure and Post-closure Process

17.2.1 Closure System Design

While many existing landfilled elements will be integrated into the design of a landfill closure system (e.g., gas collection, leachate management, stormwater control), a substantial new feature is the final landfill cover, often referred to as a cap. The primary objective of a landfill cap is to minimize rainwater entry into the landfill as a means to reduce future leachate production. Another major function is to aid in the control of landfill gas. At some facilities, final cover systems are only installed after an entire landfill unit has reached its ultimate configuration and surface elevation. In other cases, distinct areas of the landfill unit are closed while operation in other areas continues. Considerations in determining which approach to pursue are discussed later in this chapter.

In general, two types of final cover systems are designed and constructed: the barrier layer approach and the capillary layer approach. A barrier layer cover system relies on a low-permeability material (e.g., geomembrane, compacted soil) to prevent liquids from entering the landfill. The cover must be designed so the intercepted rainwater is routed off of the surface of the landfill via overland flow, channelized flow, or subsurface flow above the barrier layer. This type of design is common in modern landfill operations and is often the technique specifically required by regulation. Barrier systems integrate well with a GCCS, as collected gases under the geomembranes or compacted soil can be extracted at designated exit points. The intent of a capillary layer system is to promote evaporation and transpiration of infiltrating rainwater. Under certain climatic conditions, if an appropriate thickness and gradation of soil is selected, along with selected vegetation, infiltrating moisture can be retained within the cover soil layer until it is removed through evapotranspiration. Figure 17.1 provides typical cross-sections of both cover system types.

Components of a cover system include layers of different soils (and possibly geosynthetics), each selected to serve a desired function. The final soil layer above the waste is applied and graded to smooth out uneven spots and to provide needed slope for moisture drainage. This layer is important to protect other cover system components from damage by underlying waste; excavated on-site soils are commonly used. Since gas will accumulate beneath a barrier layer (resulting in higher gas pressures and thus potentially high gas flux through the cap), a gas venting layer is constructed using coarse sand or a similar material that will not harm overlying geomembranes and promotes gas movement to designated extraction or exit points. Materials used for barrier layer construction are similar to those used for landfill

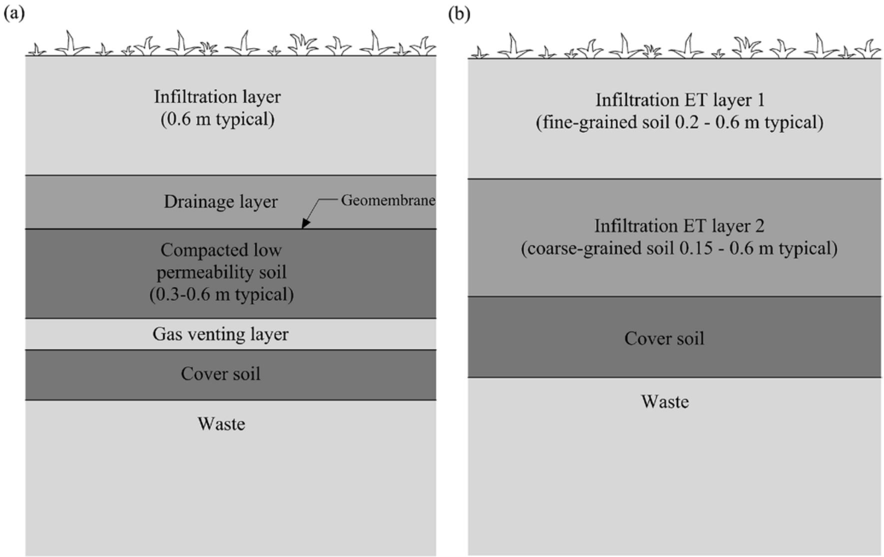

Fig. 17.1 Components of a typical landfill final cover system (**a**) barrier layer approach (**b**) capillary layer approach

Fig. 17.2 Barrier layer final cover system under construction

liners, including geomembranes, compacted soil, geosynthetic clay liners, or a combination of these materials. Figure 17.2 shows a landfill cover system being constructed using various barrier layer components.

When a barrier layer is included in the cover system, a drainage layer must be provided on top of the barrier to promote removal of infiltrating rainwater. If excessive water builds up above the barrier layer, leakage may result and the mechanical stability of the cover may be reduced. The top cover soil layer (infiltration layer) consists of soils that promote plant growth and allow for water retention and eventual evapotranspiration. Appropriate vegetation includes shallow-rooted plants consisting primarily of grasses that can help control erosion. A well-vegetated landfill surface is important to promote overland flow of water to stormwater collection points and to minimize soil loss. For a capillary layer system, the barrier layer is substituted with an infiltration layer designed with a sufficient depth and moisture retention capacity to promote necessary evapotranspiration.

17.2.2 Planning Consideration for Closure and Post-closure

A landfill closure plan should be developed with objectives to minimize further maintenance at the landfill site and leave the landfill in a condition so minimal environmental impacts occur. Some regulatory agencies require the landfill owner to prepare a closure plan as part of the initial plans for landfill operation. Table 17.1 summarizes elements of the closure and post-closure planning process, and includes a description of potential additional considerations for sustainable landfill activities.

A closure plan consists of many elements, but in general must include an overall description of the methods, procedures, and the processes to be utilized for closing the landfill, and should define the maximum volume of waste disposed of during the life of the site. More specifically, closure plans provide elements for identifying the final site configuration and topography, the site drainage plan, and the source and type of cover material. In addition, the closure plan should identify the closing sequence for phased operations, specify engineering procedures for the construction of needed infrastructure for post-closure maintenance, and outline monitoring procedures. Other elements include a description of landscaping and vegetative cover designs, and integration of landfill gas monitoring and control systems, leachate collection facilities, groundwater-monitoring systems, and surface water management.

A major part of planning for closure and post-closure is determining appropriate funds needed for such activities; it will typically be a regulatory requirement that availability of such funds be demonstrated prior to and during landfill operation. An accurate determination of closure funding will consider the operating life of the site and reasonable cost estimates of final cover materials, gas vents, and similar items. Necessary funds for closure and post-closure will be determined along with a funding mechanism to ensure that funds are adequate to close the facility when waste receipts stop and to provide for PCC and maintenance (additional discussion provided in Chap. 18). Upon closure, a landfill will require inspection by the appropriate regulatory agencies. Unauthorized access to the site should be controlled by the installation of a fence or other structure.

Table 17.1 Elements of landfill closure and post-closure

Closure element	Description	Potential issues with sustainable landfill practices
Final grading	Landfill surface is graded to achieve target final design elevations and slopes	More rapid and differential settlement may occur as a result of efforts to enhance waste stabilization
Capping system	An engineered series of soil (and probably geosynthetic) layers are constructed to provide a means to minimize water entry into the landfill	To achieve efficient gas collection under accelerated decomposition conditions, alternative cap types and placement timing may be required. Rapid settlement, as well as liquids entrance/exit issues, may also impact cap design
Gas control	Additional gas collection devices and collection infrastructure are installed prior to closure	Greater gas generation may necessitate additional or larger collection devices. Liquids removal from gas collection devices may be required
Leachate control	Infrastructure for removing, treating, and disposing leachate must continue to operate	LCRS and storage systems must accommodate the potential additional leachate production resulting from recirculation or to accommodate anticipated recirculation rates
Monitoring system installation	Equipment and instruments may be installed during closure to allow data collect in post-closure period	Sustainable landfill technologies often involve a greater degree of monitoring relative to normal landfill operation
Routine maintenance	Cover system and infrastructure must be monitored and maintained	Additional settlement may require more frequent maintenance
Leachate management	Leachate removal equipment must be monitored and LCRS operated	Added leachate volume may require more frequent maintenance and monitoring, including monitoring of seeps
Gas management	GCCS must be maintained, operated, and monitored for a designated period following closure	Additional gas volumes requires more frequent maintenance and monitoring, the presence of liquids may create additional challenges in efficiently collecting gas from devices
Monitoring	Needed data must be collected, recorded and submitted to regulatory agencies	Additional monitoring instruments and measurements may be required

Long-term care, maintenance, and monitoring of a solid waste facility following its closure may be required for as long as 30 years or more, depending upon regulatory requirements and site-specific conditions. Objectives of long-term care include maintaining final cover, collecting and treating leachate, monitoring groundwater, and controlling gases. Routine maintenance of the landfill cover system will include repairing erosion damage, adding needed vegetation and soil amendments, routine vegetative maintenance to control overgrowth, and ensuring successful operation of surface water management components. Drainage systems must be maintained, as drainage control problems can result in accelerated erosion. Differential settling of drainage control structures can limit their usefulness and may result in failure to direct stormwater properly off the site. In instances where erosion problems are noted or drainage control structures need to be repaired, proper maintenance procedures should be implemented immediately to prevent further damage. Failure to maintain the physical integrity of the landfill cover will promote additional infiltration into the landfill and eventually cause generation of larger leachate quantities. This will also exacerbate problems associated with leachate collection and disposal.

Record keeping requirements include site inspections and summary reports at some specified frequency during the years following closure. For instance, quantities of leachate removed and transported must be recorded, and monitoring of gas, groundwater, surface water, and leachate are commonly required. As described in Chap. 16, monitoring landfill gas and leachate provides valuable information about the landfill's conditions, and as discussed in a following section, will be instrumental in determining whether or not PCC criteria are met.

The LCRS and GCCS will continue to be operated after closure and therefore will require attention during PCC. Both systems must be maintained to ensure effective operation. LCRS maintenance includes periodic leachate collection pipe cleaning, collection tank cleaning, and pump preventative maintenance and repairs. Collected leachate must be treated or disposed of in an appropriate manner, and the quantity of leachate treated or removed should be recorded. GCCS maintenance will consist of regular maintenance of pipes, hoses, wellheads, blowers, pumps, and other infrastructure. Withdrawal pipes and collection lines may require condensate removal and repairs if damage from differential settlement occurs.

17.3 Closure Considerations for Sustainable Landfills

17.3.1 Waste Filling

The point of transition from an active, operating landfill to a closed facility depends on site-specific conditions, operating objectives, and regulatory requirements. Operators have pursued several different approaches with respect to implementing the initiation of closure. One approach is to delay closure construction as long as possible; waste filling continues, expanding laterally in new disposal areas as necessary, with a final cover system constructed over a very large areas, often the entire landfill unit. Another approach involves bringing distinct sections of the landfill to final topographic conditions as soon as possible and closing these areas as part of individual construction projects.

The first such approach is illustrated in Fig. 17.3. A landfill with the capacity to dispose of 15 years of waste is filled to a specified waste height that is short of the permitted final topography. Waste filling progresses laterally until the specified waste height is reached, and then the entire landfill is filled to the permitted waste height. A closure system is then installed for the entire landfill. This approach has

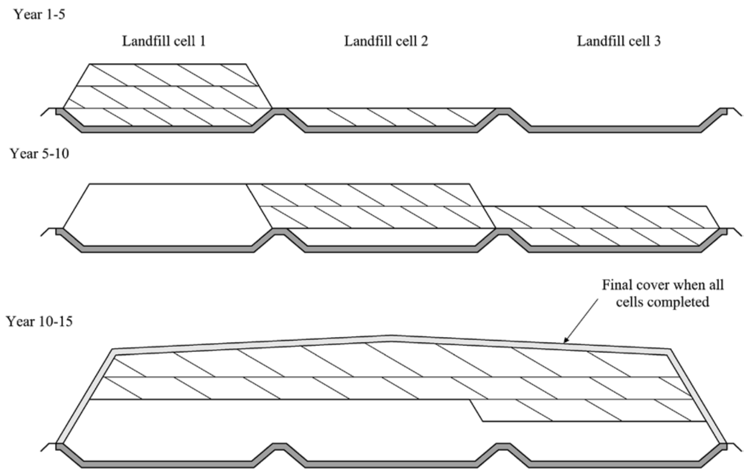

Fig. 17.3 Illustration of landfill final cover system installation after entire landfill reaches final permitted elevation

advantages at sites where active waste decomposition is still occurring. Installation of the final cover system can prove problematic because waste degradation will be accompanied by volume reduction and landfill settlement, which in turn results in more maintenance (e.g., additional grading to address differential settlement, fixing pipes that break because of induced stresses). In addition, construction of the final cover system likely precludes additional waste disposal in this area or landfill reclamation.

An alternative approach is illustrated in Fig. 17.4. For the same landfill and waste disposal capacity as the previous example, waste is filled to the permitted closure elevation as soon as possible, and upon reaching sufficient size, this area is closed. At sites operated to promote rapid waste stabilization, this approach has the disadvantage of placing the final cover system while settlement is actively occurring, thus resulting in the maintenance and inefficiency problems avoided for the first approach. This approach, however, does allow the operator to more effectively control seeps (Chap. 11) and collect landfill gas more efficiently (Chap. 13). In addition, earlier closure allows the owner to access escrowed post-closure funds collected throughout the operational life of the facility.

Both approaches described above pose some disadvantages with respect to sites practicing rapid waste stabilization. A hybrid approach that has been suggested to realize the advantages of both approaches is to install cover systems that function similarly to a traditional closure system (e.g., efficient gas control, control of leachate seepage) but that are less costly and therefore may be removable, and thus allow the addition of more waste, facilitate maintenance, and support landfill reclamation. Examples of such systems are described in the next section.

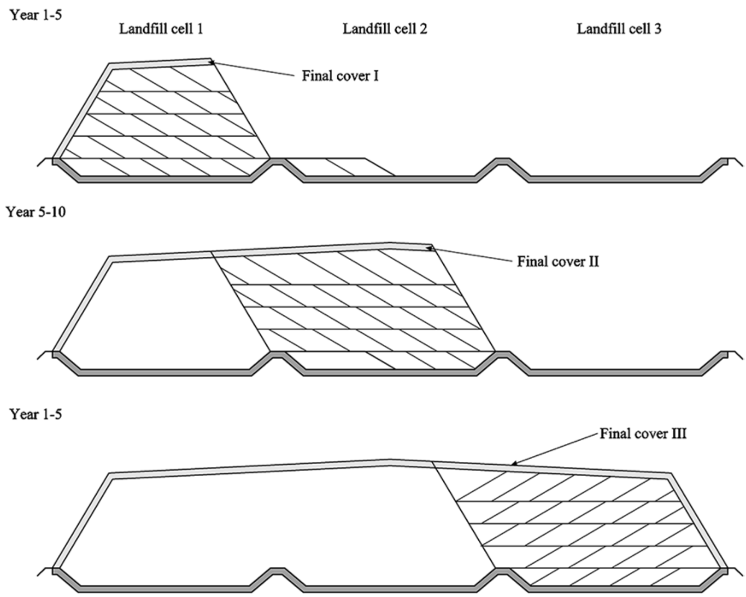

Fig. 17.4 Illustration of landfill final cover system installation throughout operation

17.3.2 Alternative Cover Systems

Geomembranes are common components in landfill final cover systems, resting above a suitably-prepared foundation and gas collection layer, and below an erosion layer designed to promote stormwater runoff and evapotranspiration. An alternative configuration, one that lends itself to several sustainable landfill practice objectives, utilizes the geomembrane as the uppermost layer of the cover system (i.e., the geomembrane is exposed at the surface of the landfill without a soil cover). Constructed using a traditional geomembrane, this configuration has been termed an exposed geomembrane cap (EGC). Figure 17.5 shows an EGC in use at a landfill in Florida, US.

One service an EGC might provide with respect to sustainable landfilling is improved gas collection. It is well recognized that placement of a geomembrane as part of a traditional cap greatly enhances the efficiency of the gas collection system. The construction of a landfill final cover system normally occurs during a later period of landfill operation, when the landfill has reached the final planned grade and when no more waste is accepted. Since much of the gas generated from waste stabilization forms during the earlier years of landfill operation, especially when liquids addition is practiced, the use of a geomembrane during early operational periods is beneficial. When well-constructed, an EGC provides an excellent barrier to gas escape; gas collection devices such as horizontal extraction wells can be constructed directly beneath the EGC so a vacuum can be applied to facilitate gas removal from the entire surface.

