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4 Biotic and Abiotic Processes

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INTRODUCTION

The goal of waste management is to contain or control the movement of contaminants from a storage or disposal facility to levels that ensure the health and safety of the public and the environment. Questions concerning the behavior of contaminants in the environment inevitably lead to the conclusion that abiotic and biotic processes are key driving forces that determine the fate and effects of hazardous and radioactive materials. This is not surprising when considering that it has taken ecosystems millions of years of evolution to be effective at capturing and/or redistributing materials in the environment. Consequently, when contaminants are introduced into the environment, ecosystem processes begin to influence the distribution and transport of these materials, just as they influence the distribution and transport of nutrients that occur naturally in ecosystems. What has become abundantly clear is that a fundamental understanding of the basic principles and interrelationships of material flow in ecosystems can be applied to predicting and altering the fate of many anthropogenic materials in the environment (Whicker and Schultz, 1982). Restoration of disturbed lands, practices for applying fertilizers and pesticides to agricultural lands, and disposal alternatives for hazardous and radioactive waste have all benefited from applying our understanding of ecosystem processes to the correction of environmental problems.

The relative importance of biotic and abiotic processes in mobilizing waste contaminants is dependent on the waste type (high-level waste, uranium mill tailings, and so on), waste form (liquid, solid, gaseous), method of disposal (landfill, incineration, and the like) and environmental factors including the climate, geology, and ecology of the disposal area. Historically, most wastes were buried on or near the ground surface in shallow excavations or natural depressions using technology similar to that used at municipal landfills. As regulations have become more stringent, performance criteria for landfills dictate that rigid standards be met in limiting waste migration (McAreny et al., 1985).

Abiotic and biotic processes encompass a broad spectrum of interrelationships; however, we will focus on a few key processes that directly relate to waste management. While it is convenient to discuss those processes individually in this chapter, the strong interdependencies and feedback mechanisms argue for a more holistic treatment of the subject. As a compromise, we will attempt to point out interdependencies and feedback mechanisms between processes as appropriate in the chapter.

In the last fifteen years there has been a tremendous proliferation of federal and state laws controlling virtually all aspects of wastes from cradle to grave (Fig. 1.1, Chapter 1). A major emphasis of federal and state regulations concerning all of the waste types considered in this book (low-level waste, high-level waste, transuranic waste, hazardous waste, and uranium mill tailings) is on measuring, predicting, and controlling certain components of the hydrologic cycle (US NRC, 1983; US EPA, 1985). This is especially true for disposal technologies that use the surface (uranium mill tailings) or near-surface (low-level, transuranic, and hazardous waste) environment where most hydrologic processes occur. Hydrologic transport, particularly through fractures, is also a major concern at the candidate high-level waste (HLW) repository at Yucca Mountain, Nevada (see Chapter 8), despite the very low annual precipitation and the extremely small percolation rates at the proposed repository levels of several hundred meters below the ground surface (US NRC, 1983). Therefore, our discussion of abiotic processes as they relate to waste management will be focused on surface water balance and erosion, including the role of biota, in modifying the hydrologic response of the disposal unit, and subsurface water movement through soils and other geologic media.

Our treatment of biotic processes, in addition to their role in water balance, will include a discussion of biological intrusion into the waste leading to the uptake and biological transport of contaminants. While chemical processes are an integral part of the processes discussed in this chapter, their relationship to the treatise of this book is covered in Chapter 7.

PURPOSE OF CHAPTER

The purpose of this chapter is to identify and describe key biotic and abiotic processes that influence the mobility of a variety of waste types and how these processes influence waste disposal in arid and semiarid environments. In addition, examples will be given on how a fundamental understanding of abiotic and biotic processes can be used to achieve regulatory compliance for waste site performance. Finally, we will review the state of knowledge concerning abiotic and biotic processes as they influence waste disposal, point out strengths and weaknesses in our understanding, and identify some of the key technical issues for future research.

DESCRIPTION OF DISCIPLINES

General

The subject of abiotic and biotic processes encompasses many disciplines because of the interdependencies and feedback mechanisms concerning both the structural and functional attributes of ecosystems. For example, hydrology, as a discipline, requires some understanding of oceanography, meteorology, limnology, soil science, geology, geomorphology, climatology, plant physiology, biogeochemistry, and chemical, civil, and environmental engineering. Likewise, biotic processes are strongly dependent on the hydrology of ecosystems in that the vertical and horizontal distribution of many organisms and chemicals is strongly related to the vertical and horizontal distribution of water. Legal and political considerations also play a key role in determining how and to what level these disciplines are applied to waste disposal problems.

A field of endeavor that has had a major impact on our understanding of ecosystem structure and function is radioecology or, as it's also known, radiation ecology. Beginning in 1946 and extending to the Nuclear Test Ban Treaty of 1968, the large-scale introduction of fallout radionuclides into the environment from atmospheric testing of nuclear weapons provided the ecologist with unprecedented opportunities to gain fundamental understanding of how the environment is structured and how it works (or functions). The field of radioecology arose from research on the ecological relationships that govern the distribution, transport, and effects of radionuclides in ecosystems (Whicker and Schultz, 1982). Much of our current risk assessment technology for predicting the effects of radionuclides in the environment was derived from radioecological research and the related discipline of radiobiology, which is the study of radiation effects on molecules, cells, organ systems, and organisms. As with hydrology, radioecology is very much a multidisciplinary field of endeavor and requires strong contributions from physical, biological, and chemical sciences.

Because hydrology and related disciplines involve complex data sets that are three dimensional and variable in space and time, measurement and modeling strategies require a good understanding of mathematics, statistics, and computer science. Ideally, mathematical models reflect our level of understanding of the environment and, based upon that understanding, can be used to forecast the behavior of contaminants over the long time frames for which data are generally unavailable. Models are also useful in planning the direction of research needed to fill in knowledge gaps. On the other hand, our ability to conceptualize and construct complex computer models of contaminant transport in the environment can easily outstrip our ability to make the measurements to validate them. Consequently, modeling and measurement programs must be closely coordinated to optimize the acquisition and use of research results.

Biotic Processes

"Biotic processes," as used in this chapter, refer to mechanisms whereby living organisms, populations, and/or communities influence the ability of a waste site to contain waste. Biota can have very beneficial or detrimental effects on the performance of a site in isolating waste, as will be discussed in following sections. Radioactive fallout from atmospheric testing of nuclear weapons led to major advances in our understanding of biotic processes in ecosystems. Because the behavior of environmental radioactivity is largely determined by the structural and functional attributes of ecosystems, observations on the distribution and transport of radionuclides provided great insight on how ecosystems are structured and how they work (Comar, 1965; Whicker, 1983). For example, the behavior of soluble forms of radionuclides such as Sr-90, Sr-89, Ba-140, and Ca-45 has been studied to elucidate the cycling of the nutrient calcium (Hsiao, 1963).

Likewise, Cs-137, Rb-86, and K-40 generally mimic the behavior of potassium (Davis, 1963) while I-131 and I-133 behave identically to stable iodine (Hanson, 1963). Tritium (H-3) has been especially useful in studying a variety of physiological and ecological problems on water relationships (IAEA, 1967; Elwood, 1971). Plutonium, which does not have a close nutrient analog, has been used to study soil erosion because of its propensity to adhere tightly to soil particles (Hakonson et al., 1976; Hakonson and Nyhan, 1980). In fact, radioecological studies of plutonium and other relatively insoluble radionuclides in terrestrial ecosystems have shown that the major mechanism whereby plutonium enters food chains is through the ingestion of contaminated soil particles associated with food items (surficial deposits on plant tissue and soil on the pelt and in the gastrointestinal tract of prey species) (Romney and Wallace, 1977; Hakonson and Nyhan, 1980).

The literature on the transport of radionuclides into and through biological pathways is extensive (Adriano and Brisbin, 1978; Anonymous, 1980; Hakonson and Nyhan, 1980; Whicker and Shultz, 1982; Whicker, 1983). Depending upon the source and solubility of radionuclides, transfer by biotic processes can lead to elevated (above background) radiation doses to target organisms, including humans. In some cases, radionuclide concentrations increase with increasing trophic level, which is sometimes referred to as biomagnification. For example, Cs-137 concentrations in carnivore flesh can be two to three times higher than in their primary herbivorous prey. An example is in the lichen–caribou–Eskimo food chain where Cs-137 concentrations in eskimos increased by a factor of three over that in their herbivorous prey (Hanson, 1967). Another example is in the mule deer—puma food chain, where Cs-137 levels increased by a factor of two from prey to predator (Pendleton et al., 1964).

However, many of the longer-lived radionuclides are relatively insoluble in environmental and physiological fluids and are discriminated against as they move to higher levels in the food chain. The actinides, including plutonium, are good examples of radionuclides that do not readily pass through biological membranes (Watters et al., 1980; Anonymous, 1987). As mentioned previously, many radionuclides with low solubilities in the environment can enter food chains primarily by physical (soil attachment, ingestion, and inhalation) rather than physiological processes.

Abiotic Processes

Abiotic processes are those that involve physical factors such as wind and water. As used in this chapter they refer primarily to hydrologic and associated erosional processes that influence the stability of waste sites and the mobilization of contaminants. The history of surface water balance and soil erosion research is tied closely to the collapse of the agricultural heartland (the Dust Bowl) and the concurrent collapse of the national economy (the Great Depression). These events provided significant impetus for existing soil and water conservation research (such as that by Bennett, 1939). Not only were the economics imperative, but the New Deal provided a moral and patriotic basis for public works and conservation for the general welfare. It was within this setting that some significant advances were made, many of them based on work initiated in the previous decade (such as that by Nelson, 1958; Meyer, 1982; Renard, 1986).

Of particular interest to hydrology and erosion in arid areas was the Taylor Grazing Act of 1934, which resulted from the recognized need to control the grazing of domestic animals on public land. This legislation opened the door for future research in arid areas by providing the need for a technological basis for grazing management systems. An interesting contribution was "Soil Erosion and Stream Flow on Range and Forest Lands of the Upper Rio Grande Watershed in Relation to Land Resources and Human Welfare" by Cooperride and Hendricks (1937), wherein overgrazing and timber cutting were identified as two main factors contributing to accelerated erosion and flooding. Findings of this type have guided much of the range and forest research in the western United States.

A key source for the study of semiarid and arid rangelands is "Rangeland Hydrology" by Branson et al. (1981). Although the book does not emphasize true deserts, it is a valuable source for specifying the differences between hydrologic characteristics in the West versus the more humid East.

A recent discussion of watershed processes and erosion and sediment yield models was published as part of the U.S. Department of Energy (DOE) sponsored Symposium on Environmental Research on Actinide Elements (Anonymous, 1987). Lane et al. (1987a) described, in detail, watershed processes, sediment yield models, and two upland erosion models. They identified criteria for application of more complex models and illustrated the applications with examples.

Section 208 of Public Law 92–500, the 1972 amendments of the Clean Water Act, specifically focused on pollution emanating from areal sources (as opposed to point sources) and provided an impetus for the development of hydrologic models, erosion models, and nonpoint-source pollution models, and coupled models addressing all three aspects. Most of these models were developed for cultivated croplands (such as those by Crawford and Donigian, 1973; Donigian and Crawford, 1976; Beasley et al., 1977; Wischmeier and Smith, 1978; and Knisel, 1980) to evaluate the influence of various farming practices in controlling soil erosion, herbicide and pesticide transport to groundwater, and irrigation schedules to optimize water use. The CREAMS Model (Knisel, 1980) was subsequently extended to semiarid and arid conditions (Nyhan and Lane, 1982) and the SPUR Model (Wight and Skiles, 1987) was developed specifically for rangelands. However, the SPUR model did not have the nonpoint-source pollution emphasis of the earlier models.

Subsurface hydrology has its quantitative foundation in the experiments performed by Darcy (1856) on water flow through sands. The results of these experiments led to the formulation of Darcy's Law, to be discussed in the following sections. The similarity between driving forces in unsaturated flow systems and saturated flow systems (when all air spaces in soil are filled with water) was presented by Buckingham (1907). Richards (1931) derived the equation governing unsaturated flow by combining Darcy's Law and functions for water content, conductivity, and capillary suction (capillary forces holding water in soil). In the last 30 years, subsurface hydrology, particularly for unsaturated flow conditions, has seen rapid advancement in technical areas such as analytical solution techniques, parameter estimation, coupled processes, and stochastic analyses. Readers may consult the following texts for further information: Bear (1972), Bear (1979), Freeze and Cherry (1979), and Marsily (1986).

More recently, regulations have played an important role in determining research topics in subsurface hydrology. The national program for geologic disposal of high-level radioactive wastes (Chapter 8) has emphasized flow and transport in fractured rock and coupled processes such as the combined heat–solute–water flow. Disposal of hazardous wastes in near-surface settings has also created an impetus for studying flow and transport in unsaturated media. In particular, the Resource Conservation and Recovery Act (RCRA) establishes important criteria that must be met to control migration of wastes via subsurface processes.

CONTAMINANT TRANSPORT IN ECOSYSTEMS

We re-emphasize that abiotic and biotic processes can mobilize contaminants in the environment. These processes are also coupled (that is, they influence one or more of the others), dynamic (they change with time) and are usually controlled via complex feedback mechanisms that are difficult to measure and model.

Because landfills have been and continue to be a common method for waste disposal, we will use them to illustrate how biotic and abiotic processes can lead to waste migration. The processes and interrelationships that will be described influence any type of waste disposal facility. How they apply to low-level waste (LLW) versus HLW, for example, differs only in the relative importance of the various components comprising the transport process.

Shallow land burial (SLB) has been used as a waste disposal technique since the beginning of man. As early as 6000 B.C., Neolithic and pre–Elamite civilizations, in what is now Iran, used SLB for disposal of waste (Langer, 1968). In more recent times, as a consequence of expanding populations, industry, and the development of nuclear and non-nuclear energy for power, concern has arisen about the adequacy of SLB for containing the potentially hazardous waste byproducts generated by these developments. This concern has given rise to a host of federal and state regulations controlling waste disposal (US EPA, 1985; McAreny et al., 1985).

