5c

PNL-10508
UC-702

Estimation of Natural Ground Water Recharge for the Performance Assessment of a Low-Level Waste Disposal Facility at the Hanford Site

M. L. Rockhold
M. J. Fayer
C. T. Kincaid
G. W. Gee

March 1995

Prepared for the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830

Pacific Northwest Laboratory
Operated for the U.S. Department of Energy
by Battelle Memorial Institute

Battelle

PNL-10508

PACIFIC NORTHWEST LABORATORY
operated by
BATTELLE MEMORIAL INSTITUTE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC06-76RLO 1830

Printed in the United States of America

Available to DOE and DOE contractors from the
Office of Scientific and Technical Information, P.O. Box 62, Oak Ridge, TN 37831;
prices available from (615) 576-8401. FTS 626-8401.

Available to the public from the National Technical Information Service,
U.S. Department of Commerce, 5285 Port Royal Rd., Springfield, VA 22161.

♻ The contents of this report were printed on recycled paper

PNL-10508
UC-702

Estimation of Natural Ground Water Recharge for the Performance Assessment of a Low-Level Waste Disposal Facility at the Hanford Site

M. L. Rockhold
M. J. Fayer
C. T. Kincaid
G. W. Gee

March 1995

Prepared for the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830

Pacific Northwest Laboratory
Richland, Washington 99352

Summary

In 1994, the Pacific Northwest Laboratory (PNL)(a) initiated the Recharge Task, under the PNL Vitrification Technology Development (PVTD) project, to assist Westinghouse Hanford Company (WHC) in designing and assessing the performance of a low-level waste (LLW) disposal facility for the U.S. Department of Energy (DOE). The Recharge Task was established to address the issue of ground water recharge in and around the LLW facility and throughout the Hanford Site as it affects the unconfined aquifer under the facility. The objectives of this report are to summarize the current knowledge of natural ground water recharge at the Hanford Site and to outline the work that must be completed in order to provide defensible estimates of recharge for use in the performance assessment of this LLW disposal facility.

Recharge studies at the Hanford Site indicate that recharge rates are highly variable, ranging from nearly zero to greater than 100 mm/yr depending on precipitation, vegetative cover, and soil types. Coarse-textured soils without plants yielded the greatest recharge. Finer-textured soils, with or without plants, yielded the least. Lysimeters provided accurate, short-term measurements of recharge as well as water-balance data for the soil-atmosphere interface and root zone. Tracers provided estimates of longer-term average recharge rates in undisturbed settings. Numerical models demonstrated the sensitivity of recharge rates to different processes and forecast recharge rates for different conditions. All of these tools (lysimetry, tracers, and numerical models) are considered vital to the development of defensible estimates of natural ground water recharge rates for the performance assessment of a LLW disposal facility at the Hanford Site.

A conceptual model of the LLW disposal facility was used to identify four general areas in which recharge estimates were needed: the protective barrier, the barrier edge, the natural ecosystem surrounding the facility, and the entire Hanford Site. Potential scenarios that would impact the recharge estimates were identified. They included changes in climate, soil, vegetation, and land use for periods ranging from 100 to greater than 10,000 years.

For preliminary performance assessment calculations, we recommend assuming a recharge rate of 0.5 mm/yr through the Hanford Site protective barrier. This assumption represents a conservative estimate that is consistent with lysimeter measurements made over the past 8 years and with engineering design specifications for the 1000-year design life of the barrier. At the barrier edge, a higher recharge rate of 75 mm/yr should be assumed. For the natural ecosystem surrounding the barrier edge, estimated recharge rates of 5.0 and 25.4 mm/yr should be assumed for sagebrush and cheatgrass communities, respectively. These numbers also represent conservative estimates that are supported by lysimeter data, tracer studies, and numerical modeling. For the entire Hanford Site, we recommend using the recharge distribution map reported by Fayer and Walters (1995), which reflects our current knowledge of the soils, vegetation, and climate conditions and their influence on recharge.

Field measurements, computer modeling, and the results of a 1985 review of recharge studies at the Hanford Site were used to prepare plans to address the project needs for recharge estimates. The plans include efforts to use different methods (i.e., lysimetry, tracers, and modeling) to provide the necessary data and to address several outstanding issues. These issues include the accuracy of the methods, conflicting estimates for the same location, spatial and temporal variability, and processes such as preferential flow and vapor flow. The plans will be reviewed by a panel of experts in May 1995 to ensure that the recharge task remains focused on producing the information necessary to the project.

(a) The Pacific Northwest Laboratory is operated for the U.S. Department of Energy by Battelle Memorial Institute, under Contract DE-AC06-76RLO 1830.

Acknowledgments

The authors express appreciation to the reviewers from Pacific Northwest Laboratory and Westinghouse Hanford Company for their thoughtful comments.

Acronyms

ALE	Arid Lands Ecology
BWTF	Buried Waste Test Facility
DOE	U.S. Department of Energy
ET	evapotranspiration
FLTF	Field Lysimeter Test Facility
GIS	geographic information system
HMS	Hanford Meteorological Station
LLW	low-level waste
PET	potential evapotranspiration
PNL	Pacific Northwest Laboratory
PVTD	PNL Vitrification Technology Development
SWLA	Special Waste-Form Lysimeters-Arid facility
WHC	Westinghouse Hanford Company

Contents

Figures

Tables

1.0 Introduction

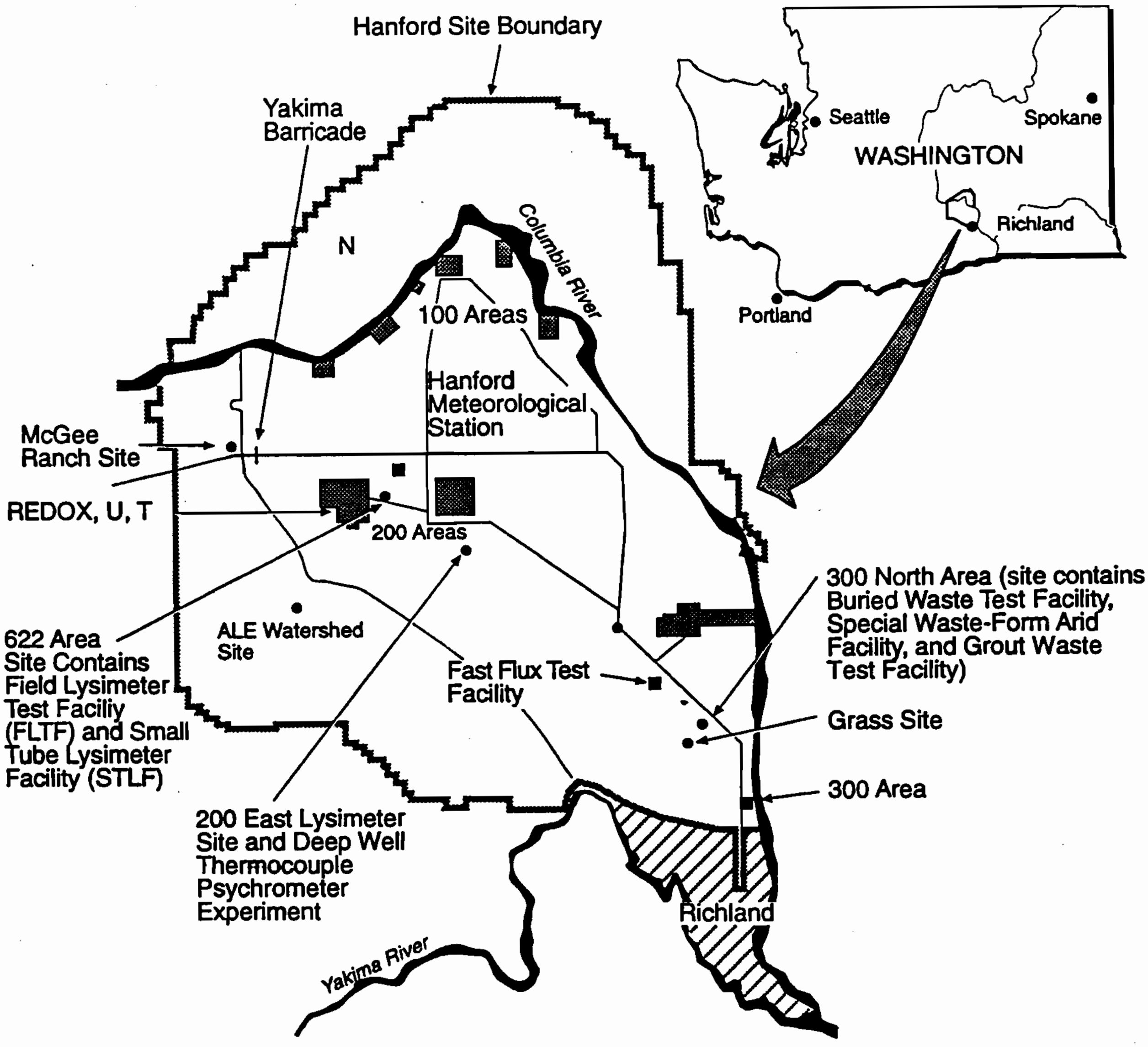
In 1987, the U.S. Department of Energy (DOE) began planning for the final disposal of all defense wastes produced at the Hanford Site since 1944 (DOE 1987). Most of the radioactive wastes are stored in single- and double-shell tanks located in the 200 Areas (see Figure 1.1). The current preferred method for the long-term disposal of low-level waste (LLW) from these tanks is to vitrify them into glass waste forms for storage in a subsurface disposal facility. This LLW disposal facility will be located on the 200 Area Plateau. The facility must be configured to enable monitoring, and the waste form must be retrievable for transfer at a later time, if required.

In 1994, Pacific Northwest Laboratory (PNL)(a) initiated the Recharge Task, under the PNL Vitrification Technology Development (PVTD) project, to assist Westinghouse Hanford Company (WHC) in designing and assessing the performance of this LLW disposal facility for DOE. The Recharge Task was established to address the issue of ground water recharge in and around the LLW disposal facility and throughout the Hanford Site as it affects the unconfined aquifer under the disposal facility.

Natural ground water recharge is the quantity of meteoric water that drains through the unsaturated zone to the water table. Quantifying natural ground water recharge rates is important because recharge water can leach contaminants from buried wastes and transport them to the unconfined aquifer. Recharge rates serve as the upper boundary conditions for analytical and numerical flow and transport models used to assess the performance of LLW disposal facilities, to evaluate the risks of such facilities, and ultimately, to help guide decisions related to public health and the safety of these facilities. Therefore, accurate and defensible estimates of natural ground water recharge rates are essential.