Fig. 17.5 Exposed geomembranes cap used as final cover (Photo courtesy of Jones Edmunds)

The benefits provided by EGC installation with respect to controlling leachate and stormwater are also greatest when EGC installation occurs earlier in the operating life of a landfill rather than towards the end when traditional cover systems are implemented. If waste is filled in the landfill unit in a manner that distinct areas of waste placement reach final grade early (see previous discussion), an EGC can be installed fairly easily. Some facilities place temporary geomembranes on side slopes to assist with stormwater management (often referred to as storm-covers) and a similar practice could be used to aid in gas collection, odor control, and seep control.

EGCs are constructed by first preparing the surface of the landfill using appropriate soil and then installing gas collection infrastructure (horizontal gas collectors, synthetic nets, manifold piping). One of the more important design concerns is the prevention of wind uplift. High wind velocities result in a pressure differential between the top and bottom of the geomembrane, so ballasting is required, either through anchor trenches within the waste/cover system or with placement of weights (e.g., sand bags, pipes) on top of the cover. The stormwater control system must be designed and constructed to accommodate the rapid runoff time and the increase in runoff quantity. As described in Chap. 11, EGCs can be integrated into the landfill's seepage control system, which is beneficial at landfills where liquids addition is practiced.

Potential operational and maintenance issues of EGCs include deterioration of geomembranes because of exposure to ultraviolet rays, the potential damage of the exposure surface from operating personnel or equipment, and the need for ballasting because of wind-induced uplift. Some new products address this concern by designing the geomembranes to be covered with a thin layer of soil, which is retained on the surface by a synthetic turf. Figure 17.6 shows an example of such a product being installed on the surface of a landfill.

Fig. 17.6 Closure Turf used as final cover

EGCs and similar systems have the potential to be used at any landfill as a replacement for traditional final cover systems; this would require regulatory approval, however, as this approach differs from those prescribed in most regulations. With respect to sustainable landfilling, EGCs might serve as temporary cover systems prior to later waste filling, reclamation, or placement of a final soil layer. Since EGCs have successfully been used as temporary covers at many landfills, the major determining factor when considering EGC deployment is cost. If an EGC must later be removed to install a traditional final cover system, EGC benefits are likely outweighed by the added cost. However, if the EGC can serve as a replacement for all or part of the required closure system, such an approach might be feasible.

17.3.3 Leachate and Gas Management

Fundamentals of leachate and gas management were reviewed in Chap. 11 and Chap. 13, respectively. Leachate will continue to be collected by the LCRS after closure and during the PCC period. While leachate volumes are expected to decline with time after placement of the final cover system, they are likely to be greater in facilities where leachate recirculation or outside liquids addition was practiced. Similarly, GCCS operation will still be required until gas production becomes sufficiently low. Landfills practicing liquids addition or other enhanced stabilization techniques should reach a point of reduced gas production sooner than traditionally-operated facilities.

With the placement of the final cover system, the volume of leachate produced should decrease. Continuation of leachate recirculation or liquids addition will certainly affect post closure leachate production, but once all major moisture inputs are stopped, if the final cover system is well designed, constructed, and maintained, leachate production should decrease to a relatively small constant rate. Leachate collection volumes from well-maintained cover systems should not be subject to major fluctuations in response to wet weather, and should decline or remain relatively constant. If such variations are encountered, the integrity of the cap should be investigated to determine continuing sources of moisture intrusion and these problems addressed.

The PCC plan will outline steps necessary for operating, maintaining and monitoring the performance of the LCRS. The ultimate goal will be to reduce or eliminate LCRS operation; steps that would need to be considered are described in the following section. Such decisions would be made based on information on both the amount of leachate produced and the chemical quality of the leachate. Chapter 2 illustrates leachate chemistry changes with time; after biological consumption of the readily biodegradable organic matter in the waste and leachate, dominant leachate constituents included refractory organic matter (large molecular weight humic and fulvic compounds), inorganic ions (chloride, sodium) and ammonia-nitrogen. As described in Chap. 11, conventional biological wastewater treatment is largely ineffective for reducing chemical constituents in mature leachate (other than possibly ammonia), and more effective treatment strategies include dilution (addition to a domestic POTW or discharge to water bodies), physical-chemical treatment processes (coagulation/precipitation or carbon absorption for organic matter), and concentration (evaporation or membrane processes). Chapter 11 also describes several leachate treatment technologies that have the potential to work well when coupled with leachate recirculation.

In a similar manner as the LCRS, the GCCS must be operated until requirements for the PCC permit are met. Landfills where enhanced waste stabilization is practical may reach this point much sooner than a traditional landfill (see Chap. 13). As gas production decreases with time, the required vacuum will decrease and necessitate adjustment at the individual wellheads and the blower station. At some point, designated wells will be removed from the collection network when they are shown to be unproductive. An ultimate goal is to switch the gas system operation from active to passive; the process for making this decision is outlined in the following section.

Once passive control is instituted, remaining gas emissions could potentially be addressed by installing passive wells (these can be equipped with solar sparking devices that combust built-up gases with or without an external fuel) or wind-driven extractors. Chapter 13 discussed the potential for biocovers to act as a polishing step to mitigate methane and other gas emissions; such options should be considered as part of the GCCS and final cover design. Additionally, as described in Chap. 14, a GCCS may be retrofitted to serve as a system that aerates the landfill to further reduce potential methane emissions. Allowing passive aeration via the LCRS at the same time might encourage additional in-situ leachate treatment.

17.4 Determination of End of Post-closure Care

Major PCC activities include maintaining the integrity and effectiveness of the final cover, maintaining and operating the LCRS, maintaining and operating the GCCS, and monitoring the groundwater quality. All of these processes are necessary to ensure the objective of environmental safety is met, but they do come at an expense to the owner, and ideally would cease or be reduced to a point when risk is sufficiently reduced. A critical element in the PCC process is thus defining the length of time that the landfill owner and operator must comply with the PCC plan and continue PCC activities. Because many regulatory programs require financial assurance (see Chap. 2) to guarantee availability of resources for PCC, the PCC period has a major impact on landfill economics. The US federal regulations specify a post-closure care period of 30 years after site closure, although less than 30 years is allowed if the landfill owner can demonstrate that the reduced period is sufficient to protect human health and the environment (US Government 2012). Similar to the US regulatory framework for PCC, the European Landfill Directive specifies that landfill monitoring and maintenance during PCC should be conducted for as long as the facility poses a hazard (European Council 1999).

Defining when a landfill poses an acceptable risk to human health and the environment is a challenge as this term is subjective and often not well defined in regulatory programs. Government agencies provide guidance to assessing risk from closed or abandoned waste sites in more general terms (e.g., US EPA 1989, 1996, 1998). This process typically involves assessing the risk posed by current and future emissions from a waste site, and considers risk pathways such as contaminant release to water supplies, soil and air, and may include an evaluation of risk to ecosystems or specific ecological receptors. The question that must be addressed is whether or not the facility, in its current and future state, will result in unacceptable risk if PCC activities are altered.

Various approaches have been proposed to assess the risk to human health and the environment that ultimately can be used as a part of the demonstration needed to establish an appropriate and technically sound post-closure care period (Barlaz et al. 2002; ITRC 2006; Morris and Barlaz 2011). These approaches suggest a framework where landfill emissions that may pose a risk to human health and the environment are monitored as part of PCC and compared to accepted risk levels to determine when a change in PCC is warranted. In some cases these landfill emissions are measurements of chemical concentration (e.g., gas, leachate), or estimates of contaminant mass release rate (a combination of the flow rate and contaminant concentration). Figure 17.7 illustrates such an approach (ITRC 2006), where PCC monitoring data are collected and evaluated as part of a modular assessment of four primary landfill components (leachate collection and control system, landfill gas collection and control system, groundwater monitoring system, and cap system).

In this approach, data are gathered and evaluated, and when the results suggest that a change in PCC activity is justified (e.g., a less-frequent maintenance or monitoring schedule), the change is implemented (Fig. 17.8). For example, a portion of the GCCS might be converted from an active collection system to a passive system; methane

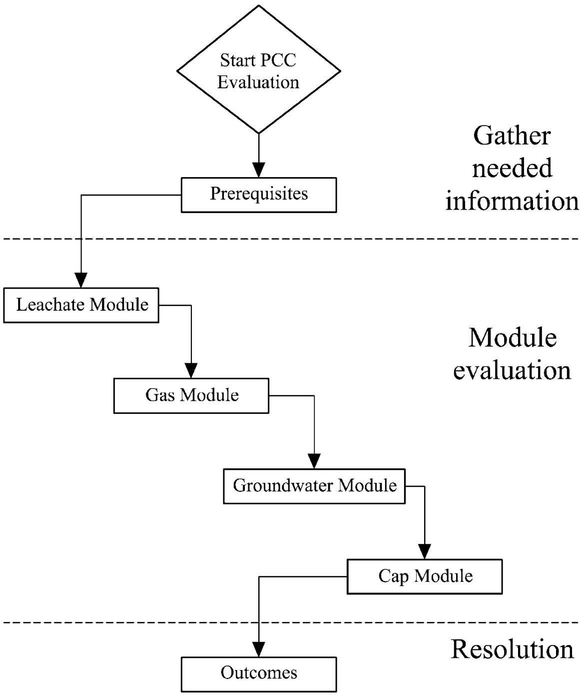

Fig. 17.7 Components of a post-closure care performance evaluation (adapted from ITRC 2006)

surface emissions in the period following the change would continue to be monitored. Under this approach, confirmatory and surveillance monitoring would allow the operators to ensure that reduced maintenance and monitoring do not result in an unacceptable risk to human health and environment. The modular approach allows for a phased reduction of PCC activities for only those components of the landfill system that warrant them. A likely outcome of this approach is not that the operator completely stops PCC, but rather the facility evolves into routine and potentially reduced long-term care.

Landfill operators implementing sustainable practices are offered the potential for reaching a custodial care phase more rapidly than conventional landfills. A landfill operated to enhance waste stabilization during its operating life should at some point have lower leachate and landfill gas contaminant release rates relative to sites where this activity was not practiced. Evidence at operating sites has demonstrated the impacts of sustainable landfill operations on landfill gas production. Evidence is less readily available with regard to leachate as the amount of liquids added during operation may be much greater, and thus even when concentrations are lower due to accelerated waste stabilization, a greater mass flow rate may be present until the landfill has had sufficient time to drain. Additionally, traditional landfills where liquids addition was not practiced may have misleadingly low leachate mass release rates as much of the landfilled waste was never exposed to added moisture and thus leachate pollutant release rates could increase in the future if final cover system integrity is ever compromised. Landfill operators practicing enhanced efforts to stabilize landfilled waste can

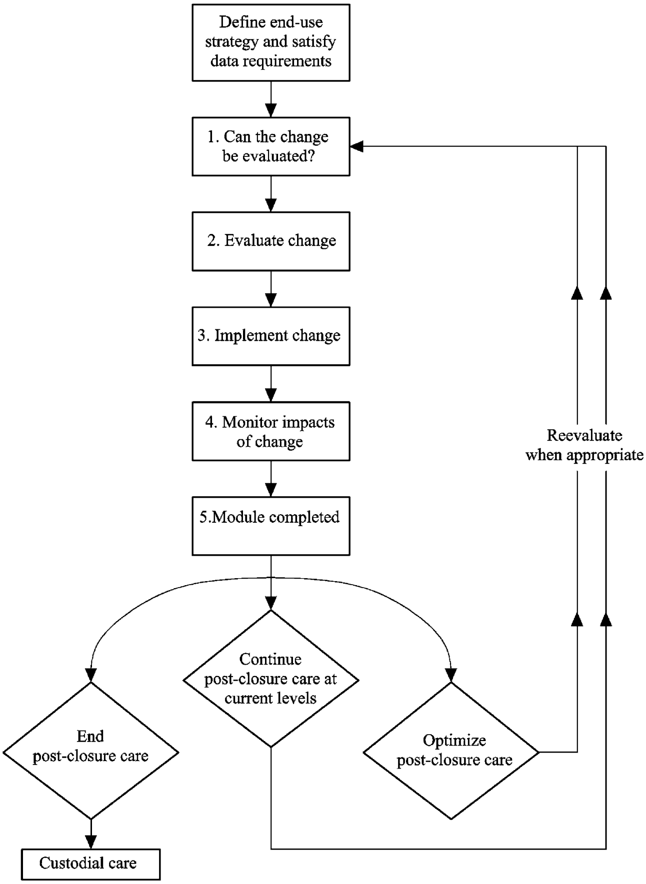

Fig. 17.8 Potential approach of the post-closure care performance evaluation process (adapted from ITRC 2006)

utilize the monitoring techniques described in Chap. 16 (e.g., solids characterization, settlement) to make a much more compelling case with regard to PCC activity modification.

17.5 Landfill Reclamation and Reuse

17.5.1 Landfill Reclamation Fundamentals

MSW landfill reclamation (also referred to as landfill mining) refers to the process of excavating previously-disposed materials from a landfill, in many cases processing it, and then re-disposal (or reuse) of materials in another location.

Table 17.2 Primary factors motivating consideration and implementation of landfill reclamation projects

Factor	Description
Environmental protection	Older landfills without a bottom liner system or with poorly functioning systems are often continuous sources of environmental pollution as a result of leachate and landfill gas releases. Removal of this waste provides an alternative to expensive ongoing remediation that may have limited effectiveness
Create new disposal capacity	At many landfill sites, older disposal areas were not efficiently used (small slopes, large amounts of cover soil). Reclamation of these areas may allow for the construction of more efficient new landfill units and thus allow a given site to expand its operational life
Reduce closure costs	When landfill reclamation reduces the overall footprint associated with permanent waste disposal (area), both closure costs and PCC costs are reduced
Material recovery	The reclamation process allows recovery of potentially valuable materials such as steel and aluminum. Soil and degraded waste can be reclaimed as cover soil in existing disposal operations and potentially off-site use

Landfill mining has been practiced to a limited extent around the world. In some cases, landfilled materials are simply excavated from an unlined disposal area and deposited in a lined landfill unit without any processing or recovery of materials; this practice is commonly referred to as *waste relocation*. In other cases, the excavated material is processed to reduce the magnitude of materials that must be disposed again. The primary factors that have motivated landfill operators to consider and implement landfill reclamation are presented in Table 17.2 and these motivating factors are discussed in more detail below. Landfill reclamation merits attention since the process has potential to reduce the environmental impact of existing landfill sites and can be integrated into purposeful material recovery operation at new facilities (described in Chap. 19).

Waste deposited in landfills operated prior to regulatory liner requirements has been documented as the source of groundwater contamination at many landfill sites (Reinhard et al. 1984). This contamination results from both leachate discharge into the groundwater and landfill gas migration. When addressing groundwater contamination problems, the preferred option (when feasible) is to remove the source of contamination; thus reclamation may be considered. However, the cost of landfill mining must be weighed against the cost and effectiveness of other techniques used to address groundwater contamination; an advantage of waste removal is that long-term liabilities are significantly reduced.

Siting new landfills has become more difficult and more costly in recent years due to increased land value in many areas, public opposition, and stricter environmental regulations. Consequently, more facilities are examining how to utilize effectively and efficiently all available airspace at existing facilities. Landfill reclamation provides opportunities for recovery of existing landfill airspace and allows for the creation of new disposal areas that use airspace more efficiently. Some facility owners have undertaken reclamation at unlined cells for future use in constructing a new lined landfill unit, while others have utilized landfill mining as a means of reducing the size of the landfill unit prior to closure to reduce costs. The recovery and sale of recyclable materials reclaimed from a landfill (particularly metals) may present an added source of revenue for landfill reclamation projects. Recovered soil (along with degraded organic matter) can be used as a substitute for excavated soils in ongoing landfill operation, and possibly used off-site. Landfill reclamation has also been considered to recover refuse-derived fuel from landfill sites for combustion and energy recovery. The financial costs and benefits of landfill mining are addressed in more detail in Chap. 18.