Low-level radioactive waste such as that generated by the nuclear power industry, hospitals, universities, and nuclear research and development facilities is typically buried in shallow earth excavations of variable size but generally averaging 15 meters (m) wide by 15 m deep by about 200 m long (Fig. 4.1) Trenches are filled with waste consisting of a very heterogeneous mixture of materials, including laboratory trash, reactor parts, and dismantled buildings. A trench cap about 1 to 2 m thick is applied as a final covering to complete the isolation of the buried waste from the biosphere.

The more than 40 years of operating experience at disposal sites for LLW demonstrates that SLB technology works fairly well for isolating buried radionuclides, although virtually none of the six commercial and six DOE sites has proven 100 percent effective (Duguid, 1977; Jacobs et al., 1980; Hakonson et al., 1982). Of the six commercial LLW sites, three are currently operational; the closure of three of the commercial sites is at least partly attributable to unanticipated problems with the integrity of the burial site.

If we examine the ecosystem processes that affect site performance, with their potential impact on dose to humans (Fig. 4.2), it is apparent that hydrology and erosion, as influenced by physical, chemical, and biological factors, account for most of the performance-related problems (Duguid, 1977; Jacobs et al., 1980; Hakonson et al., 1982).

Figure 4.1. Shallow Land Waste Burial Site for Low-Level Radioactive Waste. Typical dimensions are about 20 m wide by 20 m deep by 200 m long.

For example, erosion associated with runoff from the surface of the site can breach the cap and expose waste to the biosphere (Nyhan and Lane, 1982; Nyhan et al., 1984). Consequently, erosion rates must be within tolerances to leave the cap intact over the mandated lifetime of the facility. Likewise, water that infiltrates into the cap can accumulate in the trench (bathtub effect) and/or percolate with solute(s) into groundwater. Percolation also increases subsidence of the cap as a result of the decomposition of bulky waste in the trench. Finally, both plants and animals, besides playing an important role in water balance, can penetrate into the waste and transport radionuclides to the ground surface as a result of root uptake and/or burrowing activities.

Surface Processes

Although vegetation is important in controlling erosion and percolation (Nyhan et al., 1984), deep-rooted plants can access buried radionuclides and bring them to the surface of the site (Foxx et al., 1984). Radionuclides

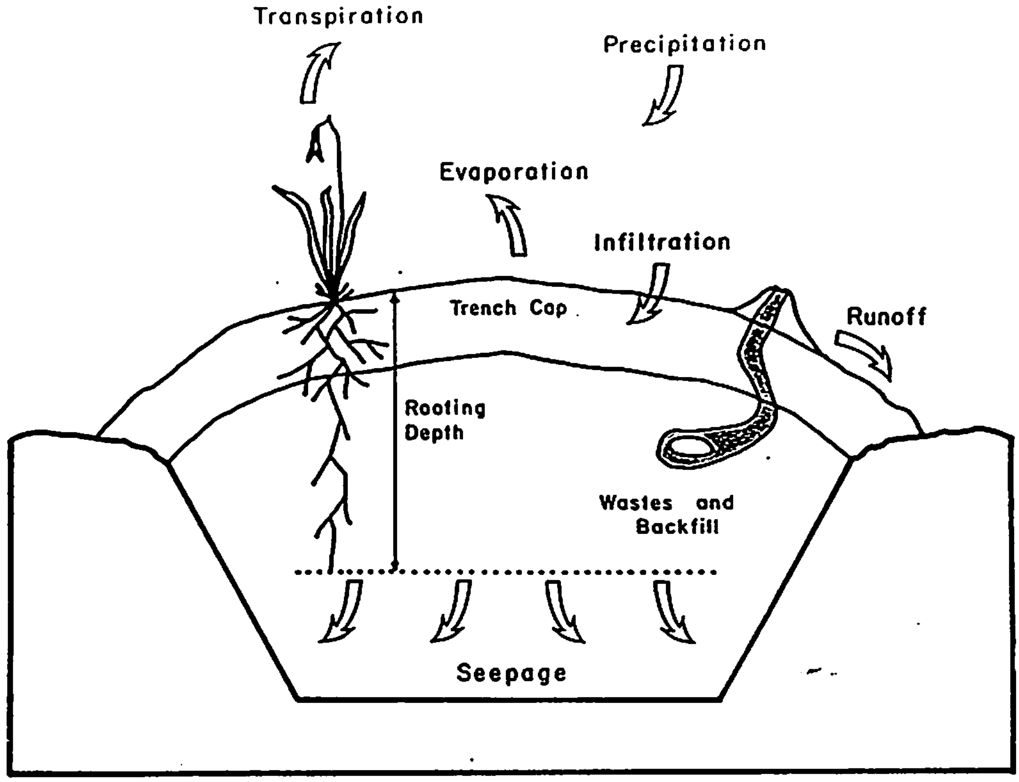

Figure 4.2. Hydrologic and Biotic Processes Affecting Shallow Land Burial Site Integrity.

in plant tissue can be transported through the food chain to humans (Anonymous, 1967) by herbivorous or nectivorous species. At Los Alamos, New Mexico, one of the pathways of tritium transport away from a controlled low-level waste site is via the soil moisture/plant nectar/honey bee/honey pathway (Hakonson and Bostick, 1976); however, radiation doses to humans who might consume this honey are very small and well within regulatory limits (ESG, 1988). Likewise, tumbleweeds growing on low-level waste sites are effective in transporting Sr-90 to the ground surface at Hanford, Washington (Klepper et al., 1979).

The importance of preventing buried waste from reaching the ground surface is illustrated by a pathway representation of plutonium behavior in terrestrial ecosystems (Fig. 4.3). Radionuclides buried below the ground surface can be absorbed by plant roots and deposited in above-ground plant tissue. However, when the radionuclides are present on the soil surface, as is the case at several waste sites, physical resuspension of soil particles (especially the clay fraction) by wind and water can deposit contaminated soil particles on plants (such as leaves, stems, and fruiting bodies) (Dreicer et al., 1984; Foster et al., 1985) and animals (such as pelt, lungs, gastrointestinal tract); (Romney and Wallace, 1977; Hakonson and Nyhan, 1980). Field studies (Hakonson and Nyhan, 1980; Watters et al., 1980) with plutonium, as well as other radionuclides, show that for every pi-

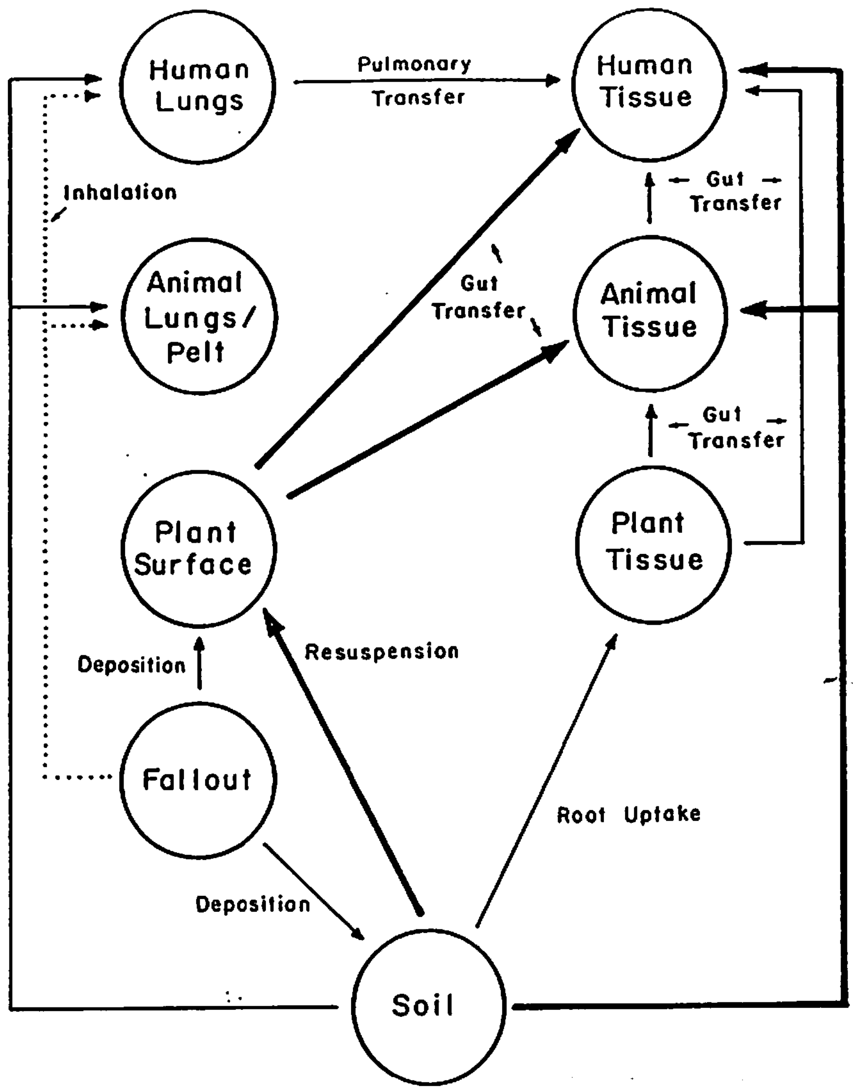

Figure 4.3. Transport Pathways for Plutonium and Other Radionuclides in Soil. Physical transport of soil particles with subsequent deposition on biological surfaces can dominate in the transport of many soil contaminants to biota.

cocurie taken up through plant roots, at least 10 picocuries (and often 100 to 1000) can be deposited in association with soil particles on foliage surfaces. Of course, most herbivores consume those radionuclides whether they are on or in the plant. Even in humans, who usually wash vegetables before consumption, as much as 50 percent of the radionuclides taken in from consuming certain vegetables may be from very small soil particles, such as clays, that are not removed from crop surfaces by standard household food washing procedures (White et al., 1981).

Physical resuspension of soil particles and

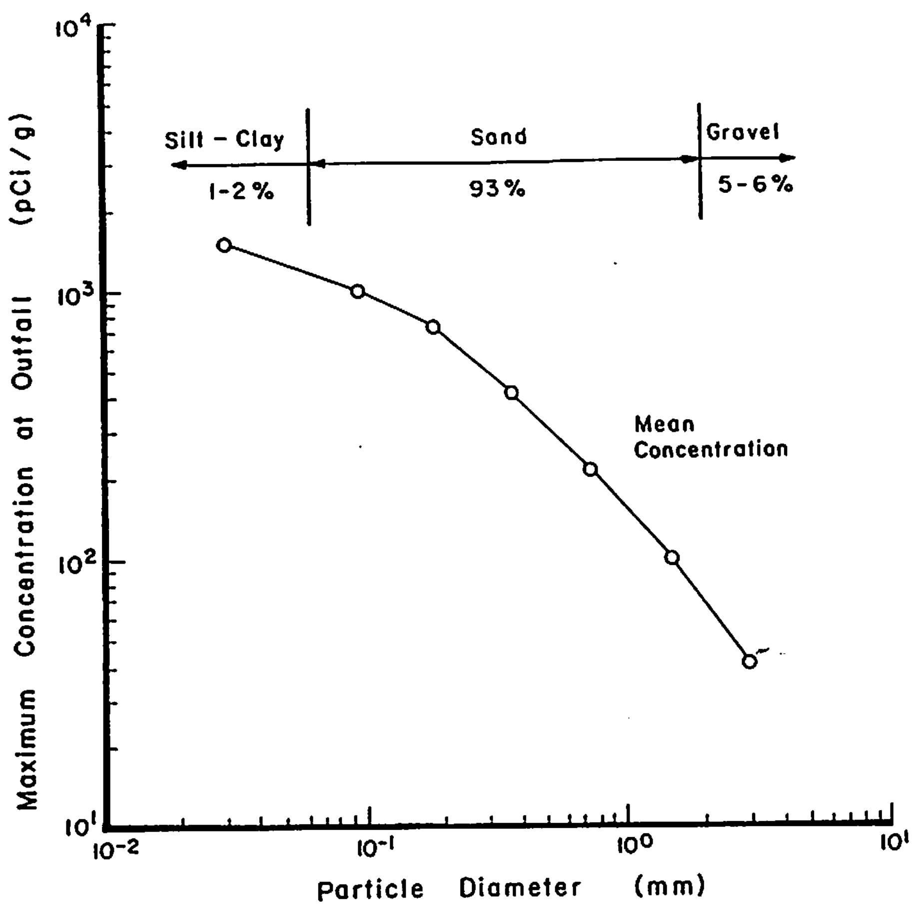

Figure 4.4. Plutonium Concentration and Soil Particle Site.

deposition on plant and animal surfaces is a very efficient mechanism for moving contaminants into biological pathways because there is often a very strong relationship between contaminant concentrations in soil and soil particle size. For example, concentrations of plutonium in the smaller silt/clay fraction of soil may be a factor of ten higher than in coarser fractions (Fig. 4.4). This is relevant because both wind and water sort particles during the erosion process, and smaller fractions are more readily eroded and transported than larger fractions. This means that the smaller fractions, which contain the highest concentrations of contaminants, are being transported to biota more frequently than the larger fractions with lower concentrations. These general relationships also apply to the translational movement of contaminants by wind and water erosion in that the very fine fractions are most easily detached and transported (Lane and Hakonson, 1982; Foster and Hakonson, 1984). Furthermore, the fine fractions are transported over longer distances than coarser fractions before they are deposited. Hence,

Figure 4.5. Low-Level Waste Debris Excavated by a Burrowing Animal.

areas that collect very fine sediments (such as reservoirs) can have high concentrations of the contaminant in sediment deposits (Sprugel and Bartelt, 1978; McHenry and Ritchie, 1980).