The objective of the Recharge Task is to provide defensible estimates of recharge rates for current and future conditions in and around the disposal facility. The scope of this task includes the disposal facility, the natural ecosystem that surrounds the facility, the Hanford Site, and any changes that might occur to these features while the disposed wastes still pose a threat to public health and safety. The objectives of this report are to summarize current knowledge regarding natural ground water recharge at the Hanford Site and to outline the work that must be completed in order to provide defensible estimates of recharge for use in the performance assessment of this LLW disposal facility.

(a) The Pacific Northwest Laboratory is operated for the U.S. Department of Energy by Battelle Memorial Institute, under Contract DE-AC06-76RLO 1830.



S9409069.13

Figure 1.1. Water Balance and Recharge Study Locations at the Hanford Site

2.0 General Considerations

Natural ground water recharge is controlled primarily by three factors: climate, soils, and vegetation. This observation has been made for deserts in Nevada and New Mexico as well as for the Hanford Site (Gee et al. 1994). Estimating recharge at the Hanford Site requires an evaluation of the interaction of climate, soils, and vegetation factors under both natural and disturbed conditions. In this section, the status of these factors at the Hanford Site is described briefly. In addition, an example is provided to demonstrate how surface disturbances on the 200 Area Plateau significantly affect recharge rates by affecting two of the primary factors (i.e., soil and vegetation).

2.1 Climate

The Hanford Site is located in the rain shadow of the Cascade Mountains. Winters are relatively cool and wet, and summers are hot and dry. The long-term average annual precipitation (from 1912 to 1980) is 162 mm (Stone et al. 1983). About 42% of the annual precipitation falls during November, December, and January. Snowfall accounts for 38% of all precipitation from December through February and about 16% of the total precipitation during November and March (Stone et al. 1983). Figure 2.1 shows the seasonal distribution of average monthly precipitation.

On average, January and July are the coldest and hottest months of the year, respectively. The average number of days with a maximum air temperature of ≤ 0 °C is 24 (Stone et al. 1983). The greatest number of consecutive days with a maximum air temperature of ≤ 0 °C is 29. The greatest number of consecutive days with a maximum air temperature of ≥ 38 °C is 11. Figure 2.2 shows the seasonal distribution of average monthly air temperatures.

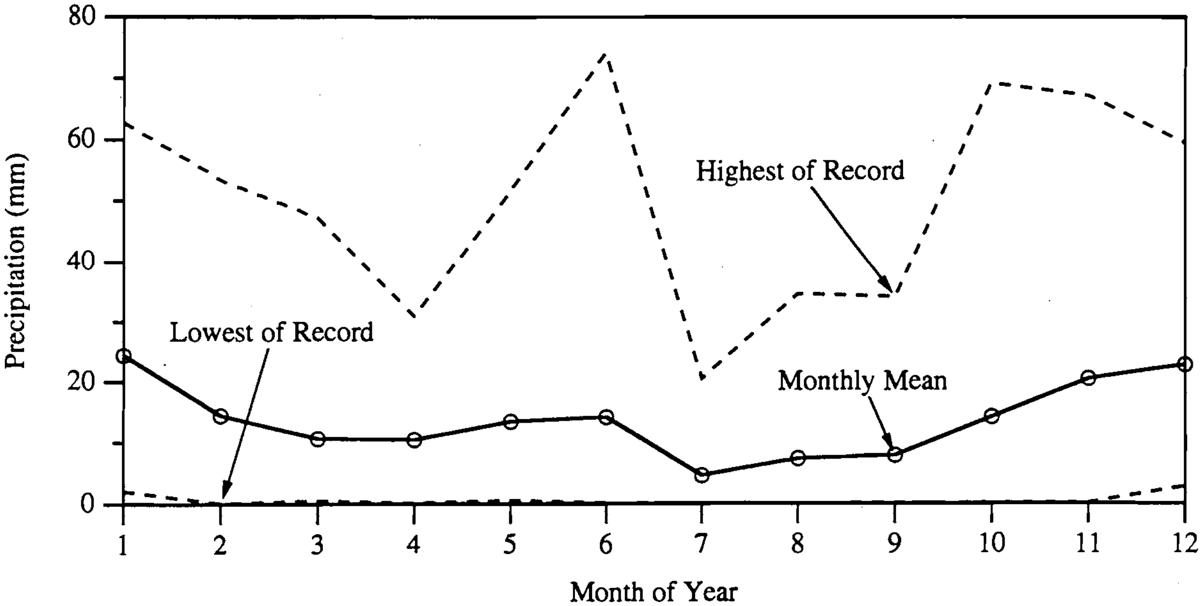


Figure 2.1. Average Monthly Precipitation at the Hanford Site from 1912 to 1980 (after Stone et al. 1983)

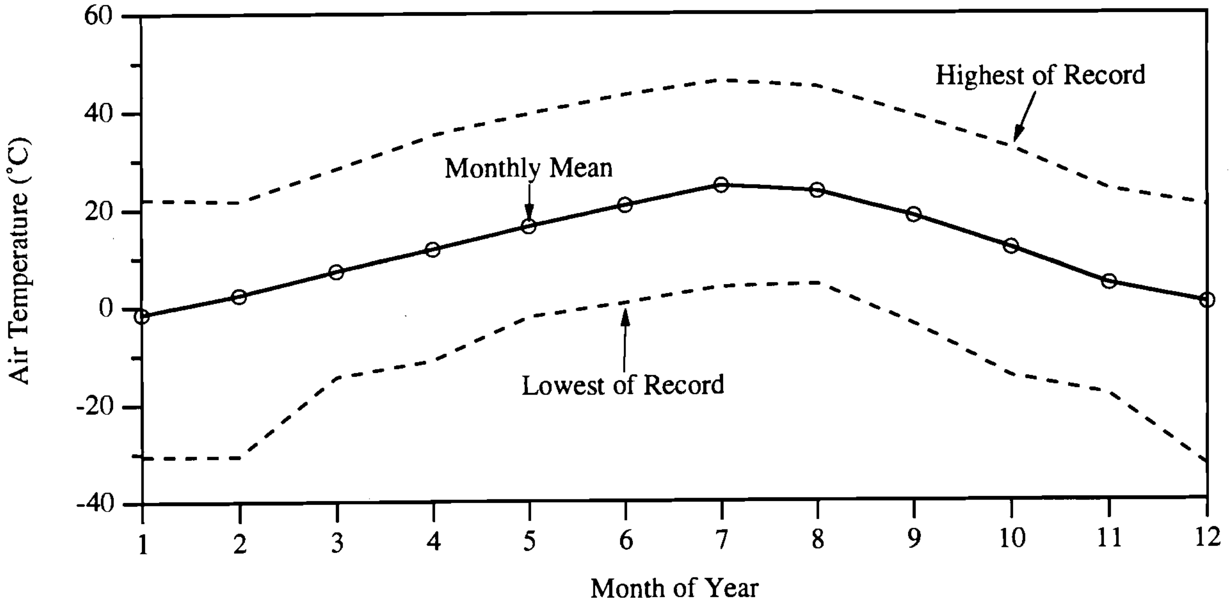


Figure 2.2. Average Monthly Air Temperatures for the Hanford Site from 1912 to 1980 (after Stone et al. 1983)

Most of the precipitation that contributes to recharge comes in the winter months, when evaporation is low. Rapid snowmelt occasionally causes high rates of runoff and infiltration, especially into local topographic lows. Gee and Hillel (1988) report an occurrence in February 1985, when a warm "chinook" wind, gusting to 72 km/h, melted most of a 200-mm (8 in.) snowpack in less than one day, causing significant infiltration and runoff. Figure 2.3 shows the seasonal distribution of average monthly soil temperatures.

2.2 Soils

Figure 2.4 shows the distribution of different soil types across the Hanford Site. Most of the surface soils on the 200 Area Plateau are coarse-textured alluvial sands, covered by a variably thick mantle of eolian fine sands and silts (Hajek 1966). These surface soils are generally associated with the Quincy soil series (mixed, mesic Xeric Torripsamments).

The surface soils are underlain by coarse, highly-permeable, glacial-fluvial sands and gravel of the Hanford Formation (Lindsey et al. 1991). These sediments are underlain by less permeable compacted silts and clays of the Ringold Formation (Tallman et al. 1979). The water table under the 200 Area Plateau is up to 100 m below the ground surface (DOE 1987).

2.3 Vegetation

The vegetation on the Hanford Site is generally classified as shrub-steppe and is composed of winter and summer annual grasses and perennial grasses and shrubs (Rickard and Vaughan 1988). This plant community, because of its mixture of shallow- and deep-rooted plants, uses soil water

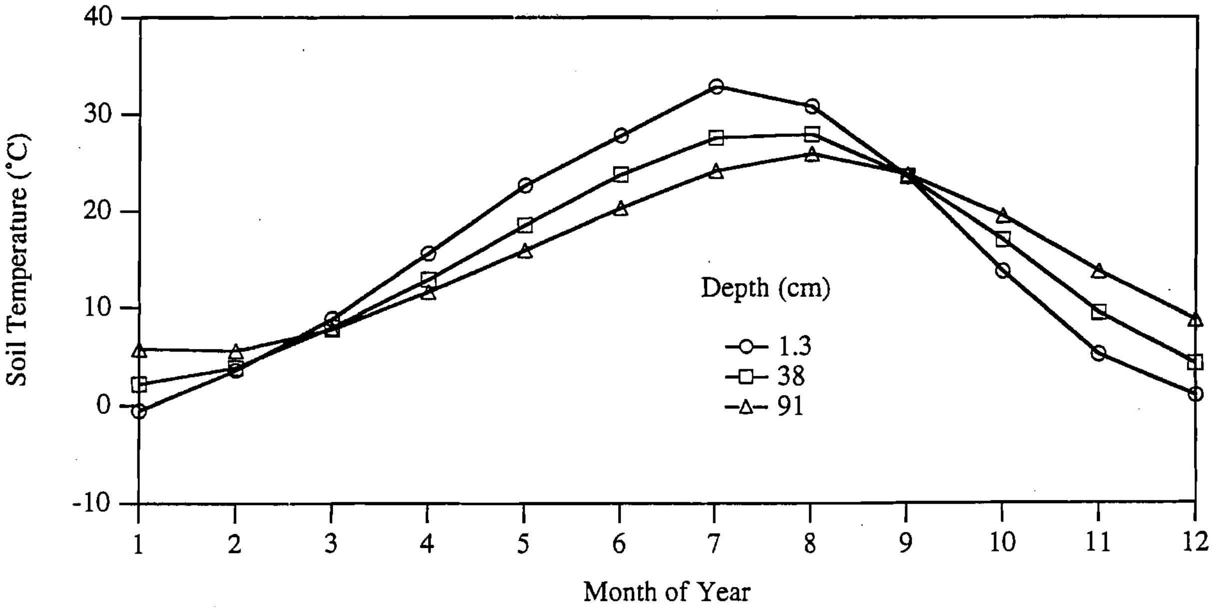


Figure 2.3. Average Monthly Soil Temperatures for the Hanford Site from 1912 to 1980 (after Stone et al. 1983)

very efficiently. Winter annuals such as poa (*Poa sandbergii* Vasey) or cheatgrass (*Bromus tectorum* L.) have roots that extend only a fraction of a meter into the soil (Link et al. 1990). These winter annuals compete efficiently for water stored near the soil surface but die in late spring after temperatures start to rise and near-surface soil water is depleted.