17.5.2 The Reclamation Process

Landfill reclamation typically consists of three basic operations: excavation, processing, and management of the resulting material. Waste is first excavated using equipment such as dozers and excavators. The excavated waste can be processed to meet several objectives, including separating bulky materials, sorting hazardous materials and other unidentified waste, screening soils from waste, and sorting materials for recycling or use as fuel. Several common mechanical techniques (such as magnets for ferrous metal removal and eddy current separators for aluminum removal) can be incorporated to recover recyclable materials.

Figure 17.9 presents a generalized flow chart of the process that some of these mining projects employed. The degree of processing is guided by the project objectives, properties, and conditions of the excavated material and processing cost and time (Jain et al. 2013). Screening of the excavated waste is the most common process used in landfill mining projects as will be described later. Following materials screening, the oversize materials may be managed in different ways depending on the material composition, processing level, and available markets. Although several components of recovered materials may have value (e.g., plastic, glass), the most typical component recovered from landfill mining (other than soil) is metal. Recovered ferrous metal and aluminum may need to meet specified quality requirements in order to have sufficient value. If no end markets exist for the oversized material, it is typically disposed of in a lined landfill. Jain et al. (2014) found that recovery of metals provided the greatest amount of carbon offsets relative to other end uses such as energy recovery and soil material reuse.

Equipment typically used in landfill mining projects includes machinery common in landfill operations and the surface mining industry. For example, equipment used for excavating landfilled wastes (e.g., excavators, dozers, loaders) is commonly used at many landfill sites. Off-road trucks are available and routinely used at most MSW landfills to move daily cover soil, among other functions. Waste can be excavated from the landfill using an excavator or backhoe and loaded onto the processing operation (e.g., screening equipment) or a dump truck (Fig. 17.10). Alternatively, a dozer can be used to scrape the waste along the slope from the top towards the bottom of the mining area and deliver the waste to an excavator, which can then be fed into the processing equipment (Fig. 17.11). Identifying and sorting

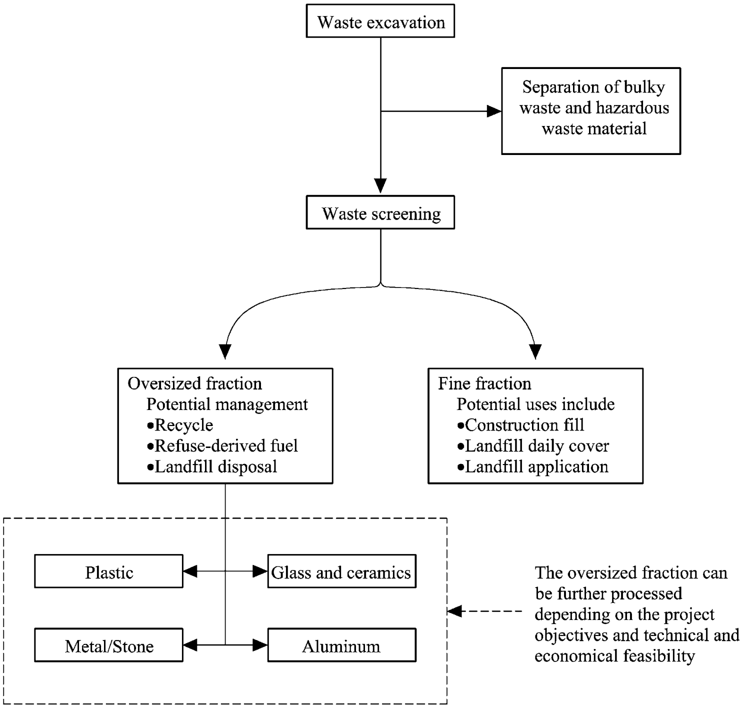

Fig. 17.9 General process for landfill reclamation

Fig. 17.10 Landfilled material reclaimed using excavation technique

Fig. 17.11 Landfilled material reclaimed using scraping technique

bulky items and hazardous wastes from the mined material are important steps. Depending on the waste processing methods and equipment used, larger-sized pieces (e.g., appliances) may also need to be sorted out before processing the mined material using a mechanical screen. A front-end loader working with the excavator can be used for this purpose.

The primary purpose of screening the mined material is to separate the soil or fine fraction from the larger components. The fine fraction, while being composed primarily of soil used as a daily cover and intermediate cover, will also include degraded organic materials (e.g., biostabilized paper, food waste) and small pieces of other waste components (e.g., glass). The two types of mechanical screening equipment most often used for screening fines from larger materials in excavated waste are trommel screens and shaker or vibratory screens. Figure 17.12 shows a landfill mining project where a shaker screen was employed. Screening the soil fraction may be difficult in landfills where waste is frozen.

The screen opening size used depends on the quality and final use of the recovered soil. If the recovered material is to be used as a daily cover at a landfill, a larger sized screen can be used. However, if a better-quality soil (for off-site application) is desired, a smaller screen size should be used. Screened materials (soil and waste) must be transported to the place of disposal and/or the location of the approved final use. Depending on the location (on-site or off-site) of the final use or disposal and the condition of the roads, dump trucks or off-road trucks can be used for hauling the processed material. In some cases conveyor are used to transport screened soil from the mining area to the stockpile (Fig. 17.13).

Fig. 17.12 Processing mined landfill material utilizing a shaker screen and overhead drum magnet

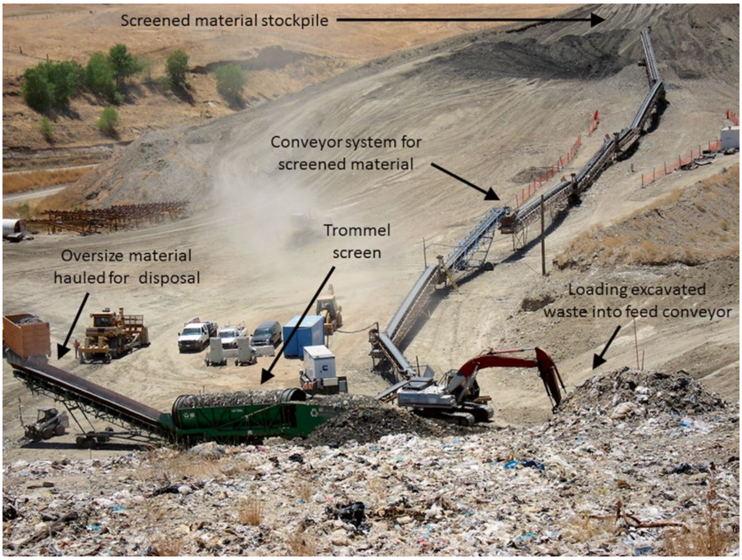

Fig. 17.13 Landfill mining processing equipment including conveyor system, trommel screen, and an excavator

As discussed, the specific processes and operating equipment used depends on the goals of the landfill mining project. Table 17.3 summarizes documented experiences from a variety of landfill mining projects in the US.

Table 17.3 Summary of documented experience and lessons learned from several landfill reclamation projects

Case study site	Description
Naples Landfill (Collier County, FL) (Murphy and Stessel 1991)	The site contained a 33-acre unlined cell that contained 15-year-old highly stabilized waste with minimal landfill gas issues. Recovering recycled material proved too expensive to process and was unsuccessful. Landfill soil recovery was successful accounting for 40–60 % mass of total excavated material. The project resulted in a potential gain of $1.00 per ton of reclaimed soil for Collier County and the US EPA (1997) reported 10 acres of land reclaimed
Town of Edinburg (NY) (NYSERDA 1992)	A 1-acre demonstration project, part of a 5-acre municipally owned unlined landfill. This landfill received waste from 1969 to November 1991. Excavation equipment included track excavator (2.4 yd^3 bucket), 2–3 wheel loaders (2.5 and 4.0 yd^3 buckets), and 1–2 20-ton dump trucks. Vibratory screens and a trommel screen were used to sort the excavated material. The project resulted in approximately 14,930 yd^3 of excavated waste in the first two phases of the project; and additional 1.6 acres yielded 31,000 yd^3 in the third phase. The contractor cost was \$3.00/yd^3 for this phase
Frey Farm (Lancaster County, PA)	The excavated material was screened using a 1-in. trommel screen. 41 % of recovered material was soil, 56 % was used as fuel at a municipal waste combustor, and 3 % was incombustible and reburied at the site. The reclaimed material had an estimated energy value of 3,080 BTU/lb. By 1996, the project resulted in 300,000–400,000 yd^3 of excavated and processed waste at a rate of 2,650 tons/week. Extensive air monitoring was conducted during the project. The project resulted in a net revenue of $13.3/ton for Lancaster County
Wyandot County (Carey, OH)	The project site was a sanitary landfill of 188 acres consisting of lined and unlined cells. Only waste relocation (i.e., no processing) was done via an excavator to excavate waste, an off-road truck hauled the material to an on-site lined unit. The overall rate of waste relocation was 300,000 yd^3 per year and as of 2006, 30 acres of land had been reclaimed. The total amount of waste excavated is approximately 1.4 million yd^3 and the cost was estimated at \$4 per yd^3. Since the project began an improvement in groundwater quality was observed
Shawano County (WI)	The site consisted of a combination of lined and unlined cells. A waste relocation project was initiated to decrease the cost of treating the leachate collected from a perimeter toe drain. The mining process consisted of excavation of waste from the unlined cell (using two excavators) and hauling it to the on-site lined cell. No screening was done. Bulk soil was separated into "clean," "mildly contaminated" and "contaminated soil." 12 acres were reclaimed by relocating 0.3–0.4 million yd^3 of waste from unlined to lined cells, and approximately 2 ft of underlying soil was scraped and stockpiled on the clay lined area. The project cost was approximately \$3/yd^3

(continued)

Table 17.3 (continued)

Case study site	Description
Central disposal systems (Lake Mills, Iowa)	The landfill had a lined cell and a 10-acre unlined cell using well-decomposed mined waste as daily cover. The excavation consisted of using one backhoe with a 5-yd^3 bucket and hauling to an on-site lined unit via four trucks. Explosivity of landfill gas became a concern on some occasions. 1,000–1,500 yd^3 of waste relocation occurred per day resulting in 10 acres reclaimed and an overall relocation of 250,000 yd^3 of waste as of 2006
Pike Sanitation (Waverly, Ohio)	The site contained 40 acres of unlined cells and a 125-acre lined cell permitted in 1996. One to two backhoes were used for excavation in conjunction with four to six off-road trucks. No materials were processed. The asbestos containing materials, if encountered, were sprayed with water to minimize movement to air. All waste moved to lined cells amounted to 700,000–800,000 yd^3 of waste at a rate of 40,000 yd^3 per month
La Crosse County (WI)	The site consisted of an unlined cell approximately 25 acres with 1.2 million yd^3 of waste and a lined cell. Excavation used 2 backhoes with 4 yd^3 buckets and material was hauled to a lined cell via 12 off-road trucks with 12 yd^3 buckets each. Soil from the cap was recovered and used for future landfill operation while larger waste (i.e., furniture) was placed in a lined cell; WTE ash was placed in an ash monofill. 25 acres were reclaimed by relocating approximately 500,000 yd^3 of waste in the first phase
Dean Forest (Savannah, GA)	Site layout consisted of 4 quadrants (three lined and one partially lined). The site contained some MSW, construction and demolition (C&D) debris, and sludge. The excavation operation consisted of excavation using two excavators and waste hauling to lined cells via 6–7 off-road trucks. Waste was not processed and was relocated at a rate of 7,000 yd^3 per day, resulting in 130 acres reclaimed and 650,000 yd^3 of waste relocated. Waste was not processed because of space and time constraints
Clovis (CA)	The site consists of unlined and clay-lined units made of a synthetic composite liner system used since 1998. Excavation consisted of a dozer scraping and pushing waste to an excavator. The waste was screened using a trommel (with a 2-in. screen) and loaded to 40 yd^3 open-top dump trucks and hauled to a lined cell. Soil, which amounted to 60 % of the total material excavated, was transported, collected, and consolidated into a soil stockpile. Waste was mined at 1,100 yd^3 per day, 190 days a year (75 % of the total working days), totaling to 2.1 million yd^3, and costing \$4.84/yd^3
Winnebago County (WI)	The site was composed of lined and unlined cells. Waste was relocated from unlined cells to a closed lined cell to fill depression on this cell. The relocated waste was spread with a dozer and an electromagnet was used to collect ferrous metals. No other processing technique was used. Approximately 3–4 acres of land were reclaimed during the project
Phoenix Rio Salado (Phoenix and Tempe, AZ)	The site comprised of more than 600 acres spanning Phoenix North Central landfill, Del Rio Landfill and various others. Only the waste that was within the project construction zone was mined. Waste was screened at two sites, of which 150,000 tons of waste was removed and segregated while 100,000 tons were screened with a trommel and grizzly screen for re-use as clean soil. As of 2005, more than 380,000 yd^3 of C&D debris, 20,250 yd^3 of MSW, and 600 tons of tires were mined. Approximately 80 % of the mined materials were re-use/recycled

17.5.3 Design, Permitting, and Operation of Reclamation Projects

Management of hazardous and other special wastes is a concern during landfill reclamation since the nature and composition of many of the wastes disposed of in old landfills is unknown. Management of hazardous waste may be costly and thus could have a significant impact on project economics. Past projects have used a variety of techniques to manage hazardous or special wastes, but several basic components should be in place as part of any project. Personnel involved in materials excavation should be properly trained to identify hazardous or otherwise prohibited wastes. The type of training should also include appropriate procedures to follow when a hazardous waste is encountered (e.g., personal protective equipment). The project should have a hazardous/prohibited waste management area so that such wastes, when encountered, can be segregated from the other recovered materials and properly managed. A detailed health and safety plan is necessary and should include specific provisions on how hazardous and prohibited wastes should be managed and the contingency procedures to follow during operations if such wastes are encountered. Table 17.4 includes a summary of health and safety plan elements that should be considered for landfill reclamation projects.

Gas and odor emissions represent potential issues both to personnel executing a reclamation project and potentially to receptors off-site. Odor issues are often less pronounced when conducting operations during cooler winter months; projects conducted during warm weather have generally reported more odor problems.

Table 17.4 Health and safety requirements for landfill planning

Health and safety requirements
Identify key personnel, site-entry procedures and control, site characterization, personal protective equipment and monitoring, decontamination, communication procedures, emergency medical procedures, and standard operating procedures
Establish procedures for managing hazardous wastes when encountered, including provisions for work stoppage when a hazardous waste is encountered, monitoring that takes place when a hazardous waste is encountered, and managing the material upon discovery
List potential hazards, including chemical compounds, biological hazards, radioactive materials, fire/explosive hazards, excavation/shoring/engulfment, extreme temperatures, noise, terrain/trip-fall/sharp objects, equipment guards, mental stress/fatigue, asbestos, drums, nuisance dusts, and confined spaces
Provide personal air monitoring equipment, including combustible gas indicators, photoionization detectors (for monitoring organic vapors other than methane), a radiation survey meter, personal asbestos monitors, and personal organic vapor badges, which should be used to characterize and monitor any vapors and/or materials emanating from the landfill during excavation activities
Provide personal equipment for specification for the work, which may include full-face air purifying respirators with high-efficiency particulate/organic vapor cartridges, Tyvek coveralls, and chemical resistant boots and gloves, in addition to normal work clothes and construction gear
Offer hazardous materials training, supervisor training, and medical surveillance training

Odor issues may be less pronounced when the waste material is well decomposed. A landfill can also aggressively operate the gas extraction system, if present, to minimize gas emissions and odor problems during mining. Chemical perfumes or masking agents may provide temporary relief from odor.