While plants can mobilize buried waste, they also play an extremely important role in water balance. In arid and semiarid climates, plants may transpire up to 100 percent of the annual precipitation back to the atmosphere (Federer, 1975; Saxton, 1982). This means that very little or no soil water may be available for percolation below the root zone.

The role of animal burrowing in mobilizing buried waste is generally unknown. A limited database (O'Farrell and Gilbert, 1975; Winsor and Whicker, 1980; and Arthur and Markham, 1983) demonstrates that burrowing animals can transport radionuclides vertically in the soil profile (Fig. 4.5) and influence water balance and erosion by changing the physical and hydrologic characteristics of the soil (Aubertin, 1971; Grant et al., 1980; Lysikov, 1982). Trench covers are disturbed soil systems, often loosely compacted, and are easily invaded by plants and animals. Burrowing animals sometimes use the void spaces left after trench backfilling as tunnels and nesting sites (Connolly and Landstrom, 1969; Arthur and Markham, 1983).

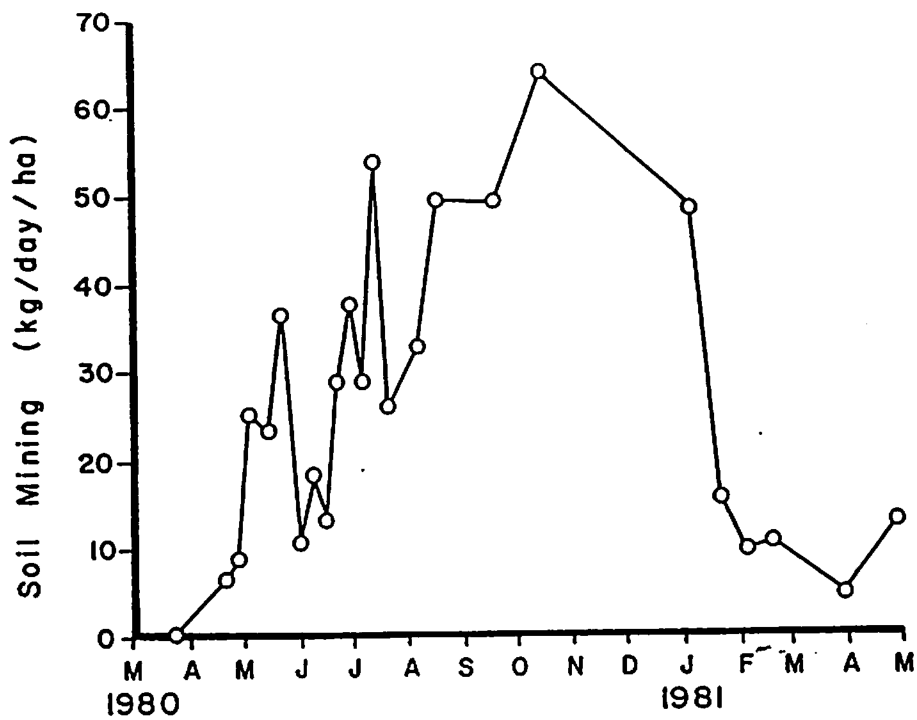

Figure 4.6. Rates of Pocket Gopher Surface Deposits on a Low-Level Radioactive Waste Burial Site.

Burrowing activities by animals play an important role in chemical cycling in the soil profile. The vertical transport of Fe, Se, Al, Ca, Mg, U, Ra, and Th from deep soil layers to the surface by the mechanical action of rodents (Maslov et al., 1967; Abaturov, 1972) has given rise to the statement that burrowing rodents serve as nutrient pumps that bring materials to the soil surface for weathering (Chew, 1974, 1976). As mentioned before, soil and chemicals brought to the surface are more readily available for resuspension and transport into biological pathways by physical processes.

Although burrowing animals can access and transport waste to the ground surface, less obvious interactions with the cover and trench backfill may be of greater importance. For example, pocket gophers that were burrowing in a LLW site at Los Alamos cast about 12,000 kilograms (kg) of soil per hectare (ha) to the surface of the trench cover during a fourteen-month period (Hakonson et al., 1982; Fig. 4.6). Displacement of that amount of soil created about 8 cubic meters of void space per hectare in the cover, or about 2800 meters of tunnel system per hectare. Soil turnover of a similar or greater magnitude, caused by burrowing animals, has been documented in many parts of the western United States (Buechner, 1942; Ellison, 1946; Thorpe, 1949; Hooven, 1971; Gunderson, 1976).

Tunnel systems created by pocket gophers

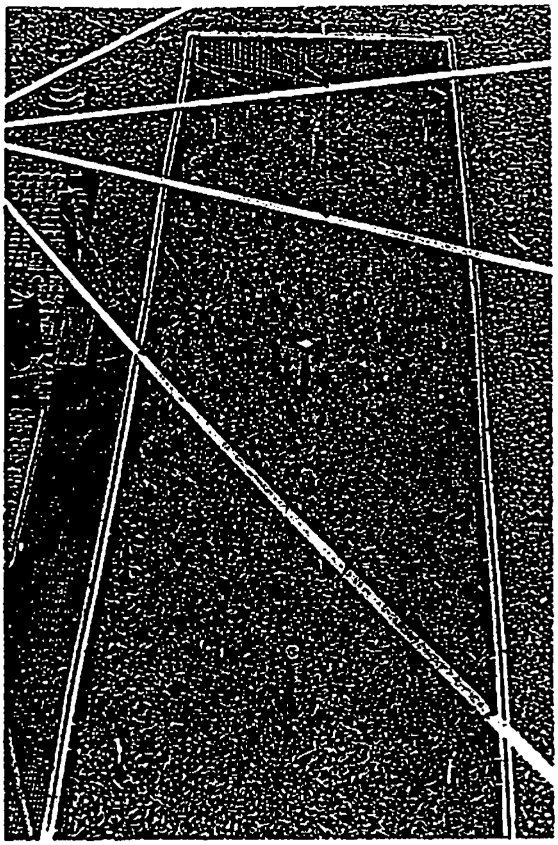

Figure 4.7. Runoff Patterns from a Vegetated Surface Disturbed by Pocket Gophers. Note ponding of water on surface, leading to decreased runoff and increased infiltration of water into the soil.

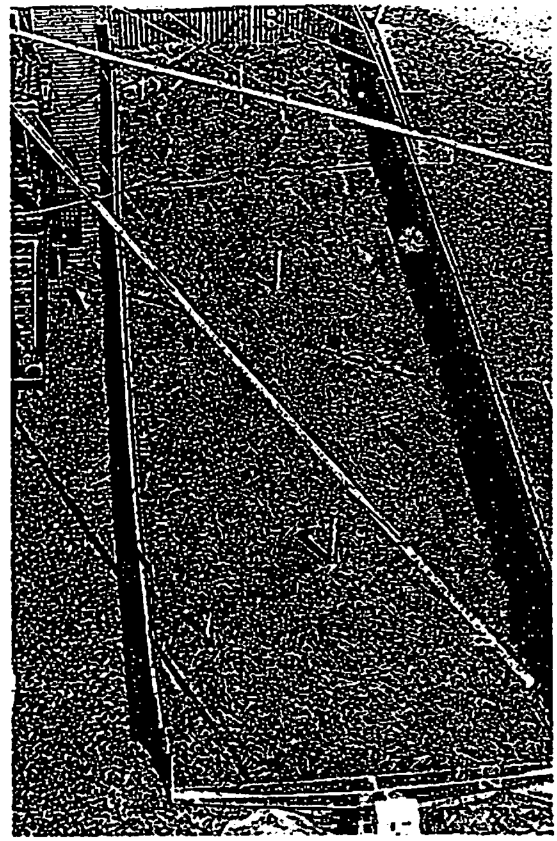

Figure 4.8. Runoff Patterns from a Vegetated Surface not Subject to Gopher Activity, showing concentrated flow moving downslope, leading to increased runoff and erosion and decreased infiltration of water into the soil.

in Colorado have been shown to increase rates of water infiltration (by decreasing soil bulk density) into the soil profile by a factor of two over similar but undisturbed profiles (Hansen and Morris, 1968). Studies on simulated LLW trench caps with a rotating boom rainfall simulator demonstrated that mounds created by pocket gophers decrease runoff and erosion and enhance the infiltration of water into the soil (Sejkora, 1989). Runoff and erosion are reduced because the mounds enhance the roughness of the soil surface, leading to decreased runoff velocities, decreased soil detachment, and increased ponding of surface water (Fig. 4.7) compared to undisturbed soil surfaces (Fig. 4.8).

Figure 4.9. Polyurethane Foam Cast (Felhauser and McInroy, 1983) of Pocket Gopher Tunnel System in Soil, showing intrusion into crushed Bandelier tuff. Note light circular area of tuff blocking an old tunnel in the topsoil, showing that materials can be displaced vertically within the soil profile by burrowing animals.

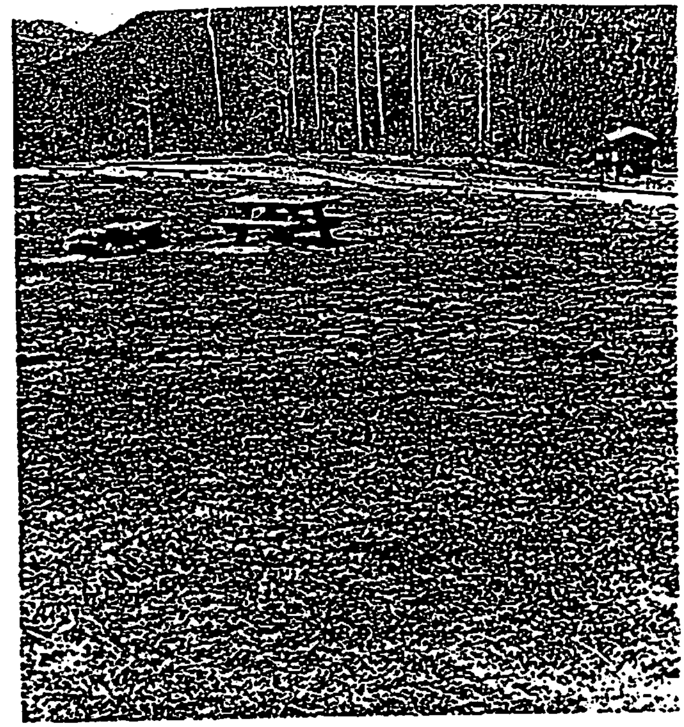

Figure 4.10. Soil Casts Made by Pocket Gopher Tunneling.

Burrowing animals may greatly alter the integrity of engineered, multilayered soil profiles by penetrating through such profiles and/or by vertically displacing the layers (Fig. 4.9). In native ranges, under high population densities, pocket gophers are estimated to turn over 15 to 22 percent of the soil near the surface in a single year (Thorpe, 1949; Hooven, 1971; Fig. 4.10). Studies have evaluated several geologic materials in preventing plant root and burrowing animal intrusion through trench caps (Hakonson, 1986). A layered soil, gravel, and cobble design (Fig. 4.11) has proven effective in limiting plant root intrusion and in eliminating pocket gopher burrowing into simulated waste underlying a trench cap (Fig. 4.12).

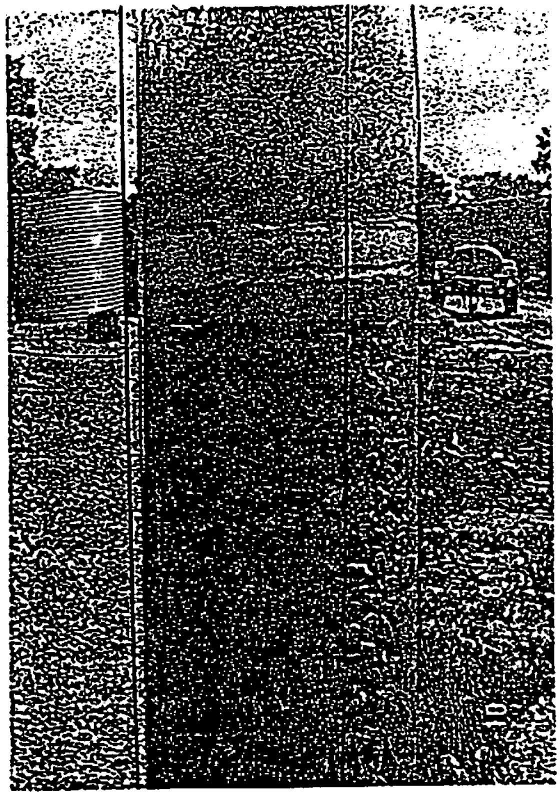

Figure 4.11. Low-Level Waste Trench Cap Profile, consisting of topsoil over graded rock capillary and biointrusion barrier. The large cobble does not store much water and, hence, discourages root penetration through this zone. The gravel and cobble also prevent pocket gopher intrusion to zones beneath the cobble.