Perennial shrubs including sagebrush (*Artemisia tridentata* Nutt.), rabbitbrush (*Chrysothamnus nauseosus* Pallus), and bitterbrush (*Purshia tridentata* Pursh), as well as summer annuals such as Russian thistle or tumbleweed (*Salsola kali* L. var. *tenuifolia* Taush) and bursage (*Ambrosia acanthicarpa* L.) are common and have extensive root systems (Klepper et al. 1985). The perennial shrubs and summer annuals suffer from water stress but generally survive during the summer months on summer rains and water stored deep in the soil profile. Figure 2.5 shows the approximate distribution of different vegetation types and land use at the Hanford Site.

2.4 Surface Disturbances

Processes that alter the climate, soil, or vegetation can affect recharge. Thus, surface disturbances such as fire, erosion, grazing, farming, industrial development, and waste disposal facilities can alter recharge rates to the ground water. For example, since 1947, many large storage tanks, ranging in size from 0.2- to 3.8-ML (55,000-gal to 1-Mgal) capacity, have been buried in the 200 Area at locations called tank farms (GAO 1989). During excavation of the tank farms, both the vegetation and surface soils were removed. Backfilled sediments, which cover the tanks to a depth of approximately 2.5 m, consist primarily of coarse sands and gravel.

Cline et al. (1980) noted that most of the disturbed areas at the Hanford Site have developed irregular stands of cheatgrass, tumbleweed, and rabbitbrush. All three of these plants have been

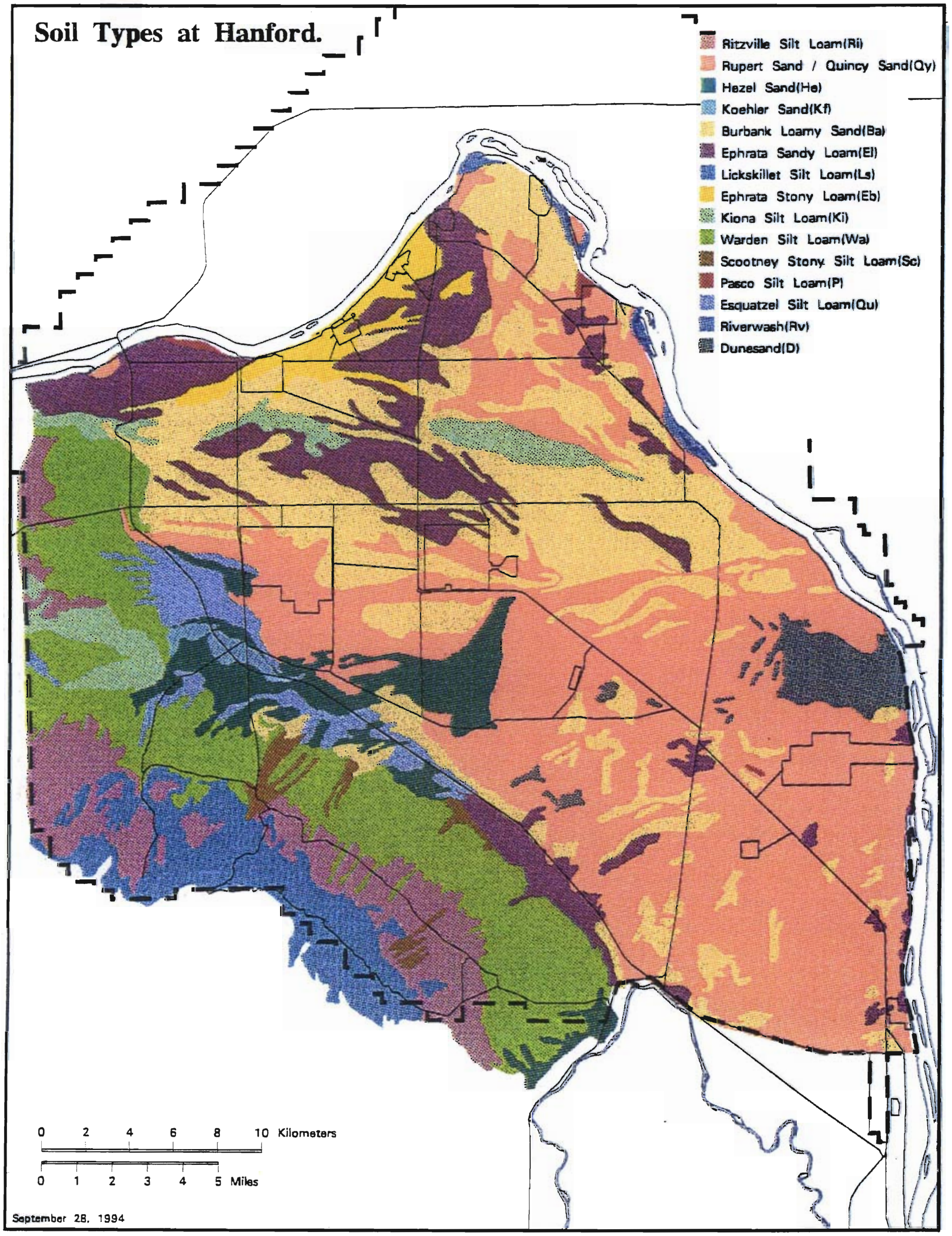


Figure 2.4. Distribution of Soil Types at the Hanford Site (modified from Hajek 1966)

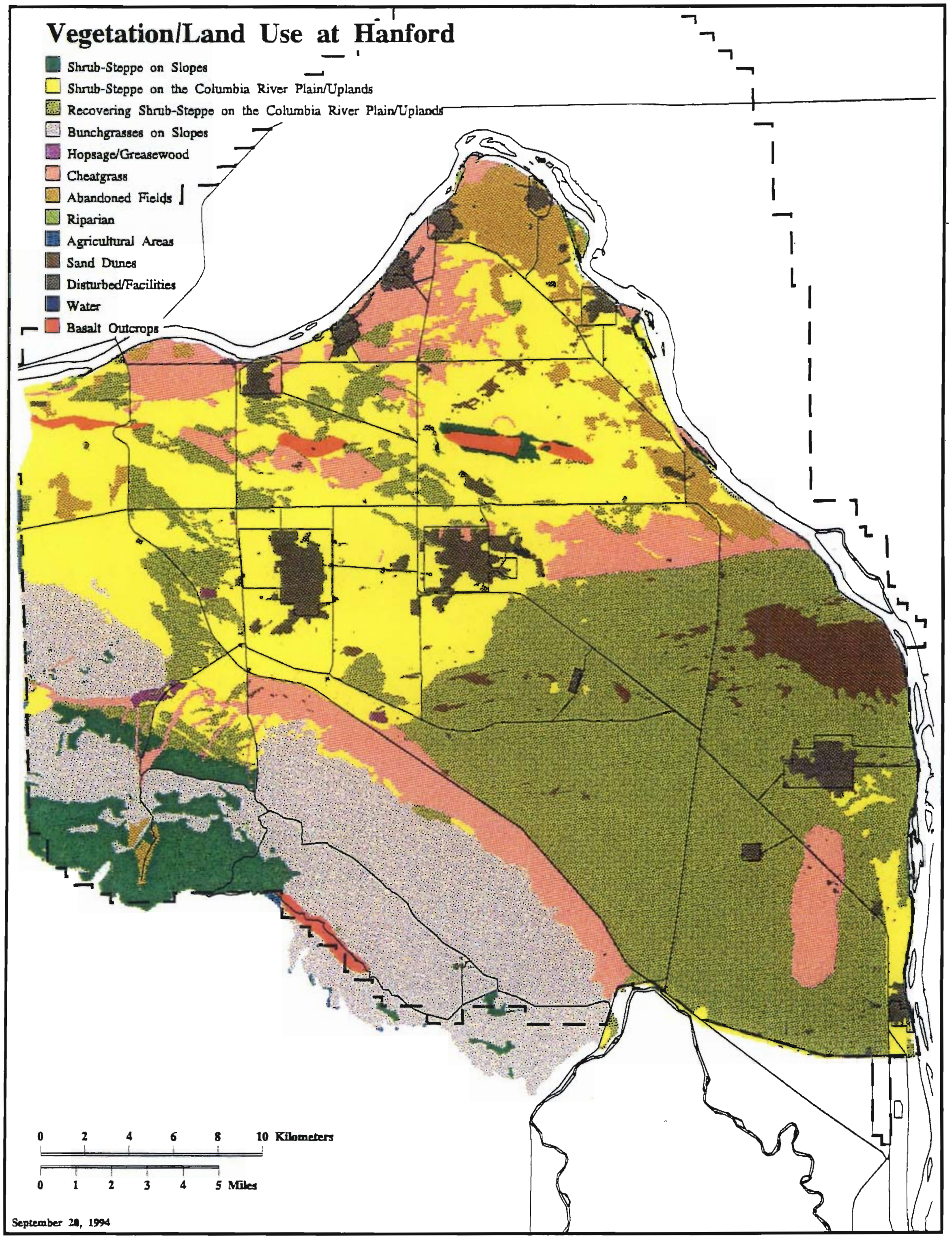


Figure 2.5. Distribution of Vegetation Types and Land Use at the Hanford Site (after Downs et al. 1993)

observed to remove radioactive elements from the soil and concentrate them in plant tissue (Selders 1950; Schreckhise and Cline 1979). This observation resulted in the regular application of herbicides to the surface sediments at the tank farms to prevent plant growth. Unfortunately, the coarse-textured sediments combined with an absence of vegetation optimize conditions for recharge and contamination of ground water. Data presented in Table 3.1 show how graveled surfaces devoid of vegetation promote recharge. The implications of surface disturbances for the LLW disposal facility will be discussed more thoroughly later in this report.