Depending on the age of the waste and degree of decomposition, gas monitoring (e.g., explosivity, toxic gases) during operations may be prudent. Methane can form explosive mixtures when mixed in certain proportions with air (Chap. 14). Elements specific to landfill gas monitoring should be included in mining operation plans and should discuss monitoring devices and frequencies, establish action levels, and specify remedial procedures if action levels are met or exceeded.

Waste excavation and screening can potentially cause the generation of dust and windblown litter. While many previous landfill reclamation projects have reported minimal dust issues because the excavated waste was moist, in the event that dust is a concern, a tanker truck to spray water around the excavation and processing area may be required. Litter control devices such as portable fences or other suitable devices may also be used.

Regulations for operating landfills require application of daily cover at the end of each day to minimize adverse impacts such blowing litter, odors, disease vectors, or fires; this might also be required for exposed waste from a reclamation operation. Landfill mining project plans or health and safety plans should address the issue of cover and should establish a protocol that is consistent with local regulations, which may include identifying the source of cover material, and the amount and frequency of application.

Mining of landfilled waste will result in a change of existing grades at the site; reclamation projects should implement a stormwater management plan to minimize the contact of stormwater with stockpiled or exposed waste. Stormwater that contacts solid waste is considered to be leachate and must be managed as such. Leachate may also be generated from excavated waste that is wet. As with routine landfill operation, stormwater can be controlled using diversion berms, by grading the surface adjacent to the waste to direct stormwater from the working face, or excavating waste in a given direction to minimize leachate generation.

17.5.4 Reclaimed Material Composition

When material is reclaimed from a landfill and processed, the two major resultant components are a fine fraction and a larger fraction consisting of waste. The fines result from a combination of the soil originally used as cover in landfill operation, degraded waste, and small pieces of disposed waste. Table 17.5 summarizes the reported composition of reclaimed material from several landfill mining studies. The fines fraction has been reported to constitute approximately 50–85 % of the recovered material (weight basis).

Potential reuse options for recovered soil include daily and intermediate landfill cover (uses inside the landfill) and construction fill (uses outside the landfill)

Table 17.5 Reported bulk composition of material extracted during landfill mining projects

Study	Fines	Identifiable bulk waste materials
Murphy and Stessel (1991)	50 % (0.5-in. screen)	10 % paper, 7 % plastic, 5 % wood, 2 % aluminum, 5 % metal/stone, 5 % glass/ceramic, 18 % misc
NYSERDA (1992)	84.50 % (0.5-in. screen)	3 % paper, 2.80 % plastic, 0.70 % wood, (2.5/1.4) metal/stone, 1.30 % glass/ceramic, 3.80 % misc
US EPA (1993) (29 samples)	59.1 % (1-in. screen)	3 % paper, 4.3 % plastic, 2 % yard waste, 5.2 % wood, 0.9 % textile, 0.6 % rubber/leather, 2.4 % metal, 2.1 % glass/ceramic, 20.5 % misc
Kilmer and Tustin (1999)	75 % (1-in. screen)	Not reported
Earle et al. (1999)	75–87 % (1/4-in. screen)	Not reported
Zornberg et al. (1999) (80 samples)	>56 %	Not reported
Jain et al. (2005) (78 samples)	58 % (1/4-in. screen)	12 % paper, 13 % plastic, 3 % yard waste, 3 % textile, 6 % metal/stone, 5 % glass/ceramic
McKnight (2005) (19 samples)	49 % (1/4-in. screen)	18 % paper, 7 % plastic, 12 % yard waste, 5 % textile, 7 % metal/stone, 2 % glass/ceramic
Quaghebeur et al. (2013) (23 samples)	40.1–67.8 % (0.8-in. (20-mm) screen)	1.9–11 % plastic, 0.5–11.6 % wood, 0.6–2.3 % textile, 0.5–14.5 % rubber/leather, 0.1–0.2 % metal, 18.5–28.3 % stone, 0.4–0.8 % glass/ceramic
Kurian et al. (2003) (58 samples)	40.1–67.8 % (0.8-in. (20-mm) screen)	0.5–13.9 % paper, 8.2–9.5 % plastic, 1.1–1.3 % yard waste, 2.9–5.4 % textile, 4.2–5.7 % metal/stone, 0.2–0.5 % glass/ceramic; 4.8–11.5 % misc
Hull et al. (2005)	51–55 % (1-in. screen)	Not reported

(US EPA 1997). Other end uses will be dictated by available markets, the quality of the material, and the regulatory framework for reuse. The issue that would most likely limit the reuse of mined landfill fines outside of the landfill environment would be the presence of trace chemicals. Given that a large variety of household, commercial, and industrial waste containing chemicals are disposed in MSW landfills, the potential impact of these chemicals on the environment if the mined residues were reused must be considered. When evaluating likely chemicals of concern, it should be noted that most organic chemicals should eventually be degraded in the biogeochemical environment of a landfill (Field et al. 1995; Reinhart and Townsend 1997). Non-degradable chemicals such as heavy metals, however, will remain in the waste unless leached out. Several investigations indicate that heavy metals would be retained in the landfill (Belevi and Baccini 1989; Finnveden 1996; Bozkurt et al. 1999). The concentrations of these chemicals in the mined material would likely dictate the degree to which mined residue can be reused outside of the landfill environment.

While most regulatory jurisdictions will not have regulated limits specific to materials reclaimed from landfills, they will often have risk-based thresholds for contaminated soil or water that may be applicable. Typically, the concentration of chemicals in the fines would have to be characterized to assess (a) the risk to human health from direct exposure of the material if it is reused outside of a landfill environment and (b) the risk to groundwater or surface water. The process used in many states is to compare a concentration that is statistically representative of the material proposed to be reused (e.g., the 95 % upper confidence limit (UCL) of the mean constituent concentration) to a health-based risk level. For use in commercial or industrial settings, some assurance would need to be provided that the property where the material was being reused remained commercial/industrial (known as *institutional controls*). To evaluate the potential risk to groundwater or surface water, the reused material may be tested for leachability and compared to the appropriate water quality risk thresholds.

17.6 Final Site Use and Configuration

Once a landfill site has been successfully closed, the owner then decides whether to isolate the site from the general public or open the site for some useful purpose, usually one focused on community activities (common for municipally-owned facilities). This decision is often made at the planning stages well in advance of the closure date. Closed landfill sites have been successfully used for parks and recreation, botanical gardens, ski slopes, toboggan runs, coasting hills, ball fields, amphitheaters, playgrounds, and parking areas. The use of a closed sanitary landfill as a green area (a community park) or open space is very common and presents relatively fewer challenges compared to a use that incorporate buildings and similar structures. The most commonly used vegetation is grass, though shrubs and small trees may be added where funds are available and if this type of vegetation is compatible with the end use and final cover design. Another use of closed landfills includes redevelopment into a golf course (see Fig. 17.14). As discussed in Chap. 19, landfills are growing in popularity as sites for placement of solar panels and wind turbines for energy production.

Closed landfills are typically not well-suited for construction of buildings, because of mechanical and geotechnical concerns, as well as potential issues associated with landfill gas accumulation and formation of explosive conditions. Small, light buildings such as concession stands, sanitary facilities, and equipment storage sheds are often required at recreational use areas. A geotechnical engineer should be consulted if plans call for structures to be built on or near a completed sanitary landfill. The cost of designing, constructing, and maintaining buildings is often considerably higher than it is for those erected on a well-compacted earth fill or on undisturbed soil. Roads, parking lots, sidewalks, and other paved areas should be constructed of a flexible and easily repairable material such as gravel or concrete pavers.

Buildings or other structures may be designed and built to accommodate for potential settlement and to minimize gas problems that might result in explosive or toxic conditions in any enclosed spaces. The GCCS and LCRS will normally still be operational, and associated infrastructure should be appropriately isolated,

Fig. 17.14 Golf course constructed on a closed MSW landfill (Photo courtesy of CDM-Smith)

protected, and labeled with precautionary signage. All construction activities should incorporate appropriate protection and repair of the final cover system, particularly any geomembranes or compacted soil barrier layers. Other issues that should be addressed at closed landfill sites include ponding, cracking, and erosion of cover material. Periodic maintenance includes regrading, reseeding, and replenishing the cover material; maintenance work is required to keep the fill surface from being eroded by wind and water.

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Chapter 18
Economics

Abstract Cost considerations are one of the most important features in landfill planning and management. This chapter presents a series of examples of how traditional landfill costs and benefits can be impacted by sustainable landfilling operations. In particular, a discussion including the types of costs (e.g., leachate management, gas recovery, and reuse) and likely or potential magnitude of costs and benefits of sustainable landfilling is presented. The reader is given multiple tools to guide the site-specific decision-making process associated with implementing sustainable landfilling of which include liquids management, gas management, and airspace recovery. A conceptual discussion of social costs is provided, in addition to economic considerations after the landfill closes, including how post-closure care plans (and timing) and landfill reclamation can affect life-cycle costs.

Keywords Landfill • Bioreactor • Economics • Capital • Operation

18.1 Overview

An important part of planning for solid waste disposal in a landfill is the estimation of construction, operating, and maintenance costs and anticipated revenues or benefits. As with any decision that would impact construction and operation at a landfill, the short-term and long-term costs and benefits of sustainable landfilling should be considered carefully and ideally compared to some base scenario so that owners and operators can make informed decisions to proceed with sustainable landfilling. These economic forecasts could be conducted prior to a landfill facility being built (i.e., a brand-new facility) or at an operating landfill that is planning future disposal areas or cells.

Short-term costs include landfill design and permitting, land acquisition (for new sites or significant expansions), site preparation, cell construction, and financial assurance. Long-term costs and benefits include operation and maintenance (O&M) over the life of the landfill, closure, gas collection and beneficial use, and post-closure care (PCC); the long-term costs also include social or external costs and benefits such as loss or gain of local amenities, pollutant emissions (including greenhouse gases), nuisances, and fossil fuel offsets, which require an intergenerational comparison of cost for future landfill effects.

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This chapter provides a review of landfill economics, including a discussion of factors that must be considered when electing to operate a landfill using sustainable technologies. A presentation of fundamental landfill economics is followed by a description of some of the major factors associated with sustainable landfill operation (e.g., flexibility in liquids management, enhanced gas production, additional air space recovery, early termination or reduction in post closure care requirements). The outcome of any economic analysis will vary depending on site-specific conditions and constraints, thus the objective of this chapter is not to provide specific information that could be used for a detailed cost-benefit analysis of sustainable landfill technologies. Rather, this chapter aims to provide guidance and highlight the important factors to consider when conducting an economic analysis involving sustainable landfilling technologies and an understanding of how sustainable practices can impact economic outcomes.

18.2 Fundamentals of Landfill Economics

Landfills are commonly owned and operated by either municipal governments or by private companies. While the cost structure and accounting mechanisms may differ between these two, the development, construction, operation, and closure of each will involve a common set of components. This section provides a basic discussion of landfill economics, including a discussion of cost elements, revenue sources, financial assurance, and the importance of economy of scale. While some sustainable landfill practices are introduced here, the next section is devoted to a detailed discussion of these considerations. Cost information consists of a combination of landfill construction rules of thumb as well as cost ranges presented in the literature for landfills in the US, although in many cases the costs (or at least the cost considerations) can be applied to landfills anywhere in the world.

18.2.1 Cost Elements

Substantial time and resources are normally required to develop a landfill project prior to any construction of the landfill unit itself. In addition to land acquisition, the site must be designed and permitted with the appropriate regulatory agency or agencies (see Chap. 3). If a permit is granted, the site must be appropriately developed, including construction of access roads and installation of required utility connections. Approximate up-front (pre-construction) costs for a landfill may range from USD 0.75 million to more than USD 1 million (Duffy 2005a; KDEP 2012). Support structures (e.g., roads, buildings) will be needed along with appropriate materials resources (e.g., borrow pit for cover soil). Table 18.1 provides a list of cost elements associated with the development and a construction of a landfill project outside of the disposal unit itself. Factors influencing the magnitude of the costs elements and related factors pertaining to sustainable landfill practice implementation are also presented.

Table 18.1 Typical costs elements for associated with landfill site development beyond those involved with the landfill unit

Cost element	Factors	Sustainable landfilling differential considerations
Site evaluation, planning, design	Planned site size, past and current land use, hydrogeological conditions, surrounding land use, geotechnical/soil conditions	None expected
Permitting	State and local regulations, inclusive of environmental/solid waste regulations and related regulations (e.g., management of surface water, wetlands, etc.), land-use regulations (e.g., zoning, conditional use permitting, certificates of need, and impacts to infrastructure)	Lack of state regulations allowing liquid addition, greater potential for permit appeal, potential increased permitting costs to address regulatory questions and comments
Borrow source	Availability and quantity of borrow material, type and characteristics of borrow material	Low permeability soils must be addressed in operations, could result in greater incurred cost
Land acquisition	Area required (buffer zone, landfill capacity, site geometry, support facilities), land costs	Potentially reduced area for waste disposal, increased buffer needs
Site fencing and access control	Cost of fencing, perimeter distance	Potentially reduced area requirements
Site buildings/ structures	Cost per area, types of buildings (offices, gatehouse, gas management, maintenance/ storage, public drop-off centers for recyclables and hazardous wastes)	None expected
Weigh scales	Scale cost, number of scales	None expected
Site utilities	Connections to electric grid, sanitary sewer, natural gas, potable water	None expected
Access Roads	Road construction and upgrade unit costs, length of roads	Potentially reduced area requirements
Landscaping	Unit cost of landscaping, area to be landscaped	Reduced area requirements
Financial assurance	Cost of maintenance of the financial assurance bond or other instrument, length of operating life, local regulations, length of post-closure care period	Potentially reduced duration of long-term care

Table 18.2 provides costs elements associated with the construction of the lined landfill unit itself. Cost elements associated with the construction include earthwork for sub-grade preparation, compacted clay liner or geosynthetic clay liner construction, geomembrane liner installation, and leachate collection system construction. The total cost for these components may range from USD 150,000 to USD 450,000 per constructed acre, and does not include earthwork needed for ground improvement or grade preparation for the constructed components (which may vary significantly from site to site). As landfill units are constructed on a frequent basis, (particularly at large sites where lined cells are constructed to provide several years

Table 18.2 Cost elements associated with the construction of the lined landfill unit

Cost element	Factors	Sustainable landfill differential considerations
Site clearing and excavation	Unit cost of clearing and excavation, soil hauling, area of construction, depth below grade	Area requirement
Site berms	Unit cost of construction and soil, berm design	Area requirement
Liner systems	Unit cost of liners, soil, drainage material, compaction, and liner installation; berm height; volume of soil; total area of liner; thickness of liner elements	Additional liner requirements
Leachate pumping and storage	Tank, pump, piping cost	Greater capacity for storage and pumping for recirculation
Leachate collection and recirculation system	Unit cost of purchase and installation of drainage material, piping; length of pipe; volume of leachate collection and recirculation pipe trenches; length of horizontal trenches and/or vertical wells for recirculation	Additional permeability in drainage layers; additional piping for recirculation, injection facilities; toe drains or similar infrastructure for managing seeps.
Gas extraction	Cost of piping procurement and installation, length of pipes, number and cost of wellheads	Increased gas generation rates, earlier installation of gas extraction system
Monitoring wells (groundwater and gas)	Number of wells and well installation, perimeter distance, well depth	Reduced area requirements, increased monitoring requirements

of capacity while not being so large as to be cost prohibitive), lined unit construction costs will be incurred throughout much of the life of the facility.

While the construction of the GCCS may lag several years behind the construction of the liner system and LCRS, it is another major capital expense associated with the landfill unit. GCCS construction may be required earlier at sites practicing sustainable landfill technologies. The capital costs associated with a GCCS include installation of extraction wells/trenches, piping network, a blower/flare system with associated controls, and a condensate management system. GCCS construction cost (exclusive of blower and LFG destruction devices) may range from USD 24,000 to USD 35,000 per acre (Duffy 2005b; US EPA 2015). Wells for monitoring for groundwater and landfill gas will require installation on the perimeter of any new lined landfill unit.