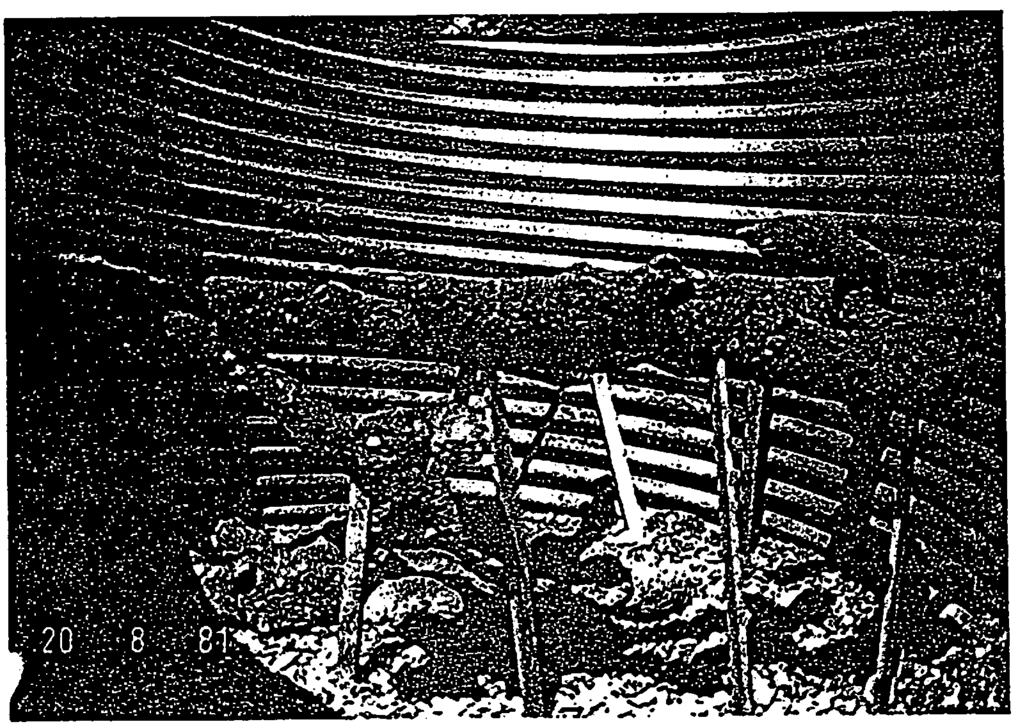

Figure 4.12. Polyurethane Foam Cast of Pocket Gopher Tunnel System in Loosely Aggregated Gravel, showing that the inability to create a tunnel prevents burrowing to greater depths.

Operating experience at LLW sites in the United States suggests that many of the short-term problems that relate to radionuclide transport invariably involve interactions with the trench cap. Those interactions, which involve both water and biota, are not well understood, particularly the role that plants and animals play in modifying water balance in the cap and the importance of biological intrusion into the waste as a radionuclide transport pathway. Few comprehensive, long-term pathway analyses have been attempted to determine the relative importance of subsurface and surface processes in transporting LLW to man. Under a private farm scenario, where a family living on an abandoned LLW site derived most of their food and water from the site, computer simulations suggested that uptake of Sr-90 by cereal grains provided the most significant, albeit very low, dose to the family (King, 1982).

The potential significance of the biological transport of buried waste in contributing to human exposure to radiation was further explored for both arid and humid site conditions (McKenzie et al., 1984) and compared with dose estimates based on several human intrusion scenarios as established by the U.S. Nuclear Regulatory Commission (US NRC, 1981). Results of the study demonstrated that biological transport processes involving both plants and burrowing animals resulted in human exposures one hundred years after site closure that were about 50 percent of those calculated for the human intrusion scenarios. Despite the uncertainties associated with the dose estimates for all of the scenarios, the study suggests that dismissal of biological transport as a significant contributing factor in radiation exposures to humans is not supported by current knowledge.

Subsurface Processes

In this subsection, we will discuss the theory and equations used to describe water movement in soil and rock because current federal and state regulations for waste disposal heavily emphasize the need to measure and model subsurface flow and solute transport.

Subsurface water moves through pores in geologic material. Equations describing flow in individual pores have been developed. However, large variations in their size and shape and the difficulty in characterizing these features make the modeling of pore flow very difficult. Therefore, simplifying assumptions have been made in order to develop practical model representations of porous media flow. One simplifying assumption is that bulk soil water flow can be represented by an average flow such as described by Darcy's Law (Darcy, 1856):

$$J = -K \frac{dH}{dx} \qquad (1)$$

where J is the approach velocity in units of length per unit time (i.e., centimeters per second); K is the hydraulic conductivity in units of length per time; H is the hydraulic potential, which is composed of both the matric or pressure potential and the gravitational potential, all in units of length; and x is the space coordinate in units of length.

Simply put, matric potential is the ability of the soil to retain water. Water moves from areas of high potential to low potential. As the soil becomes drier, the matric potential decreases and the water is held tighter by the pores. Therefore, for soil of the same texture, water moves from wetter to drier soils. Also, water moves downward because of gravitational potential. The combination of gravitational and matric potential provide

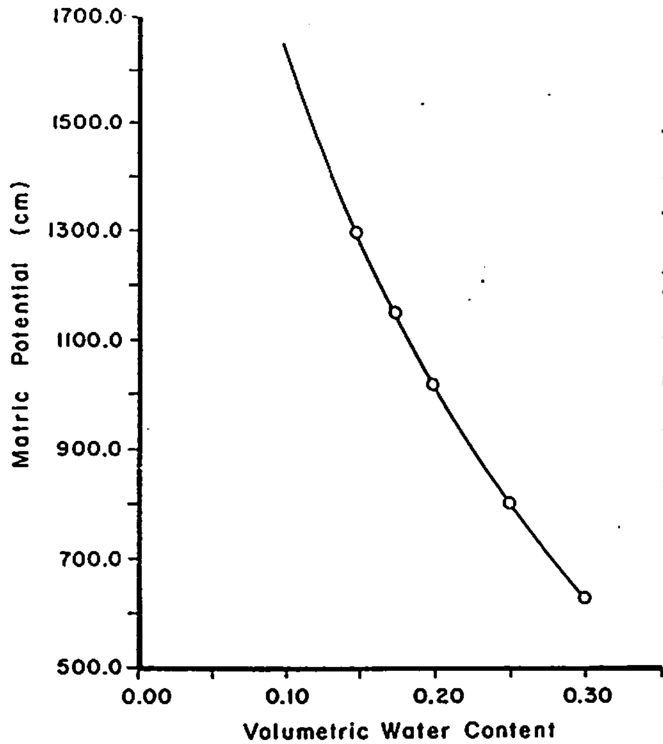

Figure 4.13. Water Content versus Matric Potential for Equation Derived by Abeele (1981).

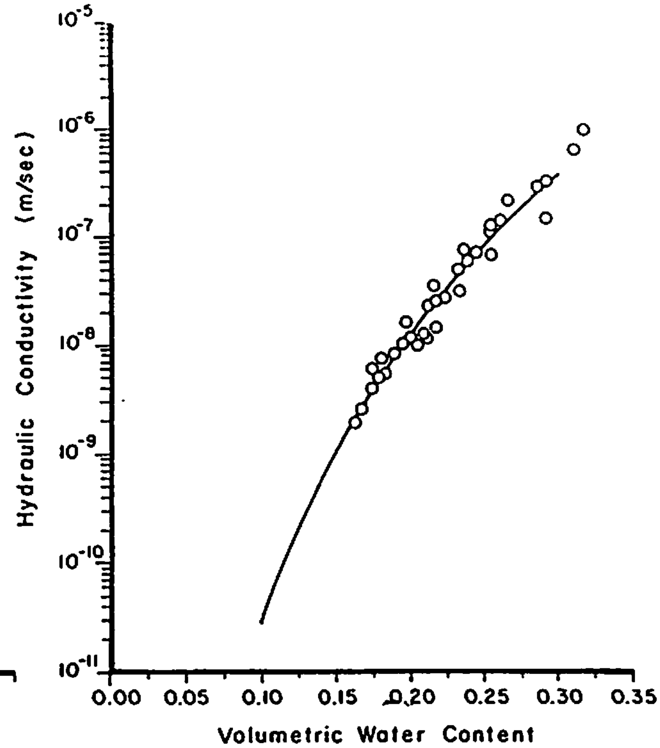

Figure 4.14. Water Content versus Hydraulic Conductivity from Instantaneous Profile Experiment (Abeele, 1981).

the driving force for water movement through porous material. By adding the values for these two potentials at two locations and dividing by the distance between two points, the gradient of the flow can be determined. The gradient gives both the magnitude and direction of flow.

When water flux is combined with terms to account for changes in the total water inventory (volumetric water content) in the soil volume, the equation in Darcy's Law becomes:

$$\frac{\partial \theta}{\partial t} = -\frac{\partial J}{\partial x} \qquad (2)$$

where θ is the volumetric water content in units of volume of water per total soil volume, t is the time coordinate in units of time, and J and x are as defined in Eq. 1. The governing equation for water movement in porous media is derived from Eq. 1 and 2 and is:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}[K \frac{\partial H}{\partial x}] \qquad (3)$$

where all the terms were defined previously. Several terms in this equation are variable with time, space, and the values of other terms in the equations. For example, matric potential and hydraulic conductivity are both functions of the volumetric water content. Matric potential varies nonlinearly with volumetric water content in crushed Bandelier Tuff (Fig. 4.13) and hydraulic conductivity, K, varies exponentially with water content (Fig. 4.14). The hydraulic conductivity is also

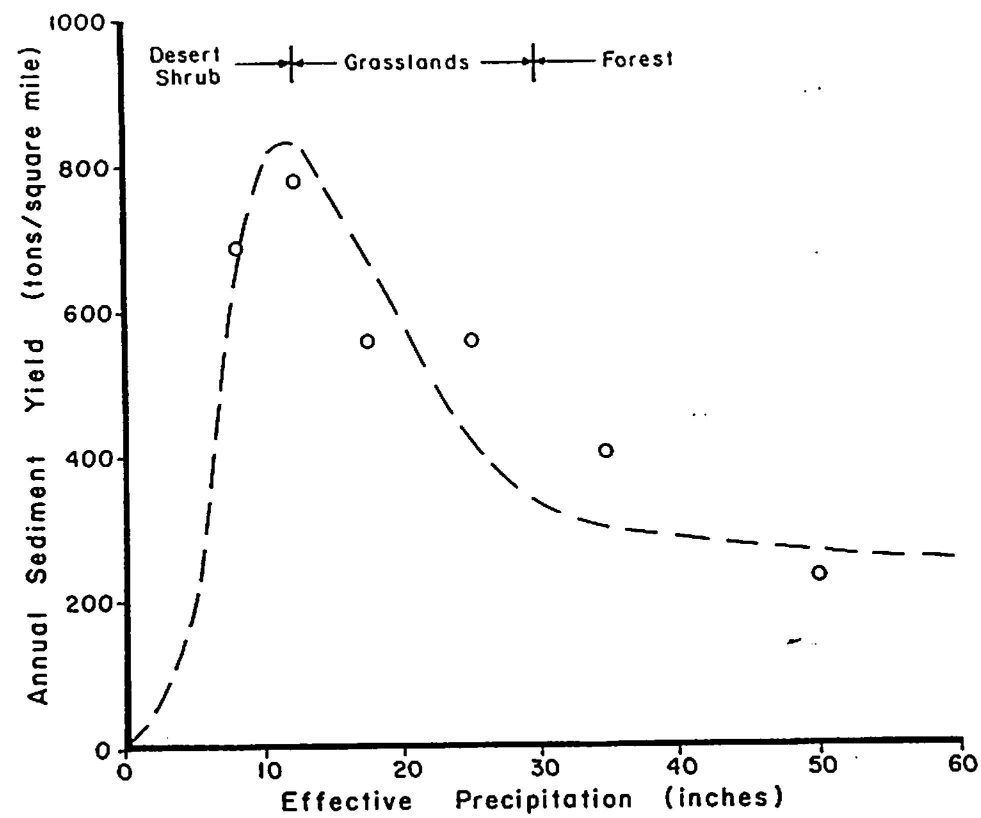

Figure 4.15. Erosion as a Function of Annual Precipitation.

dependent on the matric potential of the media.

A final equation can be written to reflect the dependence of K on volumetric water content. This is the Richards Equation (Richards, 1931) and is written in its general form as follows:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left[K(\theta)\frac{\partial H}{\partial x}\right] \qquad (4)$$

where $K(\theta)$ accounts for the fact that K is a function of θ, the water content.

Obviously, water movement is very important to contaminant migration at a waste site. For those chemicals that dissolve in water, the magnitude and direction of water flux from Eq. 3 will govern the direction and rate of movement of the chemical. In most cases, calculations for water movement can be decoupled from the transport calculations because the concentrations are so low that the chemicals do not affect the physical properties of the water. Therefore, the common approach is to solve Eq. 3 first, then solve for the transport using flux and water contents from the solution of the water phase.

RELATIONSHIPS TO TREATISE

As we have stated, the relative magnitude of the various components of water balance is strongly influenced by climatic variables as well as factors associated with the type of disposal and site design. Deep percolation (that is, below the root zone) is generally very limited (less than 1 percent of annual precipitation, and does not occur every year) in arid and semiarid (less than 50 centimeters annual precipitation) environments. In contrast, erosion is relatively high in semiarid (25–50 centimeters annual precipitation) areas due to the sparse vegetation cover and incidence of high-intensity thunderstorms (Fig. 4.15; Langbein and Schumm, 1958). However, in arid areas (less than 25 centimeters annual precipitation), erosion rates are low because the incidence of storms that generate runoff is also proportionally low.

Questions concerning the relative importance of erosion and biological intrusion in arid and semiarid versus humid areas are more difficult to answer. The erosion of trench covers in arid and semiarid areas is one of the major processes that degrade waste sites located on or near the surface because rainstorms often are of high intensity, leading to flash floods and erosion. Comparative studies of biological intrusion versus other modes of contaminant transport from waste sites are very limited. Further discussion of this issue is found in this chapter under Contaminant Transport in Ecosystems.

There undoubtedly will be exceptions to the general statements made above depending on a variety of local circumstances. Inadequate waste site designs in any climatic regime could lead to significant problems with deep percolation, erosion, and/or biointrusion. For example, cover designs that greatly reduce runoff and evapotranspiration of soil water (such as a non-vegetated, rock-armored trench cap surface) could result in nearly all of the annual precipitation moving through the system as deep percolation, dissolving contaminants, and moving them toward groundwater.