3.0 Summary of Estimated Recharge Rates at Hanford

Recharge studies have been conducted intermittently at the Hanford Site since 1969. Appendix A outlines the various techniques that have been used. Appendix B describes the results of most of the studies. In this section, a subset of the recharge rates that were estimated using lysimetry and tracer techniques are summarized to document the magnitude of recharge and demonstrate the spatial and temporal variability in annual recharge rates. In addition, the results of numerical simulations are presented to demonstrate the sensitivity of predicted recharge rates to variations in soil and vegetation types.

3.1 Lysimeter Studies

Lysimetry provides very accurate estimates of recharge for relatively short time periods and specific soil and vegetation conditions (see Appendix A). Table 3.1 shows annual recharge estimates for four sites. Brief descriptions of these sites are given below. Table 3.1 updates Table 1 in Gee et al. (1992), reflecting data collected since 1990. Although more lysimeter data exists at the Hanford Site, the data in Table 3.1 are sufficient to demonstrate the impact of soil, vegetation, and weather variations on recharge.

The 200 East closed-bottom lysimeter is 18.3 m deep, 5.7 m^2 in area, and uniformly filled with fine sand (see Appendix B). Before 1985, vegetation grew on the lysimeter and recharge rates were estimated to be less than 2 mm/yr. Between 1988 and 1991, vegetation was prevented from growing on the lysimeter and recharge rates were estimated to be 45 mm/yr (Gee et al. 1994).

The Buried Waste Test Facility (BWTF) has two lysimeters, represented in Table 3.1. One lysimeter is 7.8 m deep, 5.7 m^2 in area, filled with coarse sand, and maintained free of vegetation. In 8 years, annual recharge ranged from 24 to 111 mm/yr. A second lysimeter was 1.5 m deep, 2.3 m^2 in area, and vegetated. In some years, recharge was zero; in others, recharge was measurable when precipitation levels exceeded the transpiration capacity of the vegetation.

The Arid Lands Ecology (ALE) lysimeters are 1.5 m deep, 2.3 m^2 in area, filled with undisturbed silt loam monoliths, and vegetated with either bunchgrass or sagebrush. In eight years, no drainage has occurred.

The Field Lysimeter Test Facility (FLTF) has 24 lysimeters; data from eight are reported in Table 3.1. Most of the lysimeters at the FLTF were designed to test the performance of a capillary barrier in minimizing recharge. The lysimeters with the barrier configuration (i.e., silt loam over gravel) and vegetation prevented drainage for the entire 7 years, even when irrigated to 2 times and 3 times the average precipitation levels. The same result was achieved when vegetation was absent, but only if under ambient precipitation. When precipitation was increased to 3 times, the absence of vegetation allowed drainage to occur in the sixth year of the study.

Two other lysimeters at the FLTF were filled with 1.5 m of sand over a sandy gravel layer. These lysimeters were vegetated with sagebrush. The sand-filled lysimeter receiving ambient precipitation did not show drainage until the fourth year of the study. In contrast, the irrigated lysimeter had drainage in 3 of the 4 years of the study.

Finally, two other lysimeters at the FLTF were filled with sand, but had a 20-cm-thick gravel layer on the surface. These lysimeters were not vegetated and were intended to mimic conditions at the tank farms. Drainage was recorded in every year for both the ambient and increased precipitation treatments.

Table 3.1. Estimated Annual Recharge Rates from Lysimeter Data at the Hanford Site.

Facility	Soil/Vegetation	Irrigation	Time	Recharge (mm/yr)	Recharge (% of Precip.)
200 East	sand/tumbleweed	no	1971-1985	<2	<1
	sand/bare	no	1988-1991	45(a)	31
BWTF	sand/bare	no	1985-1986	111	48
	sand/bare	no	1986-1987	102	55
	sand/bare	no	1987-1988	40	29
	sand/bare	no	1988-1989	42	24
	sand/bare	no	1989-1990	46	39
	sand/bare	no	1990-1991	33	20
	sand/bare	no	1991-1992	24	15
	sand/bare	no	1992-1993	42	19
	sand/cheatgrass	no	1984-1986	62	35
	sand/tumbleweed	no	1986-1987	1	5
	sand/tumbleweed	no	1987-1988	0	0
	sand/tumbleweed	no	1988-1989	10	6
ALE	silt loam/sagebrush	no	1986-1994	0.0	0.0
	silt loam/bunchgrass	no	1986-1994	0.0	0.0
FLTF	silt loam over gravel/bare	2x	1987-1990	0	0
	silt loam over gravel/bare	2x/3x(b)	1990-1993	30	< 6
	silt loam over gravel/bare	no	1987-1994	0	0
	silt loam over gravel/sagebrush	2x/3x(b)	1987-1994	0	0
	silt loam over gravel/sagebrush	no	1987-1994	0	0
	sand over sandy gravel/sagebrush	no	1990-1991	0	0
			1991-1992	0	0
			1992-1993	0	0
			1993-1994	28	6
	sand over sandy gravel/sagebrush	2x/3x(b)	1990-1991	23	5
			1991-1992	0	0
			1992-1993	77	16
			1993-1994	28	6
	gravel over sand/bare	no	1990-1991	39	24
			1991-1992	78	49
			1992-1993	150	66
			1993-1994	47	30
	gravel over sand/bare	2x/3x(b)	1990-1991	251	54
			1991-1992	287	62
			1992-1993	356	74
			1993-1994	413	86

(a) Recharge estimate based on increase in soil-water storage.

(b) 2x/3x = 2 times or 3 times the long-term average.

3.2 Tracer Studies

Tracer studies supply estimates of recharge for extended periods (e.g., 35 to 10,000 years) that are much greater than traditional experiments allow (see Appendix A). As with lysimetry, tracer methods provide estimates of recharge for specific soil and vegetation combinations, although the exact soil and vegetation are less well-known because of the long periods. Furthermore, because of the various underlying assumptions, tracer methods provide a recharge estimate that is less accurate than that obtained with lysimetry. Disturbances such as those caused in creating a waste site change the surface sufficiently so that recharge rates can be altered by orders of magnitude. Such changes in recharge are not accounted for by conventional tracer techniques.

Estimates of recharge using the chloride (Cl) mass balance method are assumed to represent average recharge rates over approximately the past 13,000 years, when the Hanford sediments were deposited during the last glacial flooding event. Estimates of recharge using the ratio of ^{36}Cl to Cl are generally considered more representative of average recharge rates over the past 40 years (since the bulk of sea-level nuclear weapons testing in the 1950s and atmospheric nuclear weapons testing in the early 1960s). Both methods are described in more detail in Appendix A.

Prych (1995) used the Cl mass balance and ^{36}Cl/Cl ratio methods to estimate natural ground water recharge at the Hanford Site; the results are summarized in Table 3.2. In general, Prych's results are in qualitative agreement but are generally lower than the lysimeter and field studies reported previously and in Appendix B. Areas with silt loam soils, deep-rooted sagebrush, and shallow-rooted grasses exhibit the lowest apparent recharge rates. Areas with coarse soils and shallow-rooted vegetation exhibit moderate rates (several millimeters) of annual recharge. Results from the two tracer techniques differ by as much as two orders of magnitude. These differences may be related to the different time-scales represented by the two techniques, and is an issue that warrants further investigation.

Table 3.2. Estimates of Recharge at Hanford using Cl Mass Balance and ^{36}Cl/Cl (after Prych 1995)

		Estimated Recharge Rate (mm/yr)	
Soil	Vegetation	Cl mass balance	^{36}Cl
silt loam	sagebrush and grasses	0.01-0.11 (4 wells)	< 2.1, < 3.4 (2 wells)
loamy sand or sandy loam (0.6 m) over sand and gravel	sagebrush and grasses	0.01-0.3 (5 wells)	< 2.6 (1 well)
loamy sand (0.6 m) over sand	sparse shallow-rooted grasses	0.4-2.0 (4 wells)	5.1(a) (1 well)

(a) ^{36}Cl data were not from sufficient depth (> 5 m) to capture the entire tracer profile.

3.3 Model Predictions

Mathematical models that incorporate the processes that affect recharge are useful for understanding recharge and for predicting rates under a variety of climate, soil, and vegetation conditions. The ability to explore many scenarios quickly is the main reason that mathematical models are considered valuable tools in performance assessments. Appendix A discusses the advantages (e.g., quick results) and disadvantages (e.g., large data requirements); Appendix B recounts recent recharge modeling results.

For this report, twelve simulations were conducted to demonstrate the effects of different soil and vegetation types on predicted recharge rates over 30 years. The soil-vegetation combinations included three soil configurations (sand, silt loam, and silt loam overlying sand) and four vegetative cover types (sagebrush, bunchgrass, cheatgrass, and no vegetation). The model used was UNSAT-H (Fayer and Jones 1990), a one-dimensional numerical model that simulates the dynamic processes of water infiltration, drainage, redistribution, evaporation, and uptake by plant roots. The governing equations are based on a modified form of the Richards equation for liquid water flow, Fick's law of diffusion for the flow of water vapor, Fourier's law of heat conduction, and the theory of coupled water and heat flow in soils proposed by Philip and de Vries (1957). Simulations of the 200 East Area closed-bottom lysimeter are reported in Appendix B as a field validation test of UNSAT-H.

The sand and silt loam parameters used for these model simulations are representative of Quincy sand and Warden silt loam. Quincy sand covers a large portion of the 200 Area Plateau (see Figure 2.4), and Warden silt loam has been proposed as the soil to be used for surface protective barriers. The combination of silt loam overlying sand creates a capillary barrier effect that reduces recharge relative to a uniform profile of either soil type. The combinations of uniform sand with and without vegetation are analogous to the near-surface conditions that have prevailed at different times and different locations on the 200 Area Plateau, including the closed-bottom lysimeter.