Operation and maintenance (O&M) costs of landfills consist of waste handling, cover use, litter control, training, utilities, permitting, financial assurance, sampling and compliance monitoring, leachate treatment, and transportation. Table 18.3 presents a summary of cost elements associated with landfill operation. O&M accounts for a substantial portion of a landfill's overall cost, normally comprising

Table 18.3 Cost elements associated with landfill operation and maintenance

Cost element	Factors	Sustainable landfill differential considerations
Daily operations	Costs of equipment procurement and maintenance, personnel, utilities, leachate treatment—labor costs, waste receipt rate, leachate generation rate, utility costs	Reduced leachate treatment volume, additional monitoring requirements, additional short-term gas generation
Daily cover	Area of daily waste placement, unit cost (or revenue) of soil or alternative cover material	Increased permeability or removal of daily cover
Monitoring costs	Area of landfill, specific permit conditions, number of monitoring points (e.g., groundwater monitoring wells, leachate sumps, gas collectors), prevailing labor rates, use of third party contractors	Leachate recirculation infrastructure monitoring, additional LFG collection infrastructure (if present), potential settlement monitoring

more than 50 % of a landfill's overall cost. Reported O&M cost for a GCCS is approximately USD 4,100 per acre per year (US EPA 2015), although this figure may vary substantially depending on the number of gas collection wells, system configuration, and monitoring frequency required. O&M of automated GCCS that have set control points adjusted by a computerized control system may be expected to have reduced O&M costs compared to a site that has GCCS components adjusted manually by an operator, but these systems would carry a greater construction cost.

Monitoring of landfill gas, groundwater, and other site features associated with the landfill (e.g., stormwater, waste elevation) will be normally required throughout the operational life of the landfill (and after closure). As described in Chap. 16, an expense that might be incurred at sites implementing sustainable practices relates to additional monitoring. This could take the form of more labor in terms of collection, added laboratory analytical expense, additional fill materials to address areas of differential settlement, and additional monitoring equipment.

At the end of the landfill's operating life, the landfill must be closed according to the site's permit and applicable regulatory requirements. At some facilities, closure is implemented only when waste acceptance activities at the site have reached completion, while other facilities practice closure of smaller areas at greater frequency (see Chap. 17 for a discussion on these strategies). Closure involves the construction of final cover system (a cap). Approximate closure cap construction cost (excluding GCCS) ranges from USD 150,000 to more than USD 300,000 per acre (Duffy 2005b; KDEP 2012; MDE no date).

After the site has been closed, the landfill must continue to be cared for to ensure environmental protection and compliance with the site's permit. This will include such activities as removing and managing leachate, collecting gas, maintaining the cover system, and continued monitoring. Annual post-closure care costs (which includes site security, cap maintenance, environmental monitoring) range from USD 2,000 to USD 3,000 per acre. Additional costs (and possibly revenue) might be incurred depending on the final end use of the facility (Table 18.4).

Table 18.4 Cost elements associated with closure, post-closure, and final site use

Cost element	Factors	Sustainable landfill differential considerations
Final cover	Unit cost of procuring, delivering, and installing materials (vegetation support, geotextiles, low and high permeability soil, geomembrane, landscaping), thickness of layers, area of closure	Closure timing, potential for recovery of air space
Post-closure care	Annual cost of final cover maintenance and replacement, well monitoring, operation of leachate and gas collection systems; number of years of post-closure care	Reduced length of post-closure care period, reduced long-term gas and leachate generation
Final site use	May include electrical service, buildings, surface preparation, significant fill material (e.g., golf course), miscellaneous infrastructure—the inclusion and extent of these factors depends strongly on the final site use that is planned	Similar considerations as post-closure care. Potential could exist for more flexibility in final site uses if site-specific data show reduced LFG production, slowed settlement, and improved leachate quality relative to conditions from a traditional landfill

18.2.2 Revenue Sources

Municipalities and private companies that own and operate landfills derive their primary revenue source from the fees charged to dispose of wastes in the landfill. These tipping fees are most often based on the weight of waste disposed, as measured by scales placed near the entrance of the facility, although facility owners may also charge fees on a per-truckload or volume basis. Van Haaren et al. (2010), based on a nationwide survey, reported that the statewide average tipping fees in the US ranged from USD 15 to USD 96 per ton. The tipping fees are used to pay for the construction and operation of the landfill unit and the costs associated with closure and post-closure care. They may also include revenue for other government functions in the case of municipally-owned facilities and will include profit in the case of private operations.

Another potential source of revenue at landfills sites is the sale of electricity or processed landfill gas. Technical information regarding the use of landfill gas as an energy source is provided in Chap. 19. Since the beneficial use of landfill gas is one logical outcome of sustainable landfill practices, additional economic information on gas-to-energy is provided in subsequent sections. The electricity or processed landfill gas sale prices are highly contingent upon the electricity and natural gas prices and incentives or other governmental incentives for renewable power. Other opportunities for energy recovery at landfill sites include solar power and wind power. As described in Chap. 19, if planned for appropriately, landfills may serve as the hub of material recovery operations, thus providing another potential source of revenue for the site owner.

18.2.3 Financial Assurance

Given the known costs associated with properly closing a landfill and maintaining it during the post closure care period, regulatory agencies require that landfill owners and operators demonstrate that funds will be available to close the landfill upon completion regardless of the revenues collected by the facility. Cost elements that must be accounted for in the financial assurance demonstration include closure of the landfill unit, care of the landfill unit during the designated post-closure care period (including environmental monitoring), and possible corrective action to address environmental releases. Landfill owners must demonstrate how the funds necessary for financial assurance will be provided during the active life of the landfill. Estimates of closure and PCC costs require the following: (a) knowledge of the point at which operations make closure most expensive; (b) an assumption that a third party will perform closure activities; (c) awareness that estimates are to be revised as conditions change; (d) an understanding that PCC includes periodic and annual costs; and (e) the ability to revise the estimated costs for inflation.

The owner/operator may be required by regulations to have a detailed written estimate of the cost of hiring a third party to close the largest area of the landfill that will ever require final cover during the active life and place that cost estimate into the operating budget. If changes to the closure plan increase or decrease the maximum cost of closure, the cost estimate must be changed accordingly. Similarly, regulations may require the owner/operator to follow the same criteria for PCC and dictate the same criteria for corrective action. Owner and operators may be required to demonstrate that funds are available to meet the cost of closure, PCC, and corrective action. Several mechanisms to meet these monetary obligations are provided in Table 18.5.

Table 18.5 Examples of instruments that can be used to demonstrate the satisfaction of financial assurance requirements for landfills

Financial instrument	Description
Trust fund	Asset set aside to pay for closure, PCC, and contingencies, typically held by a third party (e.g., bank). Funds typically established through fees collected during operations
Surety bond	Site owner pays a premium to a surety company that guarantees to pay the "penalty sum" of the bond to the designated agency should the owner/operator fail to perform the agreed-upon closure and PCC. These are typically used in two forms: financial guarantee bond and performance bond
Letter(s) of credit	Commitments from third parties, typically commercial banks, to provide monies if and when needed in accordance with credit agreement signed with the bank
Insurance	Contractual agreement whereby the insurer agrees to compensate the policyholder for losses
Financial tests	Also known as "self insurance", consists of a series of tests (e.g., a government may have financial, recordkeeping, and public notice requirements, while a corporation may have size, assets, and financial soundness as part of its test)
Guarantees	A guarantee can demonstrate that the required costs (all or a portion) can be paid for and that the guarantor can fulfill the financial obligations if the owner/operator fairs to perform

18.2.4 Economy of Scale

In general terms, economy of scale involves reducing a unit cost by realizing operational efficiencies. In a landfill context, many O&M costs (e.g., equipment, maintenance, fuel, equipment operators, technicians, administrative staff, and other administrative costs) are required regardless of the quantity of waste accepted at the landfill. Thus, increasing the amount of waste accepted will reduce the landfill's unit operational cost since the amount of revenue will increase. Accepting larger quantities of waste can also allow for waste to be placed in larger daily working areas or cells, which can allow the operator to use relatively less cover soil, which may also be a cost reduction.

18.3 Costs and Benefits of Sustainable Landfill Practices

The additional costs and benefits of sustainable landfilling were briefly discussed in the previous section. Additional capital and O&M costs are borne for liquid injection and leachate recirculation, air injection (if used), additional monitoring, side slope seep control, and early construction and operation of GCCS. Potential economic benefits of sustainable landfills include an extension of the active life of the landfill with more efficient airspace utilization, reduced leachate treatment/disposal costs, deferred new cell and final cover construction, earlier beneficial reuse of land, post-closure care savings from fewer monitoring and financial assurance requirements and reduced maintenance, and larger gas production which represents an opportunity to generate additional revenue when converted to energy.

Berge et al. (2009) conducted economic modeling of traditional and sustainable landfills, and information from this work is referenced in the following discussion. The sustainable landfill scenarios included as-built (initially designed and constructed as a sustainable landfill), retro-fit (converted into a sustainable landfill at closure), and aerobic. One clear result was that without advantages associated with reduced PCC, retrofit sustainable landfill and traditional landfills carried similar present worth (PW) costs. Increased O&M costs appeared to offset advantages associated with leachate treatment and air space recovery in a retrofit sustainable landfill. As-built sustainable landfills have lower costs than traditional and retrofit sustainable landfills, mainly because of utilization of the recovered air space and reduction in leachate treatment and management cost. The cost of aerobic landfills is greater than anaerobic where gas recovery and use is possible; the difference reduces when no gas recovery is planned or where leachate treatment costs are high.

Figure 18.1 provides a breakdown of the major cost elements (construction, O&M, leachate treatment, and post-closure care) as a function of total PW (since some of the costs are incurred in the future, costs were discounted in order to compare their present worth); assumptions for the cost calculations were provided in Berge et al. (2009). The magnitude of each cost element greatly depends on many

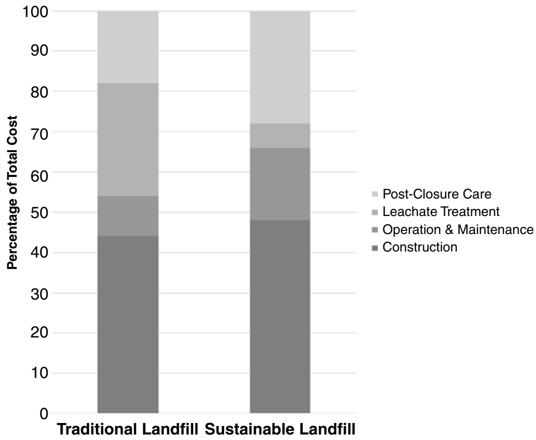

Fig. 18.1 Comparison of categorical costs for traditional landfills and sustainable landfills, adapted from Berge et al. (2009)

local factors including size of the landfill, cost of land, local/state regulatory environment, availability of materials and utilities, and other economic conditions. Construction costs represent the largest fraction of PW for both sustainable landfills and traditional landfills and may be greater for sustainable landfills than traditional landfills. Berge et al. (2009) assumed PCC to be of equal duration and is approximately 15–25 % of PW costs. PCC costs represent a greater fraction of PW for sustainable landfills because of the continued intensive operation of the landfill after closure to recirculate leachate and monitor the landfill, although this impact could vary depending on when leachate recirculation is initiated and terminated. Thus, for sustainable landfills, the potential to reduce the length of PCC can result in significant cost savings. Additional results from this analysis are presented as part of the following sections, which focus on issues related to liquids management, gas recovery, airspace gain, and external costs.

18.3.1 Liquids Management

The cost associated with the installation and maintenance of the liquids addition system is one of driving factors that influences the selection of a liquids addition approach (see Chap. 6–9). Some techniques are costlier than others (e.g., some surface techniques can be implemented with little cost and effort whereas installation of subsurface systems require more extensive resources). The availability of in-house resources (e.g., equipment, operators) has a significant impact on total project costs. If an operator has an excavator available on site, the construction of horizontal liquids introduction trenches might be a method that can be accomplished with existing landfill staff.

Table 18.6 The influence of leachate recirculation and treatment volumes on total PW costs (Berge et al. 2009)

Percent of leachate recirculated	Percent of traditional landfill leachate treated	Percent of traditional landfill treatment cost
50	50	60
75	25	35
100	0	0

Because of reduced leachate generation volume (absorbed by the waste) and partial treatment, leachate treatment costs can be significantly reduced for sustainable landfills. The potential for savings from reduced leachate treatment to outweigh the added costs from liquids addition system installation and operation is highly dependent on existing leachate treatment costs. Table 18.6 compares the present worth of sustainable landfill treatment costs with traditional landfills as a function of the amount of leachate recirculated as determined in the Berge et al. (2009) analysis; the more leachate that is recirculated, the lower the cost of leachate treatment.

The degree to which leachate can be recirculated into the landfill and stored within the waste depends on the field capacity of the waste and other factors. As shown in Chap. 6, MSW can store a large volume of moisture; operators thus realize the costs savings from deferred leachate treatment during the operating life of the landfill. A fraction of the liquids added to the landfill will return to the LCRS over time, and as indicated in Chap. 5, as waste decomposes and decreases in density as a result of increased overburden pressure, the waste's ability to sorb water reduces. Thus, at the point when new waste is no longer added to the site and when leachate recirculation is stopped, the owner and operator should be prepared for a greater leachate generation rate during the PCC period (compared to landfills where liquids addition was not practiced). This amount could be estimated with the waste characteristics and modeling tools presented in earlier chapters.

18.3.2 Gas Management

As described in Chap. 13, the operation of sustainable landfills (without air addition) can result in greater production rates of LFG, which can have multiple economic impacts. A major factor specific to costs and benefits related to LFG includes accelerated gas production during landfill operations and the difference in gas production rates after the landfill closes. Therefore, if the additional gas produced early on in the landfill's life can be captured, the difference represents additional energy production that can occur. Inefficient gas collection during the landfill's active phase, however, reduces the benefit of enhanced gas production and could add burdens such as increased gas emissions and potentially odors.

Since the potential to produce gas in a given mass of waste is fixed, accelerating gas production during active operations means that gas production after closure will be decreased relative to a traditional landfill. Thus, a lower LFG production rate would make a potential end use of the landfill site (or the ability to end PCC) more likely. Another consideration relates to lifetime greenhouse gas (GHG) emissions. Sustainable landfill operations would exhaust the bulk of the LFG production during or shortly after the landfill's operating life ends, thus the difference between the projected LFG production rate of a traditional landfill and the projected LFG production rate for the sustainable landfill would represent a reduction in lifetime GHG emissions. This certainly has obvious environmental benefits and could have economic benefits in the case where a carbon tax for GHG emitters is present.

The economic benefit of LFG recovery is subject to the market value of the energy produced. The viability of establishing a new LFG-to-electricity project will strongly depend on external factors, as the implementation of new electric generating capacity from LFG has historically mirrored the commodity price of natural gas. Note that in cases where a landfill already has a favorable contract or agreement to sell its collected LFG to an end user, collecting additional gas would be expected to enhance revenue generation provided the LFG is efficiently collected and the additional electric generating capacity can be sustained over an appropriate time horizon. Furthermore, the prevailing natural gas price may be less important at a facility that already has a contract to sell its LFG, since these agreements typically have a duration of 15 years or more.

Various factors, such as LFG collection rates, vicinity to industrial plants and their energy demand, prevailing electricity prices, and natural gas prices dictate LFG beneficial use project economics. The LFG-to-electricity construction cost ranges from USD 1,400 per kW (for a project size larger than 3 MW) to USD 5,500 per kW (for projects smaller than 1 MW) (US EPA 2015). The O&M cost ranges from USD 130 per kWh (for project size larger than 3 MW) to USD 380 per kWh (for projects smaller than 1 MW). Because of the complexities and relatively smaller number of pipeline-quality natural gas and vehicle fuel production projects, the costs of these projects are not as readily available as for electricity generation projects.