APPLICATION TO WASTE DISPOSAL

Surface Processes

Waste site design features that can be modified to influence water balance include the type and thickness of trench cover soil, the slope and length of the cover surface, the surface management practice (that is, the use of mulches, tilling practice, and the like) and the density, rooting characteristics, and transpiration potential of the plant cover. Ideally, we would like to direct as much of the incoming precipitation as possible to evapotranspiration in order to minimize problems with erosion and percolation. While runoff by itself does not contribute to waste site failure, the erosion associated with it must be within specified tolerances to ensure that the cover remains intact over the mandated performance lifetime of the site. Deep percolation can be controlled by maximizing evapotranspiration and by using cover soils that store and retard the movement of water downward through the soil.

It is important to repeat that the components of water balance are highly interdependent (that is, they are coupled processes) such that modification of one of those components can produce large changes in one or more of the others. For example, in arid and semiarid locations, a small change in evapotranspiration, which often accounts for the removal of more than 75 percent of the incident precipitation, can change seepage, which is characteristically small in arid regions, by as much as an order of magnitude. Similarly, changes in the amount of runoff can result in a commensurate change in the infiltration of water into the trench cover. While it is true that we would like to predict the influence of specific design modification on all components of water balance, it is also true that many of our techniques for measuring water balance components are subject to significant errors.

The relevance of understanding water balance to waste site design and remedial action is discussed in detail in Hakonson et al. (1989), Hakonson et al. (1982), Lane (1984), Nyhan and Lane (1982), and Nyhan and Lane (1986a, 1986b). Overall, a water balance approach to design and remediation of a shallow land burial site offers the following advantages:

- it accounts for most of the climatological, hydrological, and biological factors that influence site integrity;
- water balance models can be used to screen various designs and design modifications for effect on erosion, percolation, and the like; and
- water balance models can be used to estimate the amount of percolation entering the trench and waste for use as input to subsurface water and solute transport models.

Subsurface Processes

Any time a waste site will be located underground, concerns about the flow of fluids, liquid or gas, are paramount. An application for a disposal license requires site selection and characterization, facility design, and plans for monitoring, closure, and possible remedial action should the proposed facility fail. In all cases, the long-term effects of the proposed disposal operation on the subsurface environment must be fully assessed.

Table 4.1. Initial Candidate High-Level Waste Repository Sites in the United States.

Site	State
Vacherie Dome	Louisiana
Richter Dome	Mississippi
Cypress Creek Dome	Mississippi
Yucca Mountain[1,2]	Nevada
Deaf Smith[1,2]	Texas
Swisher[1]	Texas
Davis Canyon[1]	Utah
Lavender Canyon[1]	Utah
Hanford Site[1,2]	Washington

[1]Located in arid or semiarid region.
[2]Selected for site characterization.

One of the more recent examples of the importance of subsurface conditions on site selection is given by the HLW repository program sponsored by the DOE (Chapter 8 describes this program in detail). The Nuclear Waste Policy Act of 1982 (PL 97–425) provides guidelines for site selection based on population, but the law also stipulates that various factors such as geology, hydrology, seismic activity, and so on may qualify or disqualify a site from consideration. The initial assessment of candidate repositories involved nine sites (Table 4.1) that were deemed acceptable under the guidelines of the Act. The final three sites that were selected for further study were Hanford, Washington; Deaf Smith County, Texas; and Yucca Mountain, Nevada. All three are in arid or semiarid regions. The selection was subsequently narrowed to concentrate all site-characterization efforts on the Yucca Mountain site (see Chapter 8). The subsurface conditions and the geologic material were important factors in the screening process. Part of the reason that deserts are often selected for waste disposal is because of the low potential for subsurface movement of water and soluble compounds, making compliance with regulations concerning groundwater contamination more likely.

Site characterization (Chapter 3) requires a thorough investigation of subsurface hydrology. Using preliminary information about a site, conceptual models of the subsurface flow system are constructed to guide the site characterization process. Within the conceptual model, assumptions are made about the principal controlling features for subsurface flow such as fractures, faults, and/or soil or rock layering. The site characterization plan is designed to obtain data that test the conceptual model. The conceptual model is evaluated using a mathematical model and the requirements for data collection are refined. The monitoring equipment (such as neutron probe access tubes, tensiometers or thermocouple psychrometers) used to measure moisture distribution and flux below the ground requires a program of exploratory drilling or excavation. The results of groundwater investigations are used to verify or modify both conceptual and mathematical models of the subsurface hydrologic system at the site.

Data from site characterization are used in the actual design of the facility. The observations and models of subsurface flow and the properties of the geologic materials at the site are used to design engineering features such as liners, drains, and sumps.

A monitoring program is also required to ensure the site complies with applicable laws and regulations. The placement of monitoring stations will be based on the results of subsurface characterization activities and expected (predicted) behavior of the wastes. For example, hazardous organic wastes in a desert environment may move as a vapor, and hence a sampling scheme must be developed to consider this possibility. Without knowledge of subsurface conditions, it would be difficult to ascertain the behavior and migration paths of the vapor.

Development of a closure plan will also require knowledge of the subsurface conditions to design the best closure strategy and ensure the site's long-term integrity. The closure plan may be refined by modeling results and monitoring data collected during and after waste emplacement.

RELATIONSHIPS TO WASTE TYPES

This section will divide waste into hazardous chemical and radioactive forms for purposes of discussion. Different regulations govern the disposal of these two categories of waste, so the distinction is natural. Mixed wastes are of considerable concern because they contain both radioactive and hazardous materials. Although mixed wastes are increasingly important, final guidelines are not yet available for their disposal, so they will not be discussed any further in this chapter.

Hazardous Chemical Wastes

Hazardous chemical wastes include heavy metals and organic compounds. The RCRA guidelines for the disposal of these wastes stipulate that there be no potential for migration.

The inorganic chemicals, including heavy metals such as lead, copper, arsenic, and mercury, tend to be soluble, and hence are likely to move with water. In some cases they are also highly reactive with the minerals in soils or bedrock. The most common interaction is sorption of dissolved chemicals by solid surfaces. Traditionally, sorption in

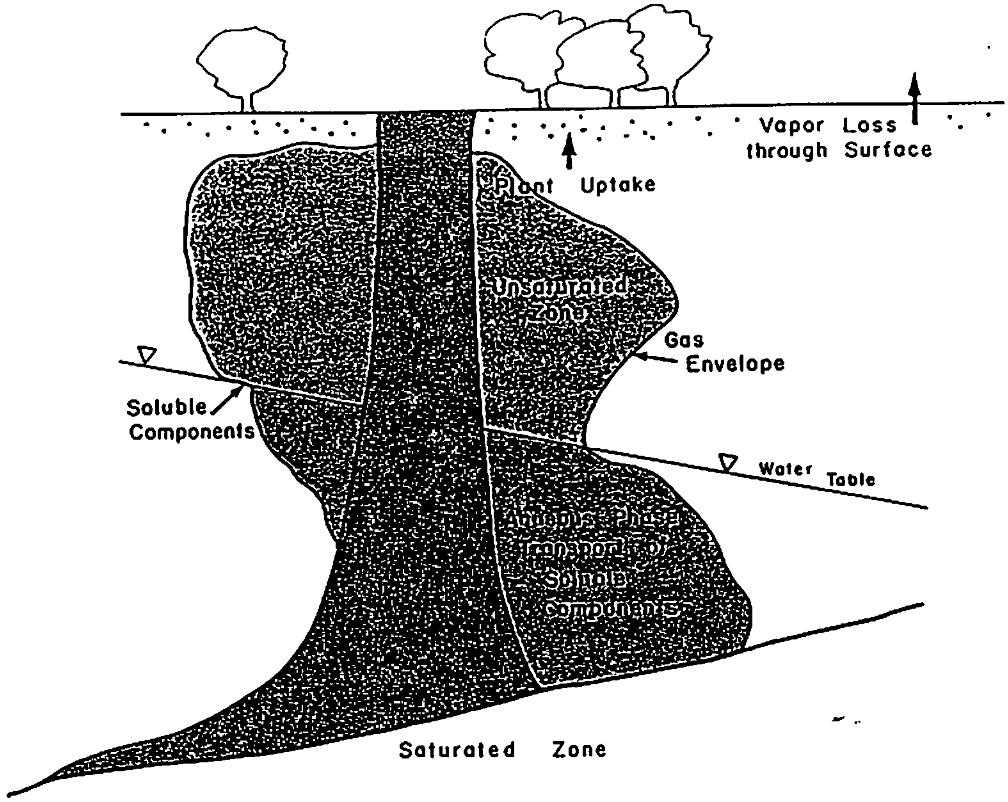

Figure 4.16. Highly Immiscible, Volatile Organic Waste with a Density Greater than Water (such as trichloroethylene) in the Subsurface Environment. The waste can exist in three phases (liquid organic, liquid organic–water, and vapor).

transport models has been described by a distribution coefficient, or K_D. The relationship between dissolved and sorbed chemicals can be expressed as

$$S = K_D C \qquad (5)$$

where S is the mass of chemical per unit mass of solid (soil or rock), K_D is the distribution coefficient with units of volume per unit mass of soil, and C is the equilibrium solute concentration in the fluid phase in units of mass per volume of fluid.

Recently, it has been recognized that the interactions between solutes and surfaces are much more complicated than is represented by Eq. 5 and more efforts have been made to incorporate geochemistry into transport calculations. Models along these lines have been presented by Cederberg et al. (1985), Jennings et al. (1982), Lewis et al. (1987), Kirkner et al. (1984), and Tillotson et al. (1980). Many of these models are quite complex and require a significant amount of data for a simulation, but they do incorporate many important processes (Gruber, 1987) that may affect waste migration.

A major complication arises in desert environments with validating geochemical models because of the limited amount of subsurface water. This leads to difficulties in obtaining sufficient volumes of soil solution for chemical analysis. As the soil dries, the water is held in thin films around a particle by very

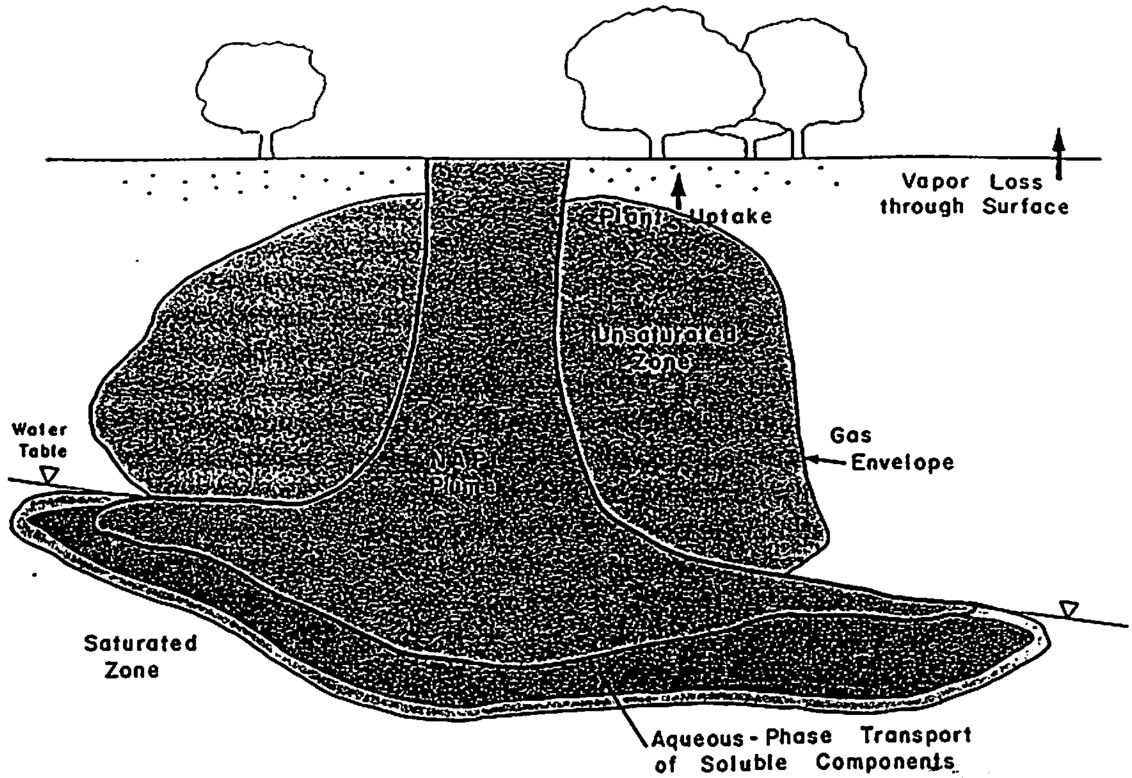

Figure 4.17. Highly Immiscible, Volatile Organic Waste with a Density Less than Water (such as oil or gasoline) in the Subsurface Environment. The waste can exist in three phases (liquid organic, liquid organic–water, and gas).

strong forces. To determine sorption or other geochemical processes such as precipitation or dissolution, samples are needed to assess the chemical composition of the aqueous solution and associated solid amtrix.

Organic compounds in desert environments have especially complex migration behaviors because transport may occur in one or more chemical phases. Schwille (1988) describes spreading models for chlorinated solvents in subsurface systems. In unsaturated systems, a gas mound will form in the pores around the organic liquid because of the highly volatile nature of many of these compounds. This subterranean vapor cloud can migrate by convection or diffusion and may come into contact with an aquifer where the organic component can resolubilize into the water. Another key feature of some organic wastes is their density relative to water; when denser than water they will migrate to a saturated zone, creating an organic plume that will migrate downward under the influence of gravity to a zone that is effectively impermeable to the organic liquid. The local geometry of the subsurface region will govern the migration of the organic, and the direction may or may not coincide with the direction of groundwater flow. If the organic chemical is less dense than water it will float on top of the saturated zone. In addition, both lighter and denser chemicals may contain soluble components that will dissolve and be transported by the groundwater flow. These behaviors are depicted in Figures 4.16 and 4.17.