The soil hydraulic properties were represented using the van Genuchten (1980) water retention and Mualem (1976) hydraulic conductivity models. The model parameters for the sand and silt loam were estimated from water retention and hydraulic conductivity data reported by Rockhold et al. (1988) using the RETC code (Yates et al. 1992). The soil hydraulic properties were assumed to be nonhysteretic. The soil hydraulic properties and other model parameters used for these simulations are given in the input files listed in Appendix C. All simulations were conducted assuming isothermal conditions and vapor flow. Reasonably accurate simulation results have been reported using UNSAT-H in the isothermal mode, as long as the vapor flow option is used (Fayer and Gee 1992; Fayer et al. 1992). Using the isothermal mode also significantly reduces the required simulation time.

The model domain was 5 m. The node spacings varied from 0.2 cm at the soil surface to 20 cm at the bottom of the model domain. For the silt loam overlying sand, the upper layer was 30 cm thick. Although this thickness of silt loam is much less than the 2 m proposed for protective barriers at the Hanford Site, it is sufficient to demonstrate the capillary barrier effect. The node spacings were gradually reduced to 2 cm at the interface between the different material types. A uniform initial tension of 500 cm was used for all simulations. Internodal conductances were computed using the geometric mean of the values in adjacent grid blocks.

Simulations were conducted for the years 1957 through 1992. To minimize any effects from the initial conditions, the simulation results from years 1957 through 1962 were not used. Only the simulation results for the years 1963 through 1992 (30 years) were analyzed and compared. The upper boundary conditions were derived from daily weather data obtained from the Hanford Meteorological Station (HMS). A unit gradient condition was used for the lower boundary.

For the simulations with plants, potential evapotranspiration (PET) was calculated using the Penman model and was partitioned into potential evaporation and potential transpiration using two different methods. The cheatgrass model in UNSAT-H was used to partition PET for cheatgrass.

The leaf area model in UNSAT-H was used to partition PET for bunchgrass and sagebrush. The maximum rooting depths for cheatgrass, bunchgrass, and sagebrush were assumed to be 0.6, 1.0, and 3.0 m, respectively. Other required plant parameters, given in Appendix C, are based on the work of Fayer and Walters (1995).

Figure 3.1 shows the average annual precipitation and predicted drainage (recharge) rates for the 12 simulations. The average annual precipitation for the 30-year (1963 to 1993) simulation period is 160 mm. Annual precipitation ranged from a low of 75.9 mm in 1976 to a high of 281 mm in 1983. These values are approximately 53% less than and 74% greater than the long-term annual average (1912-1980) of 162 mm reported by Stone et al. (1983).

The predicted drainage rates depicted in Figure 3.1 illustrate the impact of soil and vegetation on recharge. The average, minimum, and maximum drainage rates for the 30-year simulation period are given in Table 3.3.

For the simulations with uniform sand, the predicted drainage rates vary by up to 2-3 orders of magnitude between the results obtained using sagebrush parameters versus those obtained with no vegetation. The 30-year average annual drainage rates predicted for the uniform sand with no vegetation and with sagebrush are 22 and 0.5 mm/yr, respectively.

The simulation results for uniform silt loam show a similar trend. The 30-year average annual drainage rates predicted with no vegetation and with sagebrush are 7.6 and 1.0 mm/yr, respectively. Note that the predicted annual average drainage rate for the unvegetated sand is only about 3 times greater than the predicted annual average drainage rate for the unvegetated silt loam. However, the predicted annual average drainage rate for the sand with sagebrush is only 50% as great as the annual average drainage rate predicted for the silt loam with sagebrush. This difference is caused by the different soil hydraulic properties and indicates that the silt loam conducts water faster than the sand at low matric potentials.

The 30-year average annual drainage rate predicted for the silt loam overlying sand with no vegetation is 1.5 mm/yr. This value is 20% of the rate estimated for the uniform, unvegetated silt loam. The textural contrast between the silt loam and sand creates a capillary barrier, which increases the storage capacity of the overlying silt loam and reduces the rate of infiltration into the underlying sand. Using the sagebrush parameters, the simulations of silt loam overlying sand predicted an average annual drainage rate of 0.2 mm/yr.

The transpiration values (not shown) obtained from the simulations with silt loam overlying sand are somewhat different from those obtained for the uniform sand. The capillary barrier at the interface between the silt loam and sand increases the storage capacity of the silt loam and reduces the flux of water into the sand. Because the root densities of cheatgrass and bunchgrass are greater than that of sagebrush in the silt loam portion of the soil profile, these plants effectively extract more water from the silt loam and have greater relative annual transpiration rates than sagebrush for most years of the simulations. In reality, plant roots tend to extend into and develop more fully in regions of the soil where more water is available. In other words, roots will tend to go wherever the water is, within the physiological constraints of the plant. This effect is not accounted for in UNSAT-H.

The annual pulses of simulated drainage shown in Figure 3.1, exhibit a time lag relative to annual precipitation. This time lag is dependent on soil type(s), stratification, antecedent water content, and plant water extraction, and is proportional to the depth of the simulated soil profile. Transient recharge pulses are also dampened with depth, so that soil profiles show a more constant flux in time at greater depth.

The time series of drainage rates depicted for the uniform sand in Figure 3.1 illustrate several important points regarding long-term monitoring issues and estimating recharge rates for specific soil and vegetation combinations. If, for example, recharge rates were determined from a 5-year record (1981-1985) of lysimeter data with sagebrush as the dominant vegetation, the simulation results in

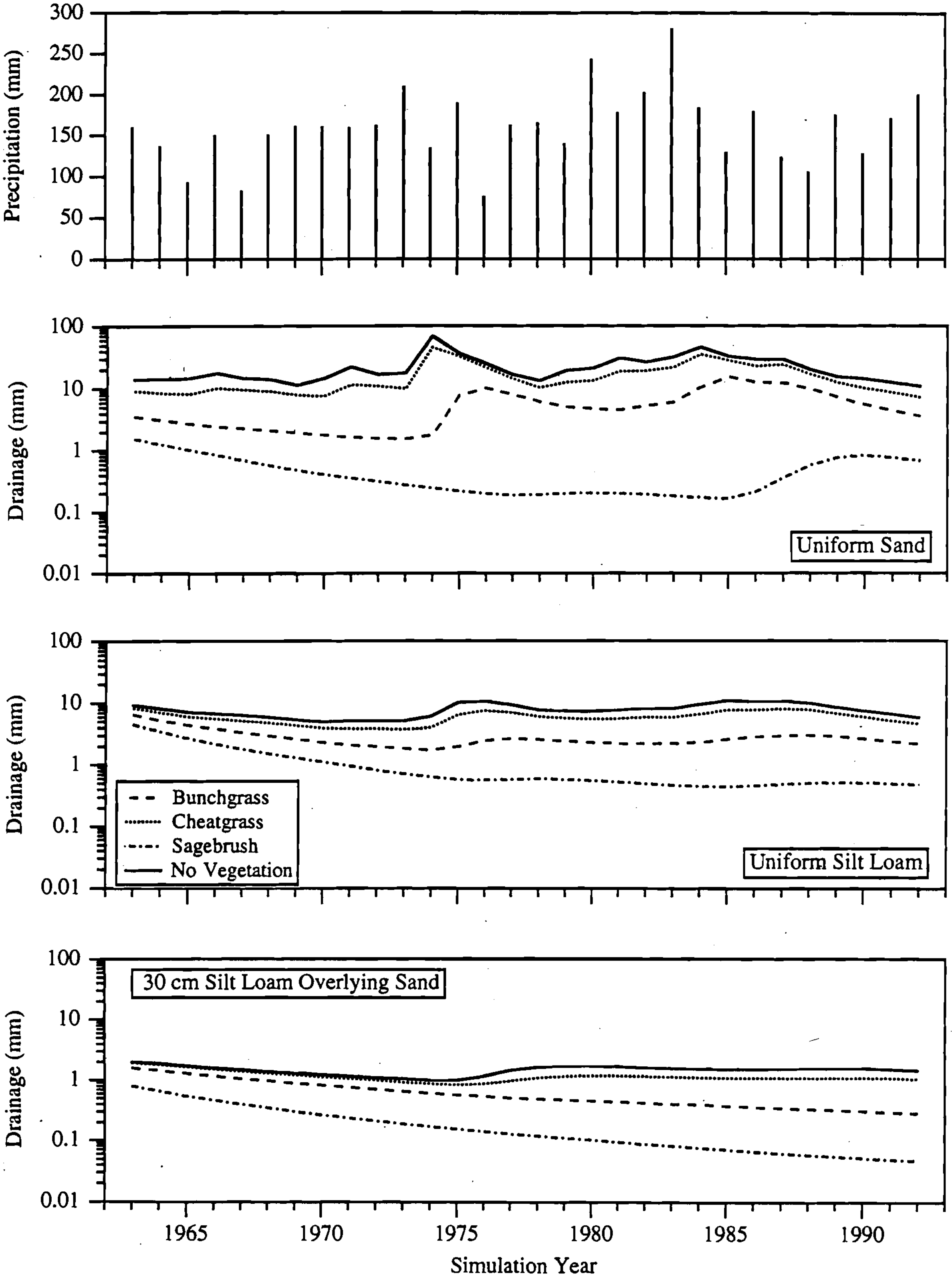


Figure 3.1. Precipitation and Predicted Drainage for Simulations with Uniform Sand, Silt Loam, and 30-cm of Silt Loam Overlying Sand

Figure 3.1 suggest that an average recharge rate of approximately 0.2 mm/yr would be estimated. However, if the dominant vegetation was cheatgrass, the average estimated recharge rate for this same time period would be approximately 24 mm/yr. This indicates a more than two orders of magnitude increase in recharge rates resulting from a change in vegetation. This is the type of change that can be expected on the Hanford Site following wildfires.

Regarding long-term monitoring issues, if a 5-year lysimeter study was conducted from 1970 to 1974, and bunchgrass was the dominant vegetation on the lysimeter, the simulation results for the sand in Figure 3.1 suggest that the average recharge rate would be approximately 1.6 mm/yr. If however, the same 5-year study was conducted from 1975 to 1979, the simulation results in Figure 3.1 suggest that the average estimated recharge rate would be 7.3 mm/yr. This factor of 4.5 increase in estimated recharge rates for two different 5-year periods illustrates the importance of long-term monitoring. This point was also emphasized by the 1985 Recharge Workshop peer-review panel, whose suggestions are summarized in Section 5.1.

The simulation results in Figure 3.1, as well as the lysimeter data in Table 3.1, show that significant recharge can occur in some years, depending on the soil-moisture status, and the timing and intensity of precipitation events. Therefore, referring to the mean annual recharge rate is really only appropriate if the mean is taken over a sufficiently long period containing a statistically significant number of extreme events.