18.3.3 Air Space Recovery

A potential major benefit resulting from the implementation of sustainable landfilling practices is the creation of disposal capacity; this is often referred to as the recovery of airspace. Since landfills are typically permitted based on dimensions, the total waste volume that can be placed is the limiting factor. The airspace gain resulting from accelerated decomposition of waste could be realized during active operations (which would be accomplished with an as-built system) and sustainable landfill operations following the time when the landfill capacity is initially reached (the airspace gain in this case could be accomplished with an as-built or a retrofit system). This concept is illustrated in Table 18.7.

The benefit of airspace gain after initially reaching landfill capacity can only be realized if additional waste can be practically be placed. As an example, Powell and

Table 18.7 Considerations when accounting for airspace gain in sustainable landfilling economic evaluations

Factor	Discussion
Permitting and planning	Accounting for future filling activities for recovered airspace must be included as part of the planning and permitting process in advance. Failure to do so may eliminate airspace recovery as one of the economic benefits of sustainable landfilling operations
Recirculation initiation during active filling	If recirculation is initiated during active filling of a given cell (or cells), a potentially large amount of the airspace that could be recovered would occur during active filling or shortly thereafter, which should be accounted for in the economic analysis
Recirculation initiation after completion of active filling	Economic evaluation should examine what degree of the airspace gain could be practically recovered, with a focus on landfill dimensions. Note that some airspace gain (e.g., on lower portions of some side slopes) may not be practically recovered or represent an airspace gain that is too small to justify re-filling with new waste
Degree of settlement	The degree of settlement (and thus airspace gain) should account for the anticipated operations time of the sustainable landfill technologies, operating conditions of the sustainable landfill technologies (e.g., leachate recirculation rates), waste composition, and waste dimensions
Landfill infrastructure disturbance	The disturbance of landfill infrastructure as part of re-filling gained airspace (e.g., temporary covers like EGCs, GCCS infrastructure) must be accounted for of re-filling of airspace is to occur after the landfill initially reaches capacity

Townsend (2004) analyzed a specific case comparing an aerobic and an anaerobic sustainable landfill and found that only when the airspace value was high enough and the operating time was short enough would the benefit be realized in the aerobic sustainable landfill case.

The addition of waste to newly-created airspace following settlement can be a challenge to landfill operators for several reasons. First, while landfill settlement is a direct result of waste decomposition, these gains may not be realized immediately; the added liquids that promote accelerated waste decomposition also occupy pore space within landfill waste mass, and excess pore pressures must be first reduced through drainage before all of the potential settlement will occur. Second, depending on how the operator sequences waste placement and closure, adding more waste to areas where significant progress toward final cover has been reached may be cost prohibitive. The potential to re-fill airspace created from accelerated waste decomposition is far less likely if a final cover system is installed. The use of an interim or temporary cover system could provide the operator the ability to achieve some of the sustainable practice benefits of a cover system (e.g., enhanced gas collection efficient, liquids control) while still supporting future additional waste placement. An approach described in Chap. 17 is the use of exposed geomembranes caps as temporary cover systems. Table 18.7 presents factors to be considered when evaluating the potential for airspace gain at a sustainable landfill.

18.3.4 Social Costs

Social or external costs of landfilling include (1) amenity and land use impacts, (2) pollutant emissions, and (3) damages due to greenhouse gas emissions. Social costs are generally more difficult to quantify, but must be considered in estimating the value of sustainable landfills compared to traditional landfills.

Amenity losses may include odors, noise, visual intrusion, reduced property values, attraction of animals, traffic, and social stigma. These impacts are immediate, affecting the generation that created the disposed waste. However, as local impacts, their effects may be felt disproportionally by the immediate landfill neighbors rather than the true population that it serves. In many cases, those affected by lost amenities are compensated by landfill owners through profit sharing or community resource building, but this does not ensure sustainability of landfilling. The value of amenity losses is relatively low and has been estimated at approximately 1 USD/ton or 2 % of a landfill's PW (Mery and Bayer 2005).

Communities operating sustainable landfills will experience similar amenity losses to traditional landfills, although the impact of odors could be greater due to greater LFG production rates if the LFG is not efficiently collected. Conversely, a sustainable landfill could be touted as being "green", thereby reducing the social stigma of hosting a landfill. The value of a "green" landfill warrants further research.

Pollutant emissions could occur as a result of uncontrolled leachate (either breaches in liners or uncollected leachate after the end of PCC). Although leachate during active operation of a landfill is largely controlled in well designed and constructed landfills, estimating future pollutant emissions requires making assumptions about the integrity of liners over many years (perhaps centuries). Long-term risks would be expectantly lower than traditional landfills due to faster waste stabilization. Estimating the cost of pollutant emissions is challenging, but again these external costs should be considerably lower than other cost components.

As discussed earlier, the release of GHG emissions is an important factor when considering sustainable landfills compared to traditional landfills. Absent efficient LFG collection systems, the use of sustainable landfill technologies represents a greater potential for GHG emissions in the early stages of a landfill's life compared to a traditional landfill. However, if the LFG is controlled efficiently, substantial reductions in lifetime GHG emissions can be realized as was reported by Amini and Reinhart (2012). The external cost of damages due to GHG releases are estimated to be 21 USD/ton of CO_2 (Handley 2010). These costs could be offset by financial benefits (both external and private) due to sale of landfill gas or electricity/heat generated by the gas. External benefits would only occur if the sales offset the use of fossil fuel. Thus, for example, these benefits would be more pronounced if the energy offsets that which would be produced through coal combustion, but would be less pronounced if the energy replaces that derived from nuclear sources. This is a fundamental consideration when examining life-cycle impacts of sustainable landfilling (Chap. 3).

18.4 Costs and Benefits After Landfill Closure

As observed in the previous section, implementation of sustainable landfill practices poses additional capital and operational expense beyond traditional landfilling, but these added costs in many cases can be offset or exceeded by the savings that result. These savings, in the form of reduced leachate disposal costs or revenue from additional energy recovery or tipping fees (from capacity gains), will depend on regional- and site-specific conditions and economics. The largest potential economic benefits, however, relate to longer-term benefits that might result from sustainable operation. The remainder of this chapter discusses two of these: the potential for reduced PCC costs and a special case of airspace reuse through reclamation of stabilized waste materials.

18.4.1 Post Closure Care Costs

After closure, the landfill enters a PCC period that involves maintaining and monitoring the site for a regulatory- or permit-defined period (and possibly for perpetuity). As described many times already in this book, one of the major motivating forces behind the implementation of sustainable landfill technologies is the rapid stabilization of waste in the landfill so that the potential for deleterious environmental emissions is greatly reduced. Given that a primary driver in PCC is to make sure that the landfill does not produce such harmful emissions, rapid waste stabilization should, in theory, result in a landfill that can exit PCC requirements much sooner than traditional landfills, or at least the degree of monitoring can be reduced sooner.

Chapter 17 outlined a potential approach for transition a landfill from PCC to a custodial care phase where only minimal maintenance and operation are required (Barlaz et al. 2002; ITRC 2006). The proposed framework involves monitoring landfill emissions that may pose a risk to the human health and the environment as part of PCC and comparing resulting data and trends to accepted risk levels to determine when a change in PCC is warranted. The framework involves collecting and evaluating data as part of a modular assessment of four primary landfill components (leachate collection and control system, landfill gas collection and control system, groundwater monitoring system, and cap system).

Leachate quality should reach stable conditions more rapidly for facilities practicing sustainable technologies, although the volume of leachate may be greater for a period of time. As long as the final cover system has been adequately maintained, this should result in reduced long-term risk to groundwater resources. When waste is rapidly stabilized, potential maintenance issues with the final cover system can be addressed earlier, thus mitigating long-term performance issues. Gas production will decrease more rapidly when liquids addition is practiced, thus reducing the longer-term risks posed by methane escape to the atmosphere.

While sustainably operated landfills show great promise in providing outcomes that reduce the length of PCC, and these savings can be readily calculated based on an assumed early exit from PCC (compared to traditional landfilling), most regulatory programs do not have established rules or guidelines for facilities to reach such an outcome. This remains one of the challenges to incentivizing the adoption of sustainable practices at facilities where the near-term benefits are marginal.

18.4.2 Landfill Reclamation

Chapter 17 described the process of landfill reclamation, where landfill waste and cover soil are excavated (mined) and processed. Proposed targets of landfill reclamation include facilities where the waste reaches a point of adequate stabilization such that the landfilled material and additional disposal capacity can be recovered. The soil fraction, when segregated from waste, can be beneficially used to replace new soil used for cover material, and possibly beneficially used outside of the landfill. Potential economic benefits include the avoided cost for new cover soil, the sale of recyclable materials reclaimed from a landfill, and airspace gain for new waste disposal. Such practices can greatly extend the operating life of the landfill and allow the receipt of additional tipping fees with much reduced expenditure of capital construction costs, as well as closure and PCC costs. The overall waste disposal footprint becomes less and thus carries with it the other benefits associated with decreased land use.

The reclamation process, of course, comes with an added expense in terms of equipment and labor. Table 18.8 presents the reclamation costs associated with a number of projects conducted in the US. Cost elements associated with the reclamation include excavation equipment and operation, processing costs (screens, magnets), labor cost, hazardous or problematic waste screening, and management of bulky items. Material transportation costs represent another major project expense, and depend on the number of size fractions the excavated waste is separated into, the production rate of each fraction, haul distance, and route condition and traffic. Other costs not listed above may be associated with the execution of a mining project such as design, permitting, mobilization/demobilization, other environmental considerations, and contingencies.

The cost effectiveness of landfill reclamation will usually depend on the amount of material that can be separated for beneficial use. Some fraction of the excavated material will require re-disposal in the landfill, and if this fraction is large, the processing costs will outweigh any savings associated with additional airspace recovery. While some of the airspace recovery costs will be associated with reclaimed materials for recycling, most will derive from the use of previously placed cover soil and degraded organic waste to replace cover soil in the active landfill operation (or to use for application outside the landfill unit). An economic feasibility analysis for landfill reclamation should include field investigations (e.g., auger borings, test pits) to estimate the relative amount of material that can serve this purpose.

Table 18.8 Summary of excavation volumes and costs for landfill mining projects in the US (IWCS 2009)

Project	City, State	Years of operation	Waste volume mined (million m^3)	Mining cost (\$/m^3)
Phoenix Rio Salado Project	City of Phoenix, AZ	1999–2005	0.31	
Clovis Landfill	City of Clovis, CA	1998–2008	1.61	$6.33
Naples Landfill	East Naples, FL	1986–ongoing		$2.94[a]
Dean Forest Landfill, City of Savanna	Statham, GA	1997–2006	0.50	
Central Disposal Systems	Lake Mills, IA	2000–ongoing	0.19	
Town of Edinburg	Town of Edinburg, NY	1990–1992	0.04	$6.54
Pike Sanitation Landfill	Waverly, OH	1996–2000	0.54–0.61	
Wyandot County Environmental Sanitary Landfill	Carey, OH	1999–ongoing	1.07	$5.23[b]
Frey Farm Landfill	Lancaster, PA	1990–1996	0.23–0.31	$11.51
La Crosse County	WI	2005–2007	0.31	
Shawano County	WI	2001–2002	0.23–0.31	$3.92[a]
Perdido Landfill	FL	2009–2011	0.38	$8.37

[a]Per ton basis

[b]No waste processing. Waste was relocated from unlined cell to a lined cell

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Chapter 19
The Role of Landfills in Integrated Materials and Energy Recovery Facilities

Abstract The book concludes with a discussion of sustainable practices for landfill design and operation within the broader context of integrated waste management and associated facilities. With the rising importance of preserving material resources and avoiding wasted potential energy, facilities implementing sustainable landfilling techniques can serve as a companion to other processes in an integrated fashion to create a more sustainable materials management system overall. The employment of technologies to extract energy from landfill gas and to use the landfill itself as an energy production center through solar cells or wind power, in addition to using landfills as waste treatment and materials recovery cells, are just a few examples of the opportunities explored.

Keywords Landfill • Bioreactor • Energy • Sustainable • Materials management • Solar • Wind

19.1 Landfills, Energy, and Resource Recovery

This book began by discussing the evolution of solid waste management technologies over the past half-century. In many countries, waste management has transitioned from open dumps to sanitary landfills, while some have gone beyond sanitary landfilling into more advanced waste treatment and recovery processes. This book provides guidance on how landfill owners and operators can plan, design, and operate landfills to be more sustainable, which is of critical importance given continued reliance on landfilling worldwide as a method to manage waste. Although landfills are still the least preferred option in most waste management hierarchies, landfilling is the method used to handle approximately 70 % of the world's wastes. The landfills we create today will remain, and based on projections (World Bank 2012), we will continue building and using landfills for many years to come. In light of this trend, it is of critical importance to view landfills as opportunities to innovate and to improve the manner in which landfills are designed and operated to optimize resource use and energy recovery.

Thus far this book has described both fundamental and practical aspects of sustainable strategies for landfill design and operation. Topics have largely focused on methods to design and operate so deleterious impacts to human health and the

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environment are minimized. Modern landfill regulations are structured to accomplish this over the short term, and implementation of sustainable practices work towards achieving such objectives over the long term. This chapter ends the book with a discussion of how landfills currently, and potentially in the future, may be integrated into a larger waste management system that holds sustainability as the paramount goal. This includes the role of landfills as both a location for energy recovery and the concept of landfills operated as components of sustainable materials management systems, not simply disposal facilities.

19.2 The Role of Landfills in Integrated Waste Management

Given that landfills will still be a necessary piece of an overall waste management system, the landfill site can host of a multi-process facility where recyclables and other materials of value can be extracted from the waste stream, potentially converted (through physical, biological, and/or chemical processes) and shipped off site for reuse or beneficially used on site. An example of on-site resource recovery is the operation of a co-located materials recovery facility for the recycling of waste constituents such as aluminum and plastic containers, followed by consolidation and export from the site to a manufacturing facility, also possibly located adjacent to the landfill. In this case, the landfill acts as a central facility where waste materials are delivered and a separate processing area on site is used to provide for the extraction of targeted recyclables. Any discards from the recovery operation can be easily transported to the landfill.

An example of on-site reuse is the segregation of vegetative waste materials, subsequent size reduction, and ultimate use as a cover material at the landfill. In this case, the reuse is beneficial because it provides a productive use for a waste material and avoids the extraction and transport of virgin materials (e.g., nearby soils) that may have otherwise been used as a cover material. Some of the vegetative material would convert to gas for possible recovery as part of a LFG-to-energy system. Table 19.1 provides several more examples of waste materials that may be beneficially used at the landfill itself.

As mentioned throughout the book, despite the presence of other technologies that can be considered more sustainable than landfills (e.g., composting facilities, energy-from-waste facilities), the landfill still plays a critical role in the event that waste production outstrips available capacity at these other facilities, if the facilities experience downtime due to equipment maintenance or failure, for disposal of WTE and MRF residuals, or if the processed materials do not meet specifications. Thus, the co-location of other waste processing technologies or facilities at the landfill site can provide economic and environmental benefits such as reduced transportation costs, utilization of energy produced and harnessed at the landfills to power these facilities, and the potential to save costs on labor by personnel cross-training to perform multiple tasks or functions at different co-located facilities. These facilities can serve as community centers that encourage and promote sustainable materials management (Fig. 19.1).