For waste sites in arid or semiarid regions, the vapor mode represents a likely transport pathway. A multiphase flow model is required because in some cases water, vapor, and immiscible liquid will be present (Pinder and Abriola, 1986). Immiscible liquids are included because many of the organic compounds such as trichloroethylene (TCE), oil, and gasoline are only slightly soluble in water and tend to move as a distinct liquid organic component. This realization has generated interest in refining our understanding of relationships for three-phase systems (Lujan, 1985; Lenhard and Parker, 1987; Parker and Lenhard, 1987; Lenhard and Parker, 1988) to provide a sound basis for conducting detailed analysis of hazardous waste sites with organics present. The development and verification of models for multiphase flow is another area where additional effort is needed to assess the performance of waste sites. Both theoretical and practical models are presented by Corapcioglu and Baehr (1985, 1987), Baehr and Corapcioglu (1987), Cohen and Ryan (1985), and Bonazountas (1985), and these are available for refinement and application to waste management.

The interactions of organic compounds with the solid matrix is also an important consideration, but the complexities of organic chemistry will limit the development of geochemical models until further research has been conducted. In aqueous solutions, the sorption of nonpolar (no effective charge) organic compounds is described by the hydrophobic sorption model (Westall, 1987). Little if any information is available on the interactions of the organic vapors with solid surfaces.

While our understanding of radionuclide and heavy metal transport in food webs is relatively comprehensive (Whicker and Schultz, 1982), the transport of hazardous organic chemicals into biotic and physical pathways leading to man is much less understood. A major difference between inorganic radionuclides and organic chemicals is that the latter have generally been formulated to be water soluble, and hence mobile in biological systems. There are some notable examples supporting the high level of concern about the fate and effects of these materials. Recent examples include Love Canal, DDT in birds and fish, and mercury in marine ecosystems leading to Minimata's disease.

Low-Level Radioactive Waste

The CREAMS (Chemicals, Runoff, and Erosion in Agricultural Management Systems [Knisel, 1980]) model has been extended to semiarid and desert conditions by its application at Los Alamos, New Mexico, and Rock Valley, Nevada (Nyhan and Lane, 1982; Lane, 1984). These applications were motivated by the need to compute a water balance in connection with studies of shallow land burial (SLB) of LLW in arid locations.

Because of siting requirements for LLW (US NRC, 1982), it is unlikely that very many future waste disposal sites will be located in or near the water table. Under unsaturated conditions, infiltration and percolation through the trench cover and below the soil plant rooting depth provides the source of water for subsurface flow and contaminant transport. Surface water management can alter the potential subsurface water flux by orders of magnitude (Lane, 1984). Therefore, the design of an SLB site must include analysis of water balance to optimize cover design, predict long-term performance, and define the water movement to the upper boundary where subsurface flow and transport begins.

A simplified representation of a water balance describes one-dimensional movement of water in the soil profile to the plant rooting depth. For net rates and amounts, the water balance equation is

$$ds/dt = P - Q - ET - L \qquad (6)$$

where ds/dt is the time rate of change in soil moisture (in millimeters per hour, per year, or the like); P is the precipitation (in millimeters) per unit area; Q is the runoff (in millimeters) per unit area; ET is the evapotranspiration (in millimeters) per unit area; L is the seepage or percolation below the root zone (in millimeters) per unit area; and t is the unit of time used for the calculations (minutes, hours, years, or the like). Values of P, Q, ET, and L are actually per unit area per unit time, but in practice are expressed per unit area with the time implicitly accounted for in the calculations (that is, as daily, monthly, or annual values). Models such as CREAMS calculate a daily water balance and then sum the data to present monthly or annual averages. Sample calculations for monthly values at seven sites in Arizona, Nevada, and New Mexico were recently summarized by Lane and Barnes (1986).

As an example of the use of water balance models in waste management, consider the problem of optimizing the trench cap design to minimize the percolation of water below the cap and into the buried wastes. The problem, simply stated, is, "Does increasing the trench cap thickness decrease the average amount of percolation through it?" and "Are the results the same with and without vegetation on the trench cap?" The reader should see Barnes and Rodgers (1987) and Chapter 6 of this book for additional information on vegetative systems for trench caps.

The trench cap profile used in the simulation consisted of 15 centimeters (cm) of sandy, clay loam topsoil over 0, 15, 45, 75, 105, and 195 cm of crushed tuff backfill. The profile was assumed to be either bare (nonvegetated) or vegetated with a 40 percent cover of native range grasses and a maximum leaf area index of 1.0 (for calculating evapotranspiration). The CREAMS model was used to simulate a daily water balance (Eq. 6) using a twenty-year (1951–1970) precipitation record at Los Alamos, New Mexico. Annual values of percolation through the trench cap were computed and averaged for the twenty-year period.

The results of the simulation are summarized in Fig. 4.18. Notice that for the bare soil, trench cap thicknesses over about 30 cm did not significantly decrease average annual percolation. This is because bare soil evaporation is very low at depths greater than 30 cm in the soil profile. In contrast, results for the vegetated trench cap suggest that average annual percolation decreased as trench cap thickness increased up to about 100 cm. This is because plant transpiration was estimated to have removed water from the soil profile as deep as 100 cm or more.

With reference to Fig. 4.18 and the above discussion, these results may be interpreted as follows. Conventionally designed trench caps at Los Alamos will probably experience significant amounts of percolation if the surface is kept free of vegetation or if the vegetated trench caps are less than about 100 cm thick. Even for vegetated trench caps thicker than 100 cm, one might expect an average annual percolation value on the order of 1 millimeter per year. Reductions in percolation beyond this level would probably require engineering solutions such as capillary barriers (see Chapter 6). These include layered soil and rock profiles and/or compacted clay barriers with drastically reduced hydraulic conductivity (see Lane and Nyhan,

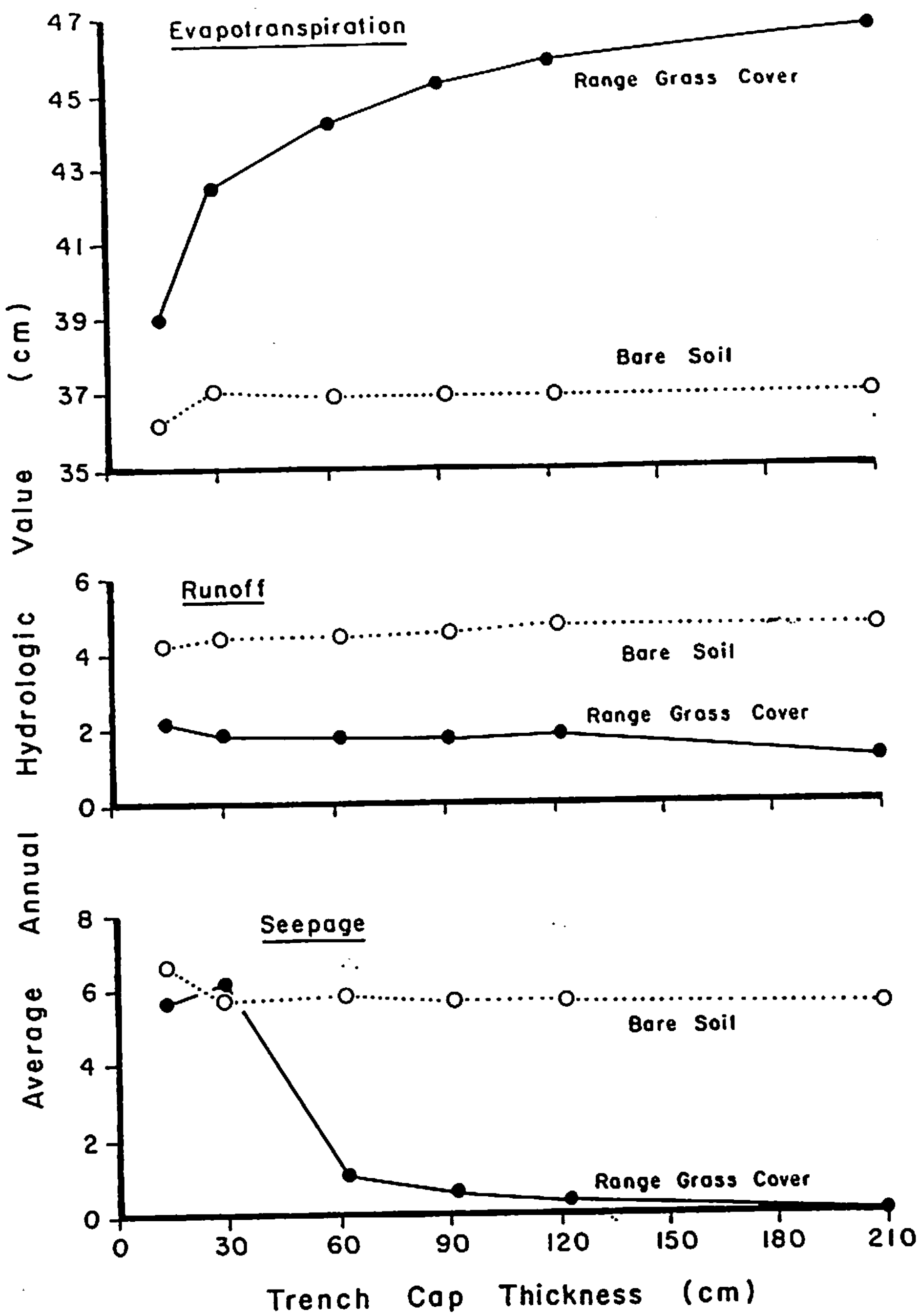

Figure 4.18. Results of 20-Year Simulations using the CREAMS Water-Balance Model. Note response of hydrologic parameters to increasing thickness in the landfill trench cap.

1984; Hakonson et al., 1989 for descriptions of capillary barrier experiments).

One of the criteria outlined in 10 CFR Part 61, the federal regulations for site characterization and licensing of disposal facilities for radioactive waste, is that a site be capable of being modeled before disposal of waste can occur. For a typical LLW site, the analysis should apply over a two-hundred-year time frame. Unsaturated conditions prevail at LLW sites in desert environments, and the primary application of subsurface flow hydrologic techniques involves calculation of water movement into, through, and out of the disposal site.

The previous discussion on inorganic hazardous wastes also applies to LLW disposal. Again, the coupling of geochemical and transport phenomena is an important technical issue (Gruber, 1987).

Transuranic and High-Level Radioactive Wastes

Transuranic and HLW are grouped herein because currently the defense transuranic (TRU) waste will be disposed at the Waste Isolation Pilot Plant (WIPP) site near Carlsbad, New Mexico (Chapter 11) and the commercial TRU repository will be in the potential civilian HLW repository (Chapter 8). Both of these sites are deep geological disposal sites with similar characterization requirements.

A critical problem in geologic systems is the occurrences of fractures and their effects on flow and transport. Flow in fractured rock has been simulated using various approaches including continuum models such as Eq. 3 or 4, dual porosity models, which assume two overlapping continua (a porous matrix and fractures), and fracture network generators. The choice of which model to use depends on the degree of fracturing between points of interest. In a highly fractured medium there is high connectivity between fractures such that the medium will respond essentially the same as a porous medium with a high conductivity. As the connection between fractures is reduced, the response will exhibit at least two distinct phases with one phase being attributed to fractures and the other to the porous matrix. In this case a dual-porosity model is used to describe the response. A dual-porosity model assumes that two continua are present and distinct properties are used for each medium. Within the model the two continua are linked by some form of exchange of water or mass (Huyakorn and Pinder, 1983). Fracture network generators are used when fracturing is low. The technique uses a statistical or probabilistic approach to characterize the fracture network (Long et al., 1982). In unsaturated fractured media, the relationships between pressure head, conductivity, and water content are not well understood. Wang and Narasimhan (1985) present a conceptual model of unsaturated flow in fractured porous media, and this model was adopted by Peters and Klavetter (1988).

If groundwater transport is assumed to be the most likely path of migration of radionuclides away from a TRU or HLW repository the recharge or amount of precipitation that percolates to the zone in question becomes an important quantity. Again, low precipitation amounts and high evapotranspiration demand make desert environments favorable for disposal of waste because of low recharge rates. However, difficulties arise in assessing the uncertainties associated with various scenarios because measurements are difficult to make in deep, unsaturated geologic systems.

LIMITATIONS OF THE TECHNOLOGY

Historically, more data have been available in the humid, more densely populated areas of the country than in desert environments. This means that all other factors being equal, we know less about hydrologic, erosion, and contaminant transport processes in deserts than we do in other areas. More information on these processes in deserts will be obtained as more desert areas are considered for waste disposal.

Surface Hydrology and Erosion

Hydrologic models such as CREAMS (Knisel, 1980) and HELP (Shroeder et al., 1984) have been extended to arid and semiarid conditions and have been shown to be more or less applicable, depending upon the site-specific circumstances and upon the modeling objectives. However, results of recent studies with relatively complex soil profiles such as trench caps with capillary and biological intrusion barriers suggest CREAMS and HELP do not represent soil moisture changes well and that two- and three-dimensional models may be needed to accurately represent the systems (Barnes and Rodgers, 1987). Neither CREAMS nor HELP addresses snowmelt as a source of precipitation or the long-term effects of plant succession and soil modification/formation on the site performance. At Los Alamos, studies show that deep percolation occurs during snowmelt (Nyhan et al., 1990), primarily because evapotranspiration during the winter is low. Hence soil water can percolate below the root zone before plants again begin to transpire (or remove) soil water during the following growing season. Improved models are needed for all of these circumstances.

A similar situation applies to erosion modeling in arid and semiarid areas. For example, the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978) has been extended to western rangelands; however, limitations of the technology have resulted in calls for better and more applicable technology (SRM, 1984; Lane, 1986). Responses to these calls for new erosion prediction technology will be discussed in a later section.