In general, for any given soil type, more drainage is predicted when no vegetation is present, or when the vegetation is shallow-rooted cheatgrass or bunchgrass, than when the vegetation is deep-rooted sagebrush. This reflects not only the greater rooting depth but also the higher wilting point of sagebrush. These results are also supported by the lysimeter data shown in Table 3.1 The average recharge rates for all simulations conducted using sagebrush parameters compare favorably with the estimates made by Prych (1995) using tracer techniques (see Table 3.2).

Table 3.3. Predicted Recharge Rates for Different Soil and Plant Types for the 30-Year Period from 1963 to 1992

	Recharge Rate (mm/yr)											
Soil Type	No Vegetation			Cheatgrass			Bunchgrass			Sagebrush		
	avg	min	max	avg	min	max	avg	min	max	avg	min	max
Sand	22.0	10.5	68.1	15.7	7.0	45.5	5.4	1.5	14.9	0.5	0.2	1.5
Silt Loam	7.6	4.9	10.7	5.8	3.7	8.2	2.8	1.7	6.4	1.0	0.4	4.4
Silt Loam/ Sand	1.5	1.0	2.0	1.2	0.8	1.9	0.6	0.3	1.6	0.2	0.1	0.8

4.0 Proposed Low-Level Waste Disposal Facility

As stated previously, the objective of the Recharge Task is to provide defensible estimates of recharge rates for assessing the safety of subsurface disposal of LLW at the Hanford Site. This requires the development of a conceptual model of the disposal site, a description of the recharge scenarios, and an acknowledgment of unaddressed issues.

4.1 Conceptual Model

The LLW disposal facility has neither been designed nor has its location at the Hanford Site been determined. However, based on the designs for other facilities, the LLW facility will likely be similar to that shown in Figure 4.1. One or more subterranean vaults will be built. The vaults will be filled with the waste over a period of time. The waste may be completely mixed with filler material that has desirable properties, or the waste may be vitrified/manufactured into objects with defined volumes and inner spaces filled with another material. The vaults and filler material will have physical and chemical properties that affect release and transport rates. Once filled with waste, the vault may be isolated from the biosphere by one or more chemical and physical barriers, such as a surface Hanford Protective Barrier.

4.2 Recharge Scenarios

The scope of the Recharge Task includes estimating recharge for the disposal facility, the natural ecosystem surrounding the disposal site, and the Hanford Site. Federal and state regulations mandate that a disposal facility meet certain criteria related to the release of contaminants and resulting exposure of the biosphere and human population. Previous studies (e.g., DOE 1987) identified the ground water pathway as most likely to result in the greatest exposure; therefore, that pathway is the focus of the recharge scenarios.

4.2.1 Processes

From the perspective of recharge, the three processes of interest are leaching, changing water table elevation, and changing ground water flux and direction.

Leaching of the Disposed Waste

The process that has the most direct impact on the shallow land burial of LLW waste is leaching of the waste form and subsequent transport of contaminants through the vadose zone and to the water table. In Figure 4.1, this process corresponds to the flux moving through the protective barrier, with a secondary contribution from any excess flux that might migrate laterally from the facility or barrier's edge. Eventually, the water flux that contributes to leaching could change as the disposal facility or barrier degrades. Finally, the flux that passes through the surface barrier may be redirected and channeled as it encounters the subsurface disposal structures.

Changing the Water Table Elevation

The process with the most impact after direct leaching is a changing water table elevation, which changes the thickness of the vadose zone beneath the facility. The time for contaminants to travel from the waste form to the water table is directly related to the vadose zone thickness. Given the thickness and dry state of Hanford sediments, the travel time can be thousands of years. This is one reason that near-surface burial at Hanford is a viable disposal option. If the vadose zone thickness were

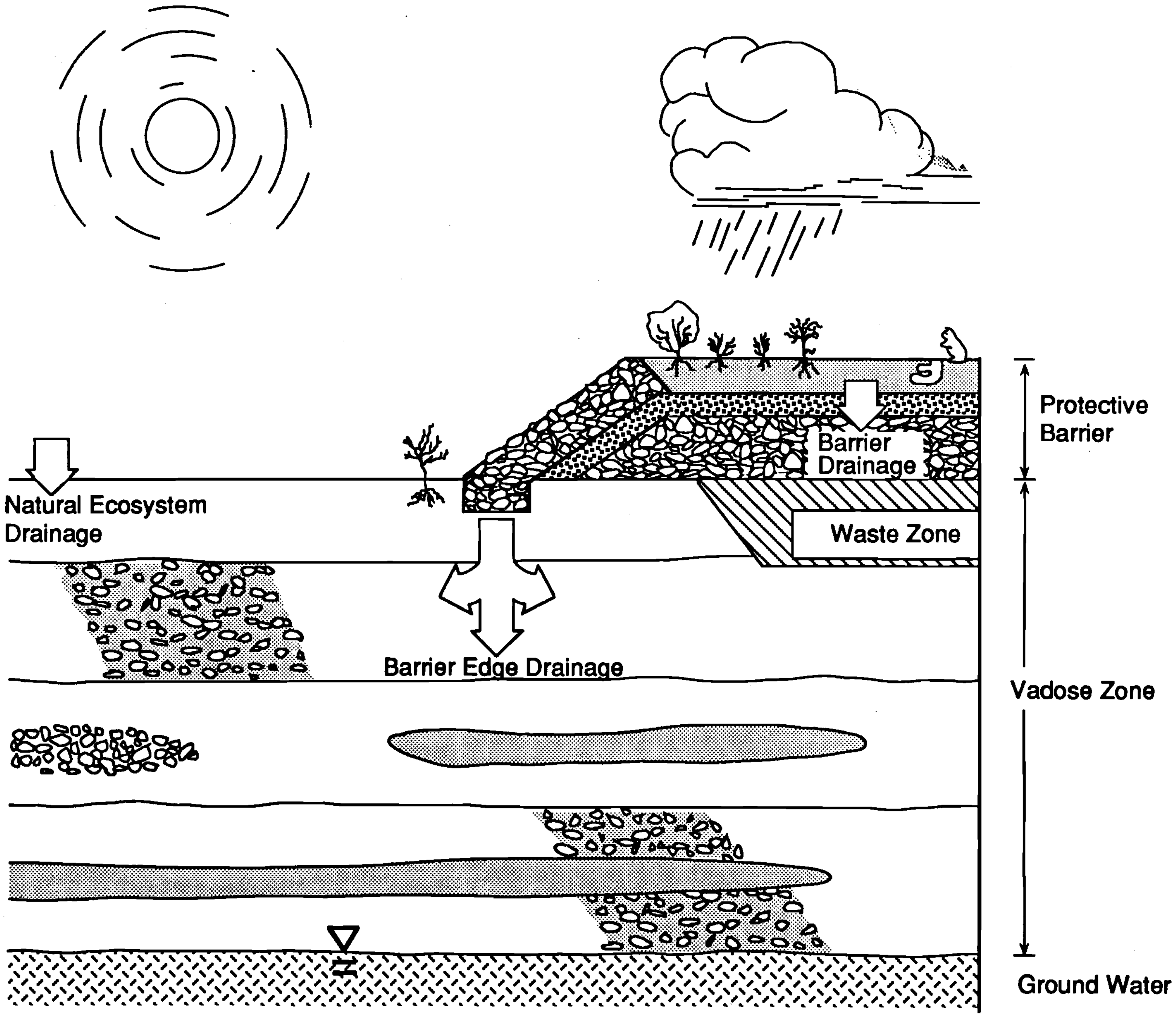


Figure 4.1. Conceptual Model of a LLW Disposal Facility

reduced by 50% by irrigation, for example, the travel time would be reduced proportionally. Thus, a travel time of 2000 years would be reduced to 1000 years, which could significantly alter the results of a performance assessment.

Changing the Ground Water Flux and Direction

The third process of interest is changes in ground water flux and direction. This process is considered important because regulations require analyzing the ground water pathway using a well located 100 m downgradient of the facility. The direction of ground water flow establishes the location of the well. The flux of ground water affects the cross section of aquifer withdrawn from a given well-pumping scenario. The cross section of aquifer pumped determines the ratio of contaminated and uncontaminated ground water pumped, which impacts the calculated exposure levels.

4.2.2 Time Scales

The time scale of interest is not clearly defined. However, the period that must be analyzed in the performance assessment can be divided into four (or more) subperiods: institutional control, facility integrity control, regulatory control, and peak concentration control. Example time periods are given in Table 4.1 for each subperiod with analysis considerations.

Table 4.1. Example Time Periods and Analysis Considerations

Time Period (years after site closure)	Considerations
0 to 100	*Institutional Control.* The federal government will retain control of the facility. If signs of facility degradation occur during this period, the government can perform maintenance or remediate the site if necessary.
100 to 1000	*Facility Integrity Control.* For example, the Hanford Protective Barrier (Wing 1994), which is proposed as a surface cover, has a design life of 1000 years. During this time, the performance analyses of the facility would assume that the barrier meets its design specification of limiting drainage through the barrier to 0.5 mm/yr. There is no design specification for the quantity of water that infiltrates at the edge of the barrier. The LLW disposal facility itself has not yet been designed. However, when the facility is designed, various components may have different design lives, which may or may not coincide with the design life of the surface protective barrier.
1000 to 10,000	*Regulatory Control.* Performance assessments must be conducted for this period that postdates the design life of the disposal facility. During this period, some protective features of the facility may still function, although at a level below the original design specifications because of degradation.
10,000 to Primary and secondary peaks	*Peak Concentration Control.* Regulations in existence in 1994 indicate a need to analyze the facility for 10,000 years. However, experience on the Grout project (WHC 1993) shows that some reviewers want analyses continued until peak concentrations have been forecast (and shown to be within acceptable limits) for all contaminants.

4.2.3 Variables

There are five major variables that could alter recharge rates during the life of the disposal facility: vegetation, soil, land use, climate, and degradation of the facility.

Vegetation

Three processes that affect the composition and health of vegetation must be considered: climate change, plant succession, and fires. Petersen (1993) reported that vegetation at the Hanford Site cycled repeatedly between sagebrush and grasses during the last 10,000 years in response to climate changes. Rickard and Vaughan (1988) speculated that competitive alien species, particularly *Bromus tectorum*, could supplant native communities. Downs et al. (1993) reported that a fire in 1984 affected roughly 360 km^2, or 38%, of the Hanford Site south of the Columbia River. Cheatgrass acts as dry tinder causing fires to spread easily once started. The burned areas at Hanford are now dominated by cheatgrass. Such a dramatic change in plant communities was forecast by the noted ecologist Aldo Leopold (Leopold 1949) who indicated that cheatgrass would eventually dominate the shrub-steppe areas of the western United States.