Table 19.1 Examples of waste materials that may be beneficially used at landfills

Waste material	Beneficial use at a landfill
Ash from waste-to-energy	This material may be used as an alternative daily cover material
Asphalt shingles	Un-processed shingles can be used on interior landfill roads to improve access and reduce dust generation
Glass	Crushed glass can be used as a permeable medium provided it meets required specifications. Examples may include permeable media surrounding liquids addition devices or gas extraction devices
Tires	Size-reduced tires may be a permeable medium used in liquids addition systems or gas collection systems
Yard waste/ vegetative waste	Size-reduced yard waste can be used as a cover material at the landfill's working face or potentially in other areas that require an intermediate cover (e.g., areas where, based on the filling sequence, waste will not be placed for several months or longer). Depending on the chemical quality and local restrictions, mulched yard waste may be used on site for landscaping or marketed as a product for businesses or individuals in the community

Fig. 19.1 Recycling drop-off center co-located at a closed landfill

As discussed in Chap. 17, landfills can serve as a repository for materials that may not currently have sufficient value to warrant extraction at the time of delivery to the landfill, but may have enough value in the future to justify excavation, processing, and resource and energy recovery. Jain et al. (2014) reported that significant environmental benefits can be realized with recovery of resources deposited in MSW landfills. When a landfill is included as a part of a larger integrated waste management facility, the tracking and planning that can go into landfill mining is greatly facilitated relative to a case where waste handling facilities are scattered throughout a community. As an example, the co-location of a landfill with a waste to energy (combustion) facility would allow the landfill to act as temporary storage in cases where the waste acceptance rate at the facility exceeds that which can be combusted—in this case, the waste is placed in the landfill and extracted at a later time when capacity becomes available.

19.3 Beneficial Use of LFG

LFG extracted using a GCCS can be described as a *medium energy value* gas because of the relatively high CO_2 content that is present. In this form, the gas can be utilized for energy recovery with a variety of technologies. Alternatively, the LFG can be first processed or cleaned to produce a *high energy value* gas that opens up other energy recovery opportunities. The specific market need for the gas dictates the type and level of processing and treatment required to deliver the gas in a form that meets the necessary specification or energy project objectives.

As discussed in Chap. 13, the kinetics of LFG production are altered when operating a landfill with liquids addition. If necessary GCCS components are in place and are designed to accommodate the liquids addition system components (and the greater amounts of liquids), tremendous opportunities exist to enhance the viability and effectiveness of a LFG beneficial use project. While the ultimate volume of gas that can be produced from the waste remains the same, the period of production is compressed into a smaller timeframe that may enhance the economic viability of a LFG-to-energy project. These higher gas production rates should be planned at the design stage of the GCCS, particularly since some LFG beneficial use technologies and markets may be more sensitive to variation in LFG collection rates than others.

The following sections outline the major types of LFG beneficial use options available for energy conversion. These include conversion to energy, medium energy content (medium BTU) application, and high energy content (high BTU) applications. Where appropriate, we provide specific commentary on how each technology's use may be impacted by sustainable landfilling operations.

19.3.1 Electricity Generation

Electricity generation is one of the most common techniques to harness the energy content of LFG. Some of the benefits of electricity generation include many years of demonstrated success at hundreds of landfill sites, operating parameter flexibility, and the ability to expand or contract the system in response to increasing or decreasing LFG collection rates. When electricity is produced, it can be used for on-site power needs or sent to the power grid. A variety of technologies are available to generate electricity from collected LFG, many of which are summarized in Table 19.2.

Table 19.2 Technologies that may be used to convert collected LFG into electricity

Technology	Description
Cogeneration (Combined heat and power, CHP)	Generate thermal energy and electricity from steam or heated water. Can be installed to recapture heat losses from turbines and engines to produce steam, thus increasing the overall efficiency to as much as 85 % (US EPA 2010; ACEEE 2009)
Combined CycleEngine	This system utilizes both gas and steam turbines. The gas turbine provides the heat needed to generate steam that is then fed to the steam turbine. Combined cycles are utilized for scales larger than most internal combustion projects (US EPA 2010) Efficiencies for combined cycles range from 54.5 % to 60 % (MNSU 2014)
Gas Turbine	Can operate at lower CH_4 concentrations; gas turbines typically require larger volumes of gas for economic feasibility resulting in effciencies as large as 60 % (US Department of Energy 2014; US EPA 2010). More resistant to wear and damage than other systems
Internal Combustion Engine	A common type of electricity generation technology, efficiencies typically range from 25 % to 35 % (US EPA 2010). CHP can be implemented with internal combustion engines as well to further enhance overall system efficiency. The LFG may need to be pretreated for removal of contaminants such as siloxanes and H_2S
Microturbine	Used for smaller-scale power generation operations; units with rated capacity as low as 35 kW are commercially available. Typically employed in areas with lower gas flow rates. Pretreatment of LFG to remove moisture is necessary in addition to the usage of activated carbon to remove other impurities. Microturbines can operate at low CH_4 concentrations. Efficiencies for this system ranges from 20 % to 30 % (US EPA 2010)
Boiler/ Steam Turbine	LFG is directly used by combusting it in a large boiler to generate steam that is fed to a steam turbine. Generating electricity in this manner is fairly uncommon (US EPA 2010)
Stirling Engine	An external combustion engine that mixes air and fuel within the cylinder of the unit to facilitate combustion. Pretreatment of LFG is not needed because of the engine's high tolerance for siloxanes and other such impurities. An average efficiency obtained is 30 % (US EPA 2010)

Internal combustion engines are one of the more common electrical generation technologies for LFG (Fig. 19.2). In electricity generation applications, a key design consideration involves the examination of actual and projected LFG collection rates so that the engine(s) can be economically phased in and out of operation. Ideally, LFG-to-energy projects are sized based on actual historical collection rates rather than desktop projections. This is especially true in the case of sustainable landfills, as field data demonstrating greater LFG production and collection rates would serve as necessary justification to implement greater electric generating capacity.

Fig. 19.2 Internal combustion engine for converting landfill gas to electricity

19.3.2 Medium Energy Content Applications

Medium energy applications are often referred to as *direct use* in that the LFG is utilized without elaborate LFG processing, often in an industrial process such as a boiler or a kiln. Another direct use application of LFG includes leachate evaporation. The combustion equipment at the receiving facility often requires minimal modification to accept the LFG, and the benefit to the receiving facility can range from partial or complete replacement of other fuels such as natural gas. End users typically must have some baseline or steady fuel demand for the benefits of LFG utilization to be maximized, although other industrial plants that may only need fuel on a periodic basis (e.g., a batch asphalt plant) could still be a viable option. The distance from the landfill to the end user must be evaluated as part of the planning and permitting process. Although gas treatment is normally not required, removal of condensate, and possibly corrosive gases and particulate matter, is typically done. The benefits of enhanced gas production from sustainable landfill operations are only truly realized if the additional gas is captured and the LFG-to-energy system's demand is large enough to accommodate additional energy potential.

19.3.3 High Energy Content Applications

While the CH_4 content of LFG is sufficiently high for combustion in many types of energy recovery units, several additional beneficial use options become available when the gas is cleaned to a level similar to natural gas. Such applications are referred to as high energy content (or high BTU content) because the LFG constituents (e.g., CO_2) that do not have sufficient energy content that can be efficiently harnessed are removed. Several technologies are available to remove major and trace LFG constituents as summarized in Table 19.3. These include various chemical wash technologies, membrane separation, and pressure swing adsorption (Fig. 19.3).

Once major problematic trace gas components are removed from LFG, the resultant gas can be used in several high BTU applications. Like other LFG beneficial use technologies, the selection of a given energy use or conversion technology depends on numerous factors including availability and quality of LFG, capital and operating cost of the technology, demonstrated use of the technology, and availability of end uses or users for the final product following conversion of the LFG. Table 19.4 presents some of the technologies that can be employed in high BTU applications.

Table 19.3 Summary of LFG cleanup technologies for high BTU applications

LFG cleanup technology	Technology description
Selexol process	Uses a solvent derived from dimethyl ether and polyethylene glycol for removing NMOCs, CO_2, H_2S, and water vapor. The solvent is regenerated at the end of the process and recycled. This process does not remove N_2 and O_2
Kryosol process	Uses methanol to physically absorb water, CO_2, and other trace constituents such as heavy hydrocarbon and H_2S in a stepwise fashion. Methanol is regenerated and reused in the process. The recovered CO_2 can be used to produce food-grade quality liquid CO_2 that can also be sold
CO_2 wash process	Gas is treated to remove H_2S and water vapor before it enters a CO_2 wash column where the gas is cooled to liquefy and accumulate on the top tray of the column. A portion of this liquid CO_2 is sent down to adsorb LFG contaminants (mainly volatile organic compounds). The exit gas constituents are CH_4 (75 %), CO_2 (25 %), and any O_2 and N_2 present in the inlet LFG; this process cannot remove O_2 and N_2
Membrane technology	Raw LFG is introduced into a vessel filled with separation polymers (typically consisting of a bundle of hollow fibers), separating CO_2 from CH_4, taking advantage of the fact that different LFG constituents flow through polymeric membranes at different rates. Provides limited removal of O_2 but N_2 is not removed
Pressure swing adsorption	Separates CO_2 from CH_4 by selective adsorption of CO_2 on the surface of special porous solid absorbents. The adsorption occurs at an elevated pressure, and when the pressure is reduced, the adsorbed CO_2 desorbs. Because of a cyclic, continuous change in pressure, this technology is referred to as pressure swing adsorption. Two types of adsorbents used for cleanup of LFG are molecular sieve and activated carbon. A molecular sieve is a packed bed of granular material, typically aluminosilicate minerals called zeolites. These materials are porous and have a high internal surface area that can adsorb CO_2. The raw LFG must be pre-treated to remove sulfides and water vapor for an effective adsorption of CO_2. A molecular sieve can be configured to remove N_2. The process does not remove O_2

Fig. 19.3 Pressure swing adsorption and membrane equipment for cleaning up landfill gas to high energy content

Table 19.4 Examples of applications for cleaned-up or high-BTU LFG

High BTU application	Description
Compressed or liquefied natural gas	Cleaned-up LFG is compressed or liquefied for use as a vehicle fuel. The fuel may be used on site or shipped to another facility for use
Hydrogen production/fuel cells	Used in combination with other technologies, cleaned-up LFG is used to produce hydrogen, with the end purpose of providing the hydrogen to run a fuel cell or cells
Pipeline-quality natural gas	LFG is cleaned up to meet the pipeline quality specification, compressed and injected into a natural gas pipeline

19.4 Additional Energy Opportunities

The space occupied by landfills, including the disposal area and associated buffer space and support facilities, represents an additional opportunity to recover energy beyond the conversion of collected LFG. Landfill sites offer unique advantages for hosting renewable energy technologies. For example, landfill sites have infrastructure that supports electricity generation and, because of their commonly rural locations, may not be a viable host for technologies that clean-up the gas to natural gas quality because of a limited base of potential users. New energy technologies provide additional revenue to site owners and job opportunities in rural areas. Renewable energy projects can offset the environmental impacts of fossil fuel-based options and of the landfill itself. In considering the use of a landfill as an energy park, several factors have to be considered including available area, climate, geographic location and compatibility with the site's closure plan. Two examples discussed in this section are solar panels and wind turbines. Detailed design, operation, permitting, and cost discussion lies beyond the scope of this book, but the following discussion presents fundamental considerations associated with these energy options and how these considerations tie in with conditions at sustainable landfills.

19.4.1 Solar Power at Sustainable Landfills

Landfills can provide favorable opportunities for solar power generation once they are closed; landfills typically have large exposed areas where solar photovoltaic panels can be placed. Harnessing solar power in this manner may represent the largest energy generation opportunity for closed landfills (Millbrandt et al. 2013). Table 19.5 details the reported characteristics that influence the suitability of solar infrastructure development at landfills (US EPA 2013).

Once a landfill is determined to be a locational fit for a solar project development, guidance related to matching up appropriate photovoltaic technology to the landfill site should be consulted. Integration of solar panels with power generation infrastructure is an integral step in the solar energy implementation. Several factors may facilitate this process (Messics 2009a), including close proximity of power lines (e.g., three-phase power may be needed for large installations), the local utility's need for renewable energy, and the presence of a LFG to energy plant on-site. As LFG production declines, energy production capacity can be supplemented with solar power. The use of generated power on-site is generally more financially beneficial (since it replaces retail-rate power) than wholesale of generated power to the grid, but the benefits of sending some or all of the produced power to the grid should be considered at the feasibility analysis step of the solar project.

Table 19.5 Fundamental considerations for the utilization of solar power at landfills

Fundamental consideration	Description
Meteorological conditions	For economic feasibility based on current panel/flexible panel installation cost, a minimum of 3.5 $kWh/m^2/day$ of solar radiation is generally advised, in addition to at least 6 h of sufficient sunlight on the winter solstice (lowest yearly sunlight exposure) as a baseline. Optimal topography includes flat or gently sloping grades (US EPA 2013)
On-site energy needs	A solar photovoltaic system can be capable of meeting 100 % to 120 % of a landfill's on-site energy requirements (US EPA 2013)
Grants or incentives that are in place (tax breaks)	Economic incentives increase the overall value of energy produced from photovoltaic cells. The Database of State Incentives for Renewable Energy (DSIRE) is a guide that provides information regarding grants, incentives and policies on federal, state, local, and utility levels in the US (Messics 2009a; US EPA 2013)

Table 19.6 Photovoltaic cell and solar panel technologies available

Types of solar technology available	Description
Fixed system	This system uses a fixed unit that is positioned to capture the most solar power for a given location
Rotating system	These systems are able to actively or passively track the sun on either 1 or 2 axis using light sensors or timed systems
Crystalline silicon	Most common type of photovoltaic technology composed of thin layers of polycrystalline and with efficacies of 11 % to 20 % (EPIA 2012)
Thin panel systems	Photovoltaic cells composed of thin layers of photosensitive materials. Low efficiencies of 5 % to 13 % are offset by this system being at a lower cost when compared to crystalline silicon (EPIA 2012)

Fig. 19.4 Ground mounted solar panels equipped with single axis tilt on top of a closed landfill (*Photo courtesy* NREL)

Table 19.6 presents a summary of available photovoltaic technologies and information regarding their potential for use at landfills. Fixed and rotating ground-mount systems are most commonly used (Fig. 19.4), though thin film panel systems that can be directly attached to the exposed geomembrane caps are gaining popularity. Tansel et al. (2013) reports that flexible (i.e., thin panel systems), while lighter and lower in cost to crystalline panels, tend to be less efficient at converting solar radiation to electricity.

Installation and operation of solar energy technology at landfill sites involves some unique challenges, with respect to both system design and construction, operation, and maintenance (US EPA 2013). From a closed landfill perspective, it is uncertain whether sustainable landfilling would pose any substantially different challenge compared to a traditional landfill. Sites can be regraded to produce a more favorable angle for panel placement, and on closed sites special care should be taken to ensure the cap is not penetrated (SRA International 2008). One consideration is timing of installation; if sustainable landfilling operations are initiated after a landfill cell's design capacity is reached, the accelerated degradation of waste likely will result in greater settlement (due to the added load from solar infrastructure), which may not occur uniformly (Sampson 2009). Additionally, greater differential settlement as a result of accelerated waste degradation would have some impact on the stability of the solar panels. Thus, fixed solar panel systems may be more susceptible to damage.

While higher energy yields are possible for panels placed on landfill side slopes, there is the potential for instability, settling, and slope failure, particularly within the first 5 years of the post-closure period (Tansel et al. 2013). Differential settlement is of particular concern (as opposed to overall settlement) and designed flexibility can help a photovoltaic array adapt to changing conditions (Sampson 2009); information on waste thickness and density, solar infrastructure weight, site soils, and placement times can be used to estimate settlement in the design process. Snow and ice accumulation on solar arrays, particularly on panels situated on side slopes, can also be problematic and remedies for these common issues have been reported (Sampson 2009; US EPA 2013).

Case studies addressing solar energy generation via photovoltaics collocated with landfills have been reported in the literature; Tansel et al. (2013) profiled two Florida (US) landfill sites, where energy yield and wind loads were examined and a sloped configuration was found to produce more favorable outcome with respect to both parameters. The maximum energy yield was 426 kWh/m^2 (at a 20° westerly tilt); a side slope placed panel arrangement was shown to decrease wind loading (at 146 mph required design wind speed) from 58 to 44 lb/ft^2 and 46 to 39 lb/ft^2 at the two landfills from loads measured on panels oriented in a flat arrangement. According to NREL, South Florida receives approximately 5.0 kWh/m^2/day on an annual average basis.