The unknown role of vegetation in modifying the hydrologic response of waste sites is a major information gap. In arid and semiarid areas, plants transpire most of the animal precipitation back to the atmosphere. Because transpiration is a function of plant species, increases in evapotranspiration can be realized by revegetating the site with plant communities that maximize removal of soil water. Small increases in evapotranspiration (that is, a few percent) can have a dramatic effect on reducing deep percolation, which is characteristically a very small term in the water balance equation (Eq. 6).

Another major limitation in our ability to apply water balance models to desert environments is the lack of information on plant root distributions. The removal of soil water through plant transpiration is critically dependent on how plant roots are distributed with depth in the soil. This information is especially lacking for native plant species that are typically used to revegetate waste sites. Whether the plants root to a depth of 1 or 2 meters, for example, is critical in determining of the amount of water available for deep percolation.

Figure 4.18 suggests that average annual percolation through a trench cap can be varied by two orders of magnitude through the manipulation of trench cap thickness and vegetative cover alone. The same response can also be achieved through manipulation of soil layers and moisture barriers within the trench cap. Because percolation through the trench cap is a principal mechanism for contaminant transport via subsurface flow, surface and subsurface hydrologic analyses must be linked together.

Subsurface Hydrology and Solute Transport

There are limitations to the application of theories on water movement through porous media to waste disposal in arid environments. These are related to modeling and the difficulty of measuring certain parameters in desert environments.

Many of the soil moisture monitoring instruments that were developed for measuring the water contents of wet soils do not function well in dry desert soils. Water content can be measured in the traditional fashion by removing a sample, weighing it, and drying the sample in an oven at 100–110°C for twenty-four hours (Gardner, 1986). However, this technique requires repeated sampling of the site, which is impractical under field conditions. Other techniques such as neutron thermalization (neutron moisture gauge) or electrical capacitance are used (Gardner, 1986) to obtain frequent in situ measurements with only initial soil disturbance during installation. Neutron measurements have come into common use, although at low water contents longer counting times are required for accurate measurements.

Tensiometers are used to measure pressure potential in unsaturated soil for both field and laboratory experiments (Cassell and Klute, 1986). Tensiometers generally consist of a ceramic cup on the end of a hollow tube with an airtight cap on the other end (Fig. 4.19). The ceramic cup is placed in contact with the soil and the tube is filled with water; a measuring device is located at the opposite end. The ceramic cup comes into equilibrium with water films in the soil, creating a tension in the tube that can be measured. Tensiometers are an accurate means of measuring soil water pressure, but their effectiveness is limited by the pore sizes of the ceramic cup. At high pressures (low soil moisture) air will enter the tensiometer, resulting in loss of water contact with the porous medium. For most tensiometers, the pressure at which this occurs is 850 cm of water (85 kilopascals), and in most desert situations the soils are much drier than this value except immediately after rainfall or snowmelt or in riparian areas.

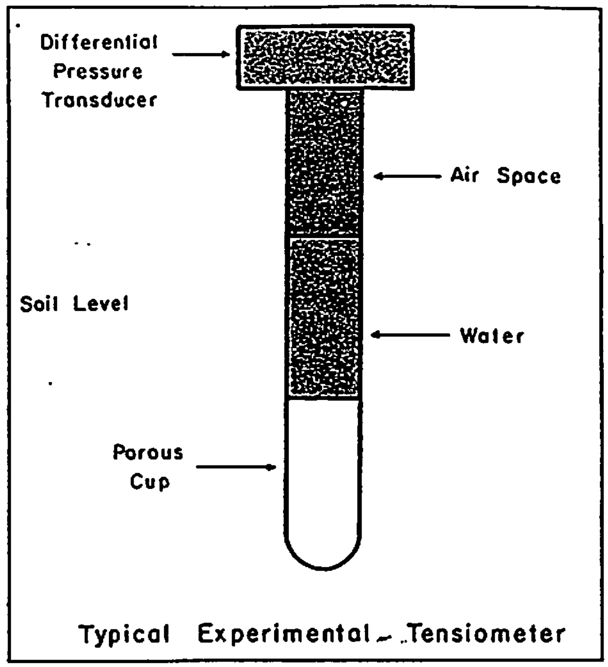

Figure 4.19. Tensiometer, Used to Measure Matric Potential in Soil. The system consists of water filled porous cup and tube fitted at the top with a device that measures change in pressure in the air space above the water.

There are limitations to gathering data for assessing a site or for evaluating a conceptual model for a site. They will be expanded in following sections of this chapter.

If the proper data are collected, the issue becomes one of using a mathematical model to assess site potential. Mathematical models such as Eq. 4 include certain assumptions made in their derivation. Among the assumptions are:

- flow occurs only in the liquid phase;
- the medium is isothermal (no temperature effects on flow);
- there are no chemical effects on liquid flow;
- the medium is rigid (no compressibility); and
- Darcy's Law is valid.

It may not be possible to test all of these assumptions by collecting field data, and in certain cases a different model may be required. An example is the case of fractured geologic material or soils with macropores (pores large enough to allow water to flow with minimal capillary or tension effects). Karasaki (1987) has shown by using a fracture network model that the concept of an equivalent porous media may not be applicable for saturated media when there is limited connectivity between fractures. In this case a model like Eq. 4 would not be applicable and a discrete representation of the discontinuous features would be required. Along the same lines, many organic hazardous wastes are volatile and may move in the gaseous or vapor form (Schwille, 1988). Again, Eq. 4 would not represent the system and a two-phase model that considers both liquid and vapor movement is needed. If the wastes were buried in the near-surface zone, temperature gradients established by solar heating may have a substantial influence on vapor migration so an energy balance model is also required.

Another major limitation in the application of models, particularly those that describe mass transport in porous material, is reliance on scale-dependent parameters. The pores in soils and rocks vary in size and distribution, and on a larger scale heterogeneities, such as layering, can be found. Scale-dependent parameters refer to increased values in a parameter as the size of the region characterized increases. Pickens and Grisak (1981) found that as the length between wells in an aquifer experiment increased so did the value of the intrinsic parameter governing the longitudinal spread of the plume. Gelhar et al. (1985) and Gelhar (1986) analyzed experiments from all over the world and found that for both saturated and unsaturated studies the intrinsic parameter increased with the size or scale of the experiment.

Scale dependency has created considerable controversy, particularly in applying the traditional equation used to describe mass transport in subsurface flow systems. For a more detailed presentation of the background and technical issues, the reader is referred to Dagan (1984, 1987), Domenico and Robbins (1984), Gelhar and Axeness (1983), Güven et al. (1984), and Neuman et al. (1987).

TECHNICAL ISSUES

Several issues have been addressed in the previous sections that are relevant and topical to the use of deserts as waste disposal sites. These will be summarized in this section.

Multiphase Flow

The movement of water or contaminants in more than a single phase is important in desert environments. The movement of water vapor is of obvious importance for evapotranspiration and may be important to moisture conditions in deep, unsaturated geologic media such as at the Yucca Mountain repository site (Ross, 1984; Weeks, 1986). Pinder and Abriola (1986) and Schwille (1988) have discussed the tendency for dense organic liquids to move in essentially three phases: water, vapor, and immiscible organic liquid.

Mathematical models for multiphase behavior of organic compounds are reported in the literature (Abriola and Pinder, 1985a, 1985b; Faust, 1985; Corapcioglu and Baehr, 1987; Baehr and Corapcioglu, 1987). However, the fundamental relationships that govern the behavior of the phases in porous media are poorly understood, although many investigations into these relationships are currently being conducted (Lujan, 1985; Ferrand et al., 1986; Parker and Lenhard, 1987; Lenhard and Parker, 1987, 1988).

Spatial, Temporal, and Scale Relationships

Questions about the influence of spatial and temporal variability and scale effects on abiotic and biotic processes represent major technical challenges that must be resolved to improve our ability to design, assess, and remediate waste sites in order to meet federal and state performance requirements. Much of the challenge stems from the fact that we make point estimates of the characteristics and processes of interest and extrapolate the results over larger areas and time. For example, a few relatively small core samples are often used to characterize the physical and hydrologic properties of soil and geologic media. Results are then extrapolated over larger areas, including entire waste sites, watersheds, and even basins. The underlying assumption is that results of our sampling represent the spectrum of conditions over the larger areas. Typically, we respond to the large spatial variability (that is, heterogeneity) that is observed in physical and functional characteristics of the environment by collecting more samples. Practical limits on the number of samples that can be collected and processed are reached very quickly. The problem is compounded when temporal variation enters the picture, particularly for attributes that change rapidly with time (such as soil moisture near the ground surface or evapotranspiration, which varies tremendously during the day and over seasons).

Unfortunately, we are constrained to using sampling techniques that require large numbers of samples to characterize spatial and temporal variation of attributes of interest. However, the need for better sampling methods has prompted researchers to apply remote sensing techniques to facilitate spatial and temporal resolution of biotic and abiotic processes and structure. Satellite, aircraft, and ground-based remote sensing techniques are being explored for measuring evapotranspiration (Barnes et al., 1990), the quantity and distribution of vegetation and runoff, erosion, and contaminant transport in desert ecosystems. These techniques are ideal for addressing questions about the scale dependence or independence of patterns and processes in ecosystems. The use of a laser-based technique called Light Detection and Ranging (LIDAR) for measuring evapotranspiration over vegetation canopies (Barnes et al., 1990) is discussed in the following section titled Recent Developments and Future Directions.

The importance of the spatial variability of porous media properties on flow and transport has been investigated in several studies and summarized by Gelhar (1986), Dagan (1984, 1987), Matheron and de Marsily (1980), and others. The variations can be random perturbations from a mean property or deterministic, as in the layering of geologic media or soils.

Beginning with the initial study by Nielsen et al. (1973), it has been observed that flux-related properties (such as hydraulic conductivity or diffusivity) have a skewed distribution that can be described by a lognormal distribution. Additionally, storage-related properties (such as the porosity or volumetric water content at a given pressure potential) can be described by a normal distribution.

Many of the studies to analyze the behavior of spatially variable systems have considered saturated porous media. Dagan and Bresler (1979) and Bresler and Dagan (1979) presented an analysis of field-scale transport in spatially variable saturated soils assuming a series of one-dimensional columns with each column having a different property. This idea was expanded by Dagan and Bresler (1983) and Bresler and Dagan (1983a, 1983b) to include unsteady conditions. Mantoglou and Gelhar (1987a, 1987b, 1987c) derived equations for multidimensional, spatially varied conditions and found effects of lateral spreading and anisotropy in the conductivity function induced by the heterogeneities in soil properties.

Temporal variability is very important in desert ecosystems because precipitation is sporadic in space and time. This variability is often overlooked, but the importance, particularly in linking surface and subsurface behavior, is critical. An example of the importance of temporal variability occurs in higher elevation systems, where moisture comes as snow in the winter months when evapotranspiration demand is at a minimum, and the potential for water movement by percolation to the waste is greatest. Analyses that assume a constant recharge rate rather than a seasonal value may lead to an erroneous conclusion about site performance.

Scale-dependent behavior has been observed in parameters governing mass transport in porous media, as described in a previous section. Questions related to both the effects of heterogeneities on subsurface flow and transport- and scale-dependent behavior, particularly for unsaturated porous media, await comprehensive field experiments to provide needed data.

Geochemical Coupling

Geochemical coupling has been addressed in previous discussions, but it represents one of the major challenges in assessing transport of chemicals in subsurface environments. Initial steps have been taken to couple geochemical models to transport models; for instance, refer to Cederberg et al. (1985), Lewis et al. (1987), and others cited previously.

Biological Coupling

Two types of biological coupling are discussed briefly in this section: plant roots and microorganisms.

As we have previously discussed, plant roots extract water and solutes from the soil and have a major influence on the movement of water and wastes. Molz (1982) discusses modeling of water and solutes with plant roots present. Current models treat plant roots as a sink for water (Feddes et al., 1975; Neuman et al., 1975; Gupta et al., 1978; Tillotson et al., 1980; Huyakorn et al., 1986) and solutes (Tillotson et al., 1980). This approach is expedient because detailed interactions between roots, water, solutes, and soils are not well understood and, therefore, are difficult to incorporate into a model (Molz, 1982).

Microbial activity has been recognized as a potential means of restoring aquifers contaminated by organic chemicals. This is an area of considerable ongoing research and is mentioned for completeness. Wilson et al. (1986) present an overview of potential applications of this method. Widdowson et al. (1987) developed a model for microbial growth in a saturated subsurface system.

Fractured Media

Unsaturated flow in fractured rocks or soils with large macropores is a major technical issue. Uncertainty remains as to the level of saturation required for fractures in unsaturated porous media to become hydraulically active. It is also possible for fractures to act as capillary barriers in unsaturated conditions.

Most studies of fractured media have concentrated on saturated systems to understand the hydraulic and mechanical properties of fractured systems. A primary assumption in these studies was that fractures were parallel plates and could be modeled using the cubic law (Snow, 1965). Recent studies have shown that flow may be channelized and a different description for flow is required (Tsang and Tsang, 1987). For unsaturated conditions, our level of understanding of fracture flow is very rudimentary.

Measurement Techniques

Throughout this chapter, considerable emphasis has been placed on the inability to measure hydrologic variables such as pressure potential or moisture content in situ under extremely dry conditions. Another complication in conducting experiments is the very slow rate of water movement at low moisture contents.

Several techniques are available for measuring either water content or pressure head, including neutron probe, electrical resistance, gamma ray attenuation, tensiometers, thermocouple psychrometers. Each of these methods has strengths and weaknesses in its application. A reader that is interested in more detail should consult Klute (1986).