Soil

Two processes that affect soil (and thus recharge) are erosion/deposition and soil development. According to Gaylord et al. (1993), "The Hanford Site is blanketed by eolian deposits and deflationary surfaces reflecting Holocene and possibly late Pleistocene eolian activity...". They go on to say that sand dunes, the most obvious manifestation of eolian accumulations, are confined to the lower elevations of the Site. The Soil Survey for Benton County (USDA 1971) also refers to the soils as being "mantled" by a wind-blown loamy fine sand. Soil development is a slow process in an arid environment. Given that the pertinent time is 10,000 years or more, the development process may be sufficient to change or alter the surface soil properties and thus affect recharge.

Land Use

Three impacts from land use changes are altered vegetation communities, irrigated farming, and structures that promote infiltration. Rickard and Vaughan (1988) reported that dryland farms invaded by *Bromus tectorum* 40 years ago have still not reverted to the native sagebrush-bunchgrass community. Irrigated farming is one of the land use options identified by the Hanford Future Site Uses Working Group (HFSUWG 1992). Irrigation has a high potential to enhance recharge; we speculate that, under current practices, recharge could be 100 to 250 mm or greater annually, although future irrigation practices may become more efficient. If development occurs, more areas could be created with structures that promote recharge such as large tracts of paved surfaces draining onto graveled shoulders.

Climate

Petersen (1993) summarized the expected changes in climate. Briefly, the potential exists for both warmer and drier conditions, and colder and wetter conditions. The colder and wetter extreme is not expected to cause more than a two-fold increase in precipitation. In the past 75,000 years the climate change has been modest (less than a 30 to 40% change in precipitation). Furthermore, the potential exists for ice-age conditions that could lead to flooding of the disposal site within the next 50,000 to 100,000 years.

Degradation

The integrity of the facility is not guaranteed beyond institutional control (i.e., 100 years). However, design features will be included that protect the facility and prolong its useful life. For example, the Barrier Program specifies that the Protective Barrier has a design life of 1000 years (Wing 1994). Assuming this to be true, the question to be answered is how the facility is to be analyzed after the end of the specified design life. Estimates of the nature and rate of degradation of the facility features are required. These estimates can then be used in an analysis of recharge for the various stages of degradation.

4.3 Preliminary Recharge Estimates

The existing recharge data were used to provide recharge estimates that can be used in preliminary performance assessment calculations. Estimates are provided for the barrier, the barrier edge, the surrounding natural ecosystem, and the entire Hanford Site. We recommend assuming a recharge rate of 0.5 mm/yr through the Hanford protective barrier. This assumption is supported by an 8-year record of lysimeter data (Table 3.1) and is consistent with engineering design specifications over the 1000-year design life of the barrier (Wing 1994). At the barrier edge, a higher recharge rate of 75 mm/yr should be assumed. This assumption is based on four years of data for a lysimeter with a graveled surface (Table 3.1) that is similar to the riprap sideslope of the protective barrier. This estimate does not include possible overland flow or lateral drainage from the barrier. Beyond the barrier, the recharge rate of the natural ecosystem can be represented with one of two rates. If the plant community is assumed to be sagebrush, an estimate of 5.0 mm/yr should be used. This is a conservative value chosen to be slightly greater than all the rates reported by Prych (1995) using tracer measurements. If the plant community is assumed to be cheatgrass, an estimate of 25.4 mm/yr should be used. This value is based on an 8-year record of water content observations at the Grass Site in the 300 Area (Fayer and Walters 1995). For the entire Hanford Site, we recommend using the recharge distribution map reported by Fayer and Walters (1995).

4.4 Outstanding Issues

Studies at Hanford have estimated recharge rates that vary over two orders of magnitude at the same location depending on the method used (Prych 1995; Fayer and Walters 1995). Two issues that must be addressed are the accuracy of the estimation methods and the variability of the estimates. How accurate should the estimates be? What estimation techniques can provide the necessary recharge information? Do discrepancies exist and can they be resolved? Enfield et al. (1973) estimated an upward thermally induced vapor flux of 0.04 mm/yr at Hanford. Some recharge estimation methods do not consider processes such as vapor flow and preferential flow, which could be very important if estimated recharge rates are much less than 0.1 mm/yr.

Allison et al. (1994) stated that the most difficult and important problem to overcome in estimating recharge is the prediction and assessment of its variability. The issue of variability relates to both spatial and temporal components of the analyses. Spatially, soil and vegetation are well-known to vary substantially across scales of one to ten meters. From the perspective of the facility, large-scale variability is imposed by the design (e.g., capillary layers, asphalt, concrete). Methods must be devised for estimating recharge for the various configurations and determining its variability.

Temporally, recharge varies seasonally in response to winter precipitation and summer evapotranspiration, and annually in response to year-to-year variations in weather, principally precipitation amounts. Figure 3.1 demonstrates how recharge varies during a 30-year period for different soil types: Fayer and Walters (1995) presented examples that show even greater year-to-year variability. The questions that must be answered include: What form should the recharge estimates take? Should the estimates be the mean for 10,000 years, the mean plus one standard deviation, the median annual value, or perhaps a time series description? Questions such as these may only be answerable when we propagate variable recharge rates through the transport calculations.

5.0 Status of Recharge Study Plans

The study of recharge at Hanford goes back nearly 40 years. The National Academy of Science Committees discussed recharge issues as early as 1957 (NRC 1957). In 1966, the Committee on Geologic Aspects of Radioactive Waste Disposal of the National Academy of Sciences reported that they were "...dubious about the concept that in arid and semi-arid lands meteoric water does not percolate downward as far as the water table but instead is lost entirely by evaporation and plant transpiration" (Galley et al. 1966). The Committee recommended that "The movement of water, both upward and downward, under varying conditions of wetting in the zone (of) aeration (at) ... Hanford, Washington, should be thoroughly studied, particularly with reference to questions about percolation of rainwater and snow melt to the water table." The 1966 review led to the first of many studies of natural ground water recharge at the Hanford Site.

In 1985, an external peer review was conducted of recharge studies at Hanford. The results of that review are summarized below to give an historical perspective to the plans of the Recharge Task. Following a summary of the 1985 workshop, the scope of work and the proposed plan for task completion for the Recharge Task are outlined.

5.1 Results of the 1985 Recharge Workshop

A recharge workshop was held at Hanford in October 1985. The purpose of the workshop was to review field and laboratory studies that were ongoing and plans to close the ground water recharge issue at Hanford (Sonnichsen 1986). A panel of five external experts in the field of arid lands hydrology were invited to the workshop to provide comments and recommendations.

The panel noted that quantification of recharge rates at Hanford is made particularly difficult by the following facts: 1) The recharge rates are of the same order of magnitude (or smaller) than the measurement errors of flux at the surface boundary, 2) the biological system (root activity, plant growth, and changes in the ecological system over time) is difficult to quantify, 3) point measurements or estimates of recharge (i.e., from lysimeters or tracer studies) are difficult to project over large areas, 4) the precipitation data base is too short in duration to determine the likelihood of extreme events with confidence, and insufficient for extending to very long periods (say beyond 50 to 100 years), 5) reliable estimates of unsaturated hydraulic conductivity are difficult to obtain, and 6) the treatment of coupled liquid/vapor flow and transport is not well advanced in practice.

The panel suggested that for specific conditions of soil, topography, plant cover, and climate, recharge could probably be estimated using the existing (1985) database and available models, with an uncertainty factor of 2 or 3. They also suggested that tracer studies, additional measurements of soil hydraulic properties, and evapotranspiration measurements could improve these estimates.

The panel made several recommendations related to quantifying natural ground water recharge rates at Hanford. The panel suggested that if lysimeter studies were to be continued, they should include comparisons of vegetated-to-bare surfaces in each location, and be designed to not only measure evapotranspiration and drainage, but also to continuously monitor soil moisture distribution and suction. The panel also endorsed a plan to make direct measurements of evapotranspiration using micro-meteorological methods to provide data to be used in conjunction with models of soil-plant-water relations, and suggested that more definitive plant phenological information would be needed to determine the effects of bimodal plant activity in spring and autumn on evapotranspiration. In addition, the panel stated that "it is essential that the soil hydraulic properties (namely the moisture versus suction function and the moisture versus hydraulic conductivity function) be established, in so far as possible, directly in the field, rather than be inferred indirectly from laboratory tests with small and disturbed samples." The panel also recommended that new tracer studies be conducted by emplacing several tracers over areas of several square meters at hydrologically representative sites, and then excavating and analyzing the tracers' flow paths at a later time to study the downward migration of the tracers in complex (layered) soil profiles. The panel also suggested that some environmental isotopes (i.e., tritium) could be useful for estimating recharge.

The panel made several recommendations regarding the use of numerical models to estimate natural ground water recharge rates. They suggested that future simulations, particularly those involving different upper boundary conditions and processes (e.g., evaporation), should be based on the mechanistic formulation of nonisothermal processes, in both the liquid and vapor phases. Related to this, they again emphasized the importance of determining reliable field data for the soil hydraulic properties, and suggested that some effort should also be made to assess the practical importance of hysteresis. The panel stressed the importance of plants in controlling evapotranspiration, and the need for a strong plant activity component in future research on soil-water dynamics. Finally, the panel suggested that all models and submodels be tested by comparison with analytical solutions, alternative models, and independent laboratory and (especially) field data.

The panel noted that the recharge studies that had been conducted at Hanford yielded important, but somewhat inconclusive results. The panel suggested that rather than closing the recharge issue, research efforts should be strengthened and intensified. The panel also emphasized that continuity of research for long-term studies was of paramount importance.

5.2 Scope of Work for 1995

Since the 1985 workshop, work on the recharge issue at Hanford continued in a discontinuous fashion under various projects. A summary of this work is provided in Section 3.0 of this report. Because there have been only limited efforts to address recharge on a site-wide basis and the specific needs of LLW have not been previously addressed, additional work has been initiated. Starting in FY 1994, the PVTD project supported a task to study recharge as it relates to the shallow land burial of LLW. The scope of work for FY 1995 contains five subtasks: 1) recharge workshop, 2) lysimetry, 3) evapotranspiration, 4) tracers, and 5) integrated recharge assessment. Each of these subtasks is briefly described below.