Another solar power case study was examined at a landfill in Pennsauken, NJ; photovoltaic panels, covering 10 acres (of a total 39 acre site), were installed on top of older, unlined waste cells from 2006 to 2008 (Messics 2009b). The site contained a LFG-to-energy plant initiated in 2004 and a landfill cap topped with grass vegetation overlying the landfill's final cover system. Solar panels were installed along the side of the landfill (ground mounted), an on the plateaus of several cells, and side slopes of another cell (2.1 MW capacity for cell-mounted panels) (Messics 2009b). Recommendations and lessons learned during the Pennsauken project included placement on older slopes minimized necessary grading and earthwork, south slope installation maximized power output, and that installation cost ranged $7–$8 per watt for plateau installation and $8–$9 per watt for side slope installation.

Flexible photovoltaic panels (<0.25 in. in thickness) were installed over 2.27-acre exposed polyolefin thermoplastic geomembrane cap section at Tessman Road Municipal Solid Waste Landfill (San Antonio, TX) in 2009. The 134.4-kW solar

Fig. 19.5 Flexible solar panels on the EGC at a landfill in Georgia, US

power system at the site complements an on-site LFG-to-energy plant. The panels were chemically adhered to the geomembrane on the south-facing side slope. The electrical conduits were installed in the anchor trenches for the geomembrane. Approximately 7,000 flexible solar panels were installed over approximately 10-acre area of the 45-acre landfill cell at Hickory Ridge Landfill (Atlanta, Georgia) in 2011 (Fig. 19.5). The panels were installed on top the thermoplastic exposed geomembrane cap. The total cost for this 1-MW system was reported to be USD 5 million.

From a sustainable landfill perspective, one unique opportunity lies in utilizing an exposed geomembrane cap (EGC) installed early (e.g., when a side slope meets its design grade but well before a final cap is to be installed) to capture LFG during initial stages of gas production and coupling solar panels with the EGC. In this case, the landfill operator would realize the benefits of additional gas production while also harnessing solar power through the use of EGC-mounted panels. As with solar energy projects with closed landfills, the feasibility scenario described above would need to be examined on a site-specific basis and account for aforementioned potential challenges such as panel placement, potential settlement, and other factors.

19.5 Wind Power at Sustainable Landfills

Wind energy projects involve placement of wind turbines on large towers. Turbine blades rotate in response to passing wind movement and this movement turns the shaft of a generator to produce electrical power. A transformer at the base of the tower steps up the voltage to the necessary level for the accompanying power

Fig. 19.6 Wind turbine on closed landfill (*Photo courtesy* NREL)

distribution system. Turbines are typically spaced apart 14 or more times the blade length. Industrial size blade lengths range from 100 to 150 fit in length.

In regions where sustained winds support economically viable wind power, closed landfills offer potential locations for wind energy projects (Fig. 19.6). Millbrandt et al. (2013) reports that wind power ranks second (behind solar) in opportunity for renewable energy resource development on landfills in the US (including closed landfill sites), with a total potential of 2,700 TWh (energy efficiency of 30–65 %, based on class II turbines with an installed energy generation density of 5 MW/m^2). Wind speeds of approximately 16 km/h (10 mph) are nominally required; wind speeds increase at greater distances from the ground. The wind speed affects the type of wind turbine that would be selected for a site, class II, the most common type of turbine is typically for sites up to 8.5 m/s average wind speed.

A landfill site may be ideally suited from a location perspective as it is often higher in elevation than surrounding land, provides a large area of tree- and building-free land, and is often already located a sufficient distance away from homes and businesses. The presence of the LFG to energy system at a site, as with solar projects, increases feasibility of wind projects at a landfill site due to in-place power transmission infrastructure (although the complications of numerous piping systems infrastructure may pose a technical challenge; Millbrandt et al. 2013). Table 19.7 details relevant resources and considerations for siting of wind turbines, sites should have adequate, sustained wind speeds.

US EPA's Wind Decision Tree is one resource available for wind-turbine siting. Computer-based geographic information systems (GIS) can also aid in consideration of many siting factors at once (economic as well as environmental and ecological impacts). While Millbrandt et al. (2013) did not consider wind power at landfill sites, given the abundance of other marginal lands and the relatively small areas of landfills, collocation may be feasible if standard wind power constraints are

Table 19.7 Siting and land usage considerations for wind turbines at landfills

Resources and considerations	Description
Wind resource maps	These maps show locations where strong, sustained winds are expected based on historical data on wind speeds and area elevation above sea level (US EPA 2012)
Topography	Landfills greater than 80 m above sea level and with wind speeds below 5.5 m/s are not appropriate for wind power (US EPA 2012)
Land use considerations	Generally, sites like landfills are preferred when possible for siting wind turbines so that green space can remain undisturbed, sometimes referred to as “marginal lands” and estimated at roughly 11 % of total US land in the contiguous 48 states (Millbrandt et al. 2013). These marginal lands include landfills, brownfields, abandoned crop land, other barren lands
Landfill-specific considerations (either on the waste footprint or within site boundaries)	At sites with a LFG to energy system, power generated via wind turbines can be “piggybacked” onto existing power infrastructure
Exclusions	Some criteria that would preclude a site from wind turbine installation (Millbrandt et al. 2013):
	• Slopes >20
	• High-value lands
	• Urban areas

met. van Haaren and Fthenakis (2011) reported use of GIS for a state-wide assessment of potential wind-farm sites in the state of New York; infeasible sites were first excluded, then economic assessment of remaining sites was performed, and impact on birds were considered. Landfills have the benefit of having no land clearing requirement, which can be a substantial cost (68–84 % of total project cost) (van Haaren and Fthenakis 2011).

A challenge for installing wind turbines on landfills is the design of a foundation that provides necessary support. Foundation types include spread footings, deep anchors, and tensionless pier foundations. In addition to utility-scale wind power projects, the use of a small number of turbines or chimneys possibly with storage capacity to provide small, site-scale power to provide energy for day-to-day landfill functions, such as sump pump, gas collection system, air blower (for air circulation to waste in aerobic systems) operation has been suggested (Stormont et al. 1998).

Hickman et al. (2014) conducted a study evaluating the potential for closed Florida landfill sites to be used as energy parks. A screening tool was created that utilized broad criteria such as landfill location, size, and site conditions to select landfill sites that might be suitable for three alternative energy technologies, landfill gas to energy, solar power, and wind power. These criteria were based on readily available data, such as atmospheric and weather conditions (e.g., historic wind speeds, cloud cover, and precipitation), landfilled tonnage, area availability, and surface irradiation. Landfills that were potentially suitable for the technologies were further evaluated using site-specific variables. Technologies were evaluated with respect to electrical production, levelized cost, payback periods, environmental impacts, energy intensity over service life and more.

Out of 27 landfills randomly-selected Florida (US) landfills, 24 (89 %) were found to be good candidates for wind turbine technologies, solar power was potentially suitable for 21 (78 %) landfills, and landfill gas-to-energy was technically feasible at 10 (37 %) sites, while 20 (74 %) were candidates for two or more technologies and eight (30 %) were candidates for all three technologies. Of the four application case studies completed, all three technologies were found to be viable during prescreening for three landfills and wind and solar was viable at the fourth. Wind was consistently the most environmentally advantageous of the three technologies. Calculated payback periods were found to be longest with wind (54–80 years), followed by solar (22–24 years) then landfill gas (2–5 years).

19.6 Landfills as Waste Treatment and Materials Recovery Operations

Landfills by their nature are intended to be the final resting place for discarded solid waste. Throughout this book, practices to enhance the stabilization of landfills were presented and techniques to extract energy at or from landfills were described. Additionally, the concept of landfill reclamation (introduced in Chap. 17) raises possibilities for perhaps the most sustainable manner in which a landfill might be operated: a treatment operation where the landfill cell serves as a temporary treatment unit designed to be emptied and later refilled.

Figures 19.7, 19.8, 19.9 and 19.10 illustrate this concept. The first landfill unit would be constructed, filled with waste, and operated using practices such as liquids addition and LFG collection and beneficial use (Fig. 19.7). Unit 2 would be built as Unit 1 is filled. After reaching capacity, Unit 1 would be closed using technologies such as an EGC (possibly equipped with solar cells) that would be less permanent (and less costly) than a traditional final cover system. Unit 1 would continue to be operated to stabilize the waste and harvest LFG while Unit 2 was filled (Fig. 19.8).

Unit 3 would come on line as Unit 2 reached capacity (Fig. 19.9). During this time, Unit 1 would be at the point where the waste is largely stabilized and thus prepared for reclamation. While Unit 4 operates, Unit 1 would be mined and made ready for acceptance of new waste upon closure of Unit 4 (Fig. 19.10). In this conceptual model, it is expected that some residual materials will be left over. As described in detail in Chap. 17, the mining process could involve varying degrees of material screening during the excavation process. The ultimate volume that would be reclaimed in this process would depend on the degree of stabilization that the waste achieved during sustainable landfilling operations, the nature of the waste, and other factors. But this concept illustrates an idealized version of what sustainable landfilling can be when planned from the beginning and cells are built, sequenced, operated, and harvested with the primary concept of preparing the waste to be treated, treating the waste, and utilizing the stabilized residuals. In light of society's anticipated continued reliance on landfilling as a means of managing discarded

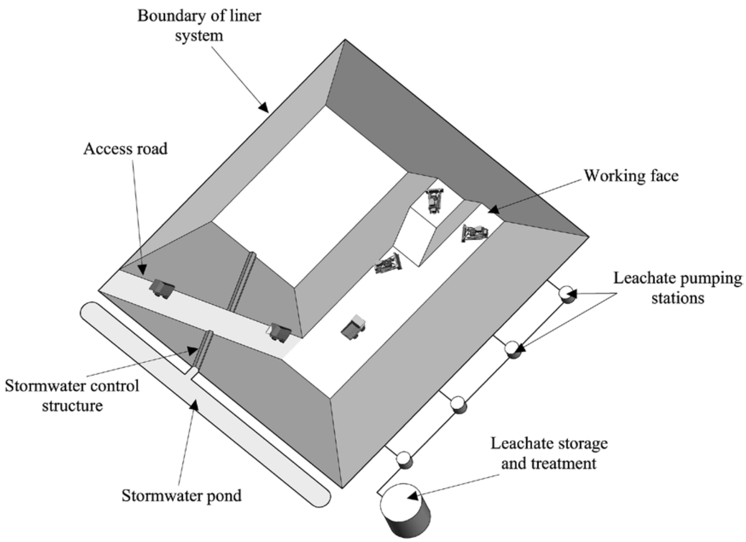

Fig. 19.7 Conceptual sustainable landfill operation. Cell 1 constructed and operated

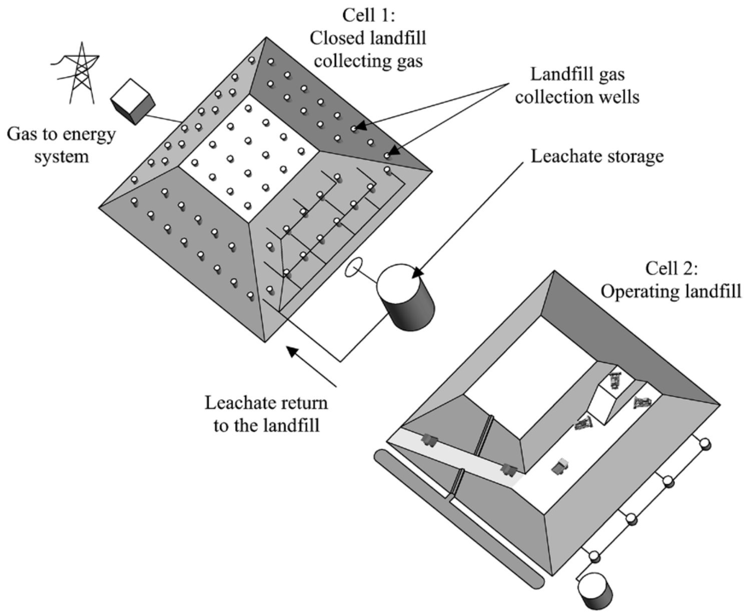

Fig. 19.8 Conceptual sustainable landfill operation. Cell 1 closed, treated, and gas harvested. Cell 2 constructed and operated

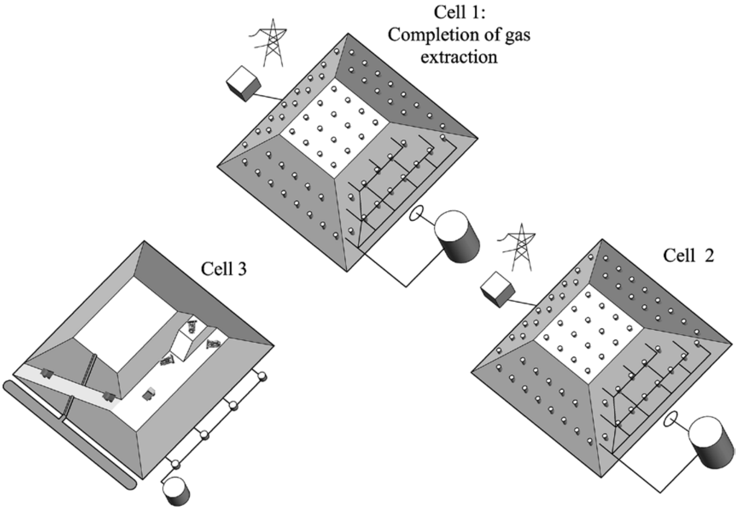

Fig. 19.9 Conceptual sustainable landfill operation. Cell 1 operated and decommissioned; Cell 2 closed, treated, and gas harvested for energy; Cell 3 constructed and operated

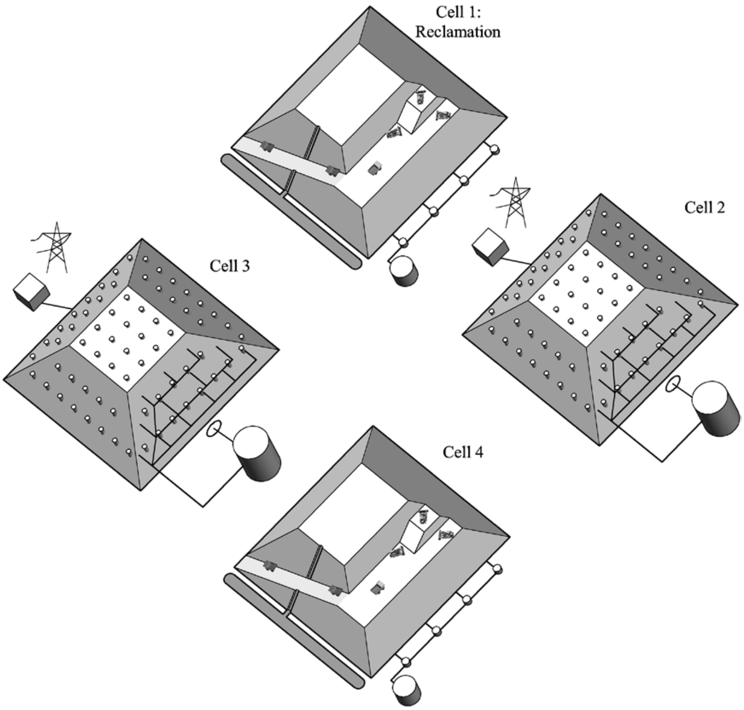

Fig. 19.10 Conceptual sustainable landfill operation. Cell 1 reclaimed; Cell 2 operated and decommissioned; Cell 3 closed, treated, and gas harvested for energy; Cell 4 constructed and operated

materials, the sustainable landfilling concept represents an opportunity to extend the life of spaces designated for disposal while harvesting the embodied energy within the discarded materials in a manner that mitigates impacts to the environment.

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