RECENT DEVELOPMENTS AND FUTURE DIRECTIONS

Surface/Near Surface Processes

One of the most significant and productive recent developments is the development of infiltration-based hydrology. Before this development, infiltration, and thus surface runoff, was most often computed based on indices (phi index) and empirical relationships (runoff curve numbers). The inadequacies of these techniques limited our ability to develop more reliable hydrologic and erosion models.

Fok (1987) presented an evolutionary tree, or line diagram, on the development of infiltration models. One important branch on this tree led to the development of algebraic infiltration equations. Examples of these are the Green–Ampt (Green and Ampt, 1911) and the Philip (Philip, 1957) infiltration equations. With respect to applications of infiltration equations to arid and semiarid areas, we emphasize developments related to the Green–Ampt equation.

In about 1980, efforts were initiated to estimate soil-water retention parameters and Green–Ampt equation parameters from commonly available soils data. For example, equations were developed to predict soil water content for a number of soil water potential values based on soil properties such as percent sand, clay, organic matter, and bulk density. Green–Ampt parameters were also described as functions of percent sand, clay, and bulk density (Rawls and Brakensiek, 1983; Rawls and Brakensiek, 1985), and in the latter case equations were developed to predict bulk density (Rawls and Brakensiek, 1983). At the same time, field infiltration experiments were conducted to extend these relationships to desert soils (Lane et al., 1987b). Relationships are now being developed to cover conditions more typical of desert and rangeland areas (Brakensiek and Rawls, 1987).

The significance of the above developments was not so much in improved predictions of infiltration parameters using textural information as it was in the philosophical change in direction this approach represented to infiltration modeling. Prior to these developments, techniques for estimating infiltration parameters were based primarily on soil classification schemes such as relating hydrologic soil groups to runoff curve numbers (SCS, 1972). Now, measurable soil properties are used to predict infiltration parameters on a routine basis.

An increased emphasis on the development of infiltration and erosion databases using rainfall simulator techniques also occurred in the early 1980s. Initial emphasis was on calibration of the USLE (Simanton and Renard, 1982; Nyhan and Lane, 1986a) but was subsequently focused upon infiltration and improved erosion prediction technology (Simanton et al., 1987).

Erosion prediction techniques (that is, equations and models), including the many improvements over the years, are empirically based. These techniques (such as the USLE; see Wischmeier and Smith, 1978) are useful for predicting average, long-term soil loss for many land use and management practices. Recently, requirements for erosion prediction have called for increased sophistication. Included are such applications as short-term soil loss estimates and erosion predictions for a wider variety of land use and management practices important in contaminant transport processes.

Recent technological advances, including those outlined above, have provided the basis for development of process-based erosion prediction models. The U.S. Department of Agriculture (USDA) formed a team of scientists and engineers in 1985 and initiated a national project to develop an improved erosion prediction technology to replace the USLE. The objective of the USDA Water Erosion Prediction Project (WEPP) was to develop a new generation of water-erosion prediction technology for use in soil and water conservation and environmental planning and assessment. This technology will have immediate application to the design and remediation of near-surface disposal facilities.

Previous experience in successful model development (such as the CREAMS model; see Knisel, 1980) showed that communication between and among scientists and potential users would be essential to the success of the WEPP. To accomplish this, the project developed and published user requirements (Foster and Lane, 1987) that described in detail the product of the project and how it was to function. These requirements served as a guide for model development and as a basis to judge performance of the final product. The user requirements were jointly developed by scientists and users in the U.S.

Agricultural Research Service, the U.S. Soil Conservation Service, the Bureau of Land Management, and later, the U.S. Forest Service.

The technology is for application to field-sized areas ranging in size from plots to individual hillslopes to areas of a few hundred hectares, depending upon the complexity of the topography, soils, and land use and management. The new procedures will consider the major factors of climate, soil, topography, and land use and how they influence erosion on cropland, rangeland, and disturbed forest areas. Erosion-prediction procedures will compute sheet and rill erosion and concentrated flow (ephemeral gully) erosion. Moreover, WEPP applications are intended for situations where overland flow and surface runoff dominate. The WEPP is not intended for undisturbed forests or other areas where runoff occurs only from small parts of the area of interest and/or subsurface flow dominates.

The empirical basis for the technology was developed from rainfall simulator (Swanson, 1965) studies on thirty cropland, twenty rangeland, and twenty forest soils at various locations across the United States. These soils were selected to represent a broad range of properties and soil erodibility. Data are being collected to obtain field estimates of infiltration parameters, interrill erodibility, and rill erodibility parameters. Soil characterization studies are also being conducted at each location to relate basic soils properties to field-measured soil erodibility parameters. Other soils will be evaluated as the WEPP study evolves.

The new generation of models will be based on fundamental hydrologic and erosion processes instead of the empirical approaches used in the past. These models will include components for climate, snow accumulation and melt, infiltration, runoff, hydraulics, erosion, soil moisture, plant growth, plant residue, tillage, and other practices disturbing the plant canopy and soil surface.

The use of innovative technology to address questions on spatial variability and scale dependence will be a major thrust for future research on abiotic and biotic processes. The value of LIDAR for measuring evapotranspiration from vegetation communities illustrates the need for—and relevance of—innovative measurement techniques.

The goal of any sampling program is to obtain a representative estimate of the structural patterns (such as the distribution and characteristics of soils, biota, and terrain) and functional processes (energy flow, water balance, and nutrient cycling) within ecosystems. How well we understand patterns and processes within ecosystems depends on the adequacy of our sampling methodology relative to the spatial and temporal variability in the parameters of interest. For example, in well mixed media (such as some surface waters and sandy soils) a few point samples may adequately represent the attributes of interest in the media. However, in heterogeneous systems, characterizing an ecosystem's attributes of interest is a major challenge when the attributes are highly variable in time and space. Our point sample estimates may poorly represent the features we are trying to understand.

Evapotranspiration from native plant canopies is a process that can be highly variable over space and time because of terrain complexities, patchiness of vegetation, and mixtures of plant species. Conventional techniques of estimating evapotranspiration rely on point estimates (that is, single points are sampled) of critical parameters. The data collected from a few to many single points are often averaged and then extrapolated over

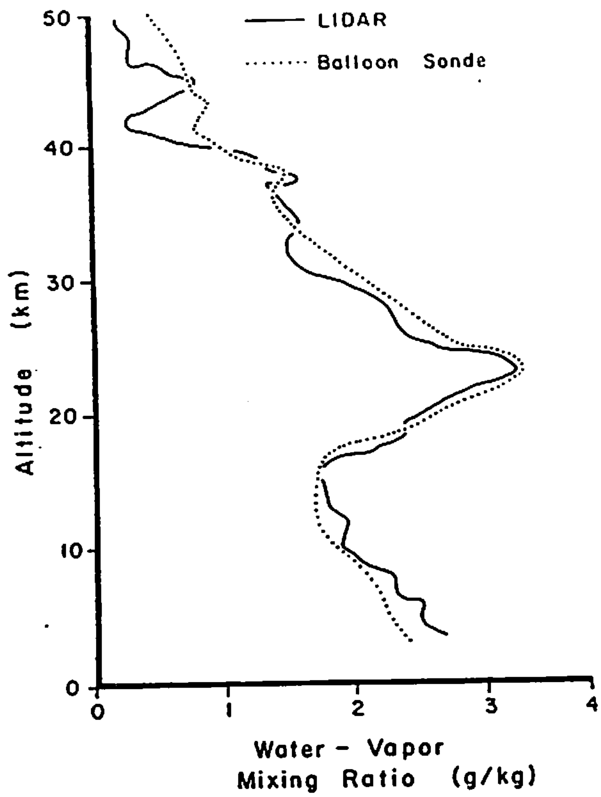

Figure 4.20. LIDAR Return, Showing Water Mixing Ratio as a Function of Altitude, with a spatial resolution of 15 m (i.e., a measure of water content of air is outlined every 15 m along the beam path).

larger areas to estimate canopy evapotranspiration. Extrapolating these estimates over larger areas works best over uniform, cultivated, agricultural crops because critical requirements such as the uniformity of soils, plant cover, plant spacing, and the wind fetch come closest to being met. Over native plant communities and rough terrain these requirements are often not met.

The application of LIDAR for measuring evapotranspiration represents an attempt to remotely measure, in detail, the water vapor content of air at many sampling points, in near real time, and over large areas of vegetated ground. The remote sensing of the atmosphere by LIDAR involves (1) repetitive firing of a short pulse of a high-intensity ultraviolet laser into the atmosphere; (2) detection of the returning backscatter as a function of time out to 1 to 2 kilometer distances; and (3) interpretation of backscatter intensity to determine the concentration of the target substances as a function of distance along the beam path. LIDAR is the optical analog of radar, in that it interrogates the atmosphere and measures the distribution (and concentration) of gases and solids as a function distance along the beam path. A RAMAN LIDAR (Cooney et al., 1985; Melfi and Whiteman, 1985) consisting of a krypton–fluoride (KrF) laser and operated at a wavelength of 248 nanometers can accurately measure air moisture content both day and night at ranges to at least 2 kilometers. A LIDAR measurement of the water vapor profile is compared with that measured with a balloon sonde (a rising balloon fitted with an instrument for measuring air moisture) in Fig. 4.20. The LIDAR system used in this study resolved the water content every 15 m along the 5-kilometer beam path. Notice the fine structure in the moisture profile obtained with the LIDAR compared to the relatively smooth profile obtained with the balloon sonde. The difference in detail between the two curves is related to the slow response time of the moisture-sensing device on the continually rising balloon. Hence, variations in the water vapor profile tend to be smoothed out with the balloon sonde technique, while much finer resolution of the water vapor profile is obtained with the LIDAR.

The relevance of this discussion to waste disposal is that the ability to accurately estimate canopy evapotranspiration over large areas will provide the basis for selecting optimum mixtures of plants to revegetate waste sites. That mixture will, among other factors, be selected to maximize transpirational losses of soil water to ensure that deep percolation of water into the waste is minimized or eliminated.

Subsurface Processes

Many of the recent developments in the modeling and analysis of the behavior of flow systems consider heterogeneities. The application of geostatistical and stochastic techniques to subsurface flow problems has led to the realization that a single deterministic solution to most problems does not exist. The trend toward using these techniques in unsaturated systems (Yeh et al., 1985a, 1985b, 1985c; Mantoglou and Gelhar, 1987a, 1987b, and 1987c) will be beneficial for waste disposal in desert ecosystems.

More emphasis has been placed on collecting field data because of the heterogeneities in the field. A rapid means of measuring pressure head was presented by Marthaler et al. (1983) and a relatively quick method to determine in situ saturated conductivity was given by Reynolds and Elrick (1985). For deeper geologic systems, techniques using radar or acoustic technology are being used and developed (Carlyle and Carlsson, 1987; McCombie et al., 1987).

Data limitations in testing various models for subsurface flow systems have led to the development of more comprehensive field experiments. Wierenga et al. (1986) describe a field validation experiment for stochastic flow and transport models in unsaturated soils. The design uses a trench that laterally accesses an experimental pad 4.5 m long by 9.9 m wide. Trickle irrigation is used to apply water and solute to the surface of the experimental pad, and the trench will be large enough for emplacing instrumentation to monitor lateral and downward spreading of the water and solutes. This relatively large-scale field experiment represents a major step forward in obtaining data for multidimensional flow and transport in unsaturated porous media.

SUMMARY AND CONCLUSIONS

Abiotic and biotic processes interact to influence the transport and fate of water, sediment, and contaminants at waste disposal sites such as SLB areas. The water balance plays a key role in these interactions and is used to compute runoff, erosion, and percolation of water into the buried wastes. These processes in turn provide pathways and transport for contaminants to enter the environment and thus affect the food web. Research and field experiments are needed to further quantify these processes and rates in arid areas.

Subsurface flow is an important consideration in the disposal of waste in desert environments because of the concern for groundwater contamination. Dry conditions present in desert environments and limited rainfall are more favorable for waste disposal activities due to the small volumes of water moving through the system. At the same time, the dry conditions are difficult to measure with current instruments and uncertainty is introduced by the inaccurate measurements.

In dry environments, some wastes, such as volatile organics, can move as a vapor (as well as a liquid) potentially contaminating groundwater in this manner. Models and constituitive relationships for multiphase flow are being developed, but more research is needed to gain a better understanding of the chemistry and physics involved in multiphase flow and transport.

Understanding the geochemical environment is important for both organic and inorganic wastes. Ignoring the chemistry may lead to inaccurate predictions if the wastes are precipitated or mobilized by the inflowing solution. The coupling of geochemical and transport models has been initiated, but further development of the thermodynamics database for more elements and minerals is needed for widespread applications to waste management.

Field experiments to validate models and gain better insight into controlling processes for both flow and transport are needed, especially for unsaturated systems. Two particular issues are the scale dependency phenomenon and flow in unsaturated fractured rock. The latter topic may require extensive laboratory studies, but field verification will be required. Field experiments need to be carefully conceived, including complete characterization of the site, to use current knowledge on the response of heterogeneous systems. Also, measurement limitations mean these very dry systems must be brought to a saturation value where the current instrumentation is effective, but questions remain as to the representativeness of the data to drier conditions.

In conclusion, the following points can be made relative to deserts as dumps:

- Erosion is relatively high in semiarid areas and low in desert areas compared to humid sites.
- Biointrusion leading to contaminant transport occurs in desert areas but the relative importance of this pathway versus others requires more study.
- The low rainfall and dry environment result in limited recharge, lowering the potential for groundwater contamination.
- Soil moisture measurements are difficult to make under extremely dry conditions, increasing the uncertainties in predicting contaminant behavior.
- Multiple phase (liquid and vapor) behavior occurs for many inorganic chemicals soluble in water; some hazardous wastes can migrate in three phases.
- Coupling of physical with biological and geochemical processes is needed to predict overall behavior.
- More field experiments are needed to enhance our understanding of these systems.
- Several new technologies are emerging that will enhance our ability to measure and model abiotic and biotic processes in deserts.

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