5.2.1 Recharge Workshop

A workshop is scheduled for May 1995 to study recharge issues that will affect LLW disposal actions. A panel of qualified experts will review the available data, facility requirements, and proposed plans to address all aspects of recharge. The panel will provide evaluations and recommendations to ensure that the PVTD project gets the information necessary to complete a defensible performance assessment. Included in the review will be the plans for implementing comprehensive field tests to evaluate the effects of spatial variability and measurement uncertainties on estimated recharge rates. PNL will participate in the workshop and prepare a detailed field experiment test plan based on peer review comments.

5.2.2 Lysimetry

The objectives of this task are to measure recharge directly and provide sufficient data for testing recharge models. Weighing lysimeter data from the FLTF and several other sites will be compiled and analyzed to support the evapotranspiration and integrated recharge assessment subtasks described below. A formal test plan will also be prepared outlining options for retrofitting several of the lysimeters at the FLTF. The lysimeters will be designed to provide data that are relevant to the conceptual model in Figure 4.1, address issues identified in Section 4.4, and reflect potential land use (irrigated agriculture) and future climate change scenarios of interest for the performance assessment of the LLW disposal facility.

5.2.3 Evapotranspiration Studies

The objective of this task is to determine the most accurate method for predicting evapotranspiration (ET), which is the combination of evaporation and transpiration. Models such as UNSAT-H use values of potential evapotransipiration (PET) to predict ET. Estimates of PET rates under arid site conditions have been shown to be significantly greater than actual ET rates (Gee et al. 1989). Therefore, a need exists for quantifying ET rates for specific soil and vegetation types, and climatic conditions at the Hanford Site.

Selected subsets of data from the weighing lysimeters at the FLTF and other locations at the Hanford Site will be analyzed to quantify actual ET rates. Detailed numerical simulations of the soil-water dynamics in the weighing lysimeters will be conducted using the UNSAT-H computer model. Observed and simulated results will be compared and the most accurate mechanistic and empirical descriptions of ET will be determined and documented.

5.2.4 Tracers

The objective of this task is to estimate recharge rates using the measured depth distribution of radioactive and chemical tracers. Depending on the tracer used, the recharge estimates can represent average rates that span time periods from 35 to 13,000 years. In FY 1995, two locations within the boundaries of the proposed facility will be drilled to 15 m to obtain continuous cores. The cores will be analyzed mainly to determine the chloride distribution. Selected subsamples from the continuous cores will also be analyzed for other tracers to determine whether they would be feasible for estimating recharge. The results of these analyses will be used to prepare for a more complete sampling campaign in FY 1996.

5.2.5 Integrated Recharge Assessment

The objective of this task is to provide an integrated assessment and evaluation of the recharge estimates made using various techniques (i.e., lysimetry, tracers, numerical simulation, etc.). In FY 1995, recharge-related data collected at the Grass Site in the 300 Area will be evaluated. Recharge estimates from several methods will be used to determine if our current understanding of recharge is sufficient to explain any differences and whether additional processes need to be considered. Also in FY 1995, supplemental data will be collected in conjunction with the Tracer task to enable recharge estimation using other techniques. These estimates will then be compared with the tracer estimates to more fully understand recharge within the facility boundaries.

5.3 Plan for Task Completion

Several activities are planned for after FY 1995 to provide the data and tools that will be needed to adequately support the performance analyses for the LLW disposal facility at the Hanford Site. These activities are focused on lysimetry, tracers, and modeling. The plans briefly outlined below are tentative. The recharge workshop that is planned for FY 1995 will include a review of these planned activities. The review will consider whether the activities are technically sound, whether they address all major issues, and whether they will satisfy the needs of the Glass PA.

Several lysimeters at the FLTF may be retrofitted to reflect potential land-use change scenarios and/or climate change conditions of interest for the LLW performance assessment. In addition, other lysimeters may be monitored (e.g., BWTF) because they have a long history, which would improve accuracy and provide extended data sets for model testing. Tracer studies may be conducted in several lysimeters to look at the effects of plant root uptake on tracer movement.

Several boreholes will be drilled at or adjacent to the site of the LLW disposal facility. Tracer profiles determined from borehole samples will be used to estimate historical recharge rates in the natural ecosystem that will surround the facility. While not sufficient for a quantitative measure of variability, the number of samples should give some indication of the potential variability to be expected. Sediment samples from these boreholes will also be analyzed to determine soil hydraulic properties to support numerical simulation studies. Field measurements of soil hydraulic properties will also be conducted nearby using a modified instantaneous profile method. Besides estimating recharge rates, another goal is to determine whether the multiple techniques produce similar estimates. To date, we have seen significant differences between methods (tracer versus tracer; tracer versus lysimeter; tracer versus hydraulic gradient). These differences in estimates need to be resolved.

One hypothesis concerning recharge at Hanford is that topographic variations affect recharge by focusing overland flow, generally from rapid snowmelt above frozen soil, into small areas where it can infiltrate readily. The concern is that, because they represent only a small percentage of the area of the entire Site, these local infiltration areas may not be adequately represented in any sampling scheme. To test this hypothesis, an integrated recharge assessment will be used. Trenches will be excavated that are oriented to run from high to low elevations in an area of undulating terrain on the 200 Area Plateau. The expectation is that low elevations, which may be prone to infiltration from overland flow, will have chloride distributions indicative of higher recharge rates than profiles at the higher elevations. Detailed spatial characterization of plant types, surface coverage, rooting depths and distributions, chloride concentrations, bulk densities, particle-size distributions, and hydraulic properties will be conducted. These data will be used to estimate parameters for numerical modeling of water flow and solute transport. Predicted recharge rates will be compared with independent estimates obtained using tracer techniques and the unit gradient method. The information obtained from these studies will be used to test the topographic hypothesis for recharge. The information will also provide estimates of the uncertainties associated with spatial variability and the measurement errors for each recharge estimation method.

If fruitful, this integrated recharge assessment approach will be used on the actual site selected for placement of the LLW disposal facility. Before the site preparation begins, nondestructive geophysical methods such as electromagnetic induction and ground-penetrating radar will also be investigated for use in conducting initial site surveys for identifying potential areas of preferential local recharge. When site preparation begins, samples will be collected as the excavation proceeds, allowing for the generation of a 3-dimensional view of the chloride distribution and soil property variations. Such information will be very useful in verifying the assumption of one-dimensionality used by the tracer methods.

The numerical model of recharge is an important tool for the performance assessment. The model will continue to be tested with lysimeter data because those data are the most accurate and well documented. Processes that are identified as important to recharge estimation will be included in the model. These processes include thermal effects, snowmelt, hysteresis, and plant behavior (e.g., germination, growth, phenology, rooting depths, succession). Future land use and climate change scenarios will be incorporated into modeling activities as required.

Fayer and Walters (1995) present a framework for evaluating ground water recharge at the Hanford Site by combining information about land use, vegetation and soil types, data from lysimeter and tracer studies, and numerical simulation results using a geographic information system (GIS). The use of a GIS effectively integrates both hard and soft data to evaluate the effects of spatial variability. The integrated recharge assessment subtask will expand the work by Fayer and Walters (1995) to further address issues of spatial variability and measurement uncertainties.

6.0 Concluding Remarks

The recharge studies that have been conducted since the National Academy of Sciences report (Galley 1966) have expanded our understanding of the near-surface water balance and ground water recharge in both natural and disturbed settings. The studies at Hanford indicate that recharge rates are highly variable, ranging from nearly zero to greater than 100 mm/yr depending on precipitation, vegetative cover, and soil types. Coarse-textured soils without plants yielded the most recharge. Finer-textured soils, with or without plants, yielded the least.

Lysimeters provided accurate, short-term measurements of recharge as well as water-balance data for the soil-atmosphere interface and root zone. Tracers provided estimates of longer-term average recharge rates in undisturbed settings. Numerical models demonstrated the sensitivity of recharge rates to different processes and forecast recharge rates for different conditions. These tools (lysimetry, tracers, and numerical models) are all considered vital to the development of defensible estimates of natural ground water recharge rates for the performance assessment of a LLW disposal facility at Hanford. Continuing the measurement of key recharge parameters (soils, vegetation, and climate) at specific waste sites will assist in estimating potential recharge conditions. However, large uncertainties in the time dependence of both vegetation and climate will require careful analyses of the interaction of these two important variables. For example, rooting depths may change over a short period (tens of years) in response to climate and alter recharge rates by several orders of magnitude.

The effort to build a LLW disposal facility at Hanford is just in the planning stages and no decisions have been made regarding its exact location, layout, or design. In lieu of the actual design and location, a conceptual model of the LLW disposal facility was used to identify four general areas where recharge estimates were needed: the protective barrier, the barrier edge, the natural ecosystem surrounding the facility, and the entire Hanford Site. Potential scenarios that would impact the recharge estimates were identified. They included changes in climate, soil, vegetation, and land use for periods ranging from 100 to greater than 10,000 years.

For preliminary performance assessment calculations, we recommend assuming a recharge rate of 0.5 mm/yr through the Hanford protective barrier. This assumption is consistent with an 8-year record of lysimeter data and with engineering design specifications for the 1000-year design life of the barrier. At the barrier edge, a higher recharge rate of 75 mm/yr should be assumed. For the natural ecosystem surrounding the barrier edge, estimated recharge rates of 5.0 and 25.4 mm/yr should be assumed for sagebrush and cheatgrass communities, respectively. These values represent conservative estimates based on the lysimeter and tracer data reported in Tables 3.1 and 3.2. For the entire Hanford Site, we recommend using the recharge distribution map reported by Fayer and Walters (1995). These estimates reflect our current knowledge of the soils, vegetation, and climate conditions. The estimates will be updated as more information becomes available.

Past recharge studies at Hanford were used to prepare plans to address the project needs for recharge estimates. The plans include efforts to use the strengths of different methods (lysimetry, tracers, modeling) to provide the necessary data and to address several outstanding issues. These issues include questions about the accuracy of the methods, conflicting estimates for the same location, spatial and temporal variability, and processes such as preferential flow and vapor flow. The plans will be reviewed by a panel of experts in May 1995 so that the Recharge Task remains focused on producing the information necessary to the project.

7.0 References

Allison, G. B., G. W. Gee, and S. W. Tyler. 1994. "Vadoze-Zone Techniques for Estimating Groundwater Recharge in Arid and Semiarid Regions." *Soil Sci. Soc. Am. J.* 58:6-14.

Cline, J. F., K. A. Gano, and L. E. Rogers. 1980. "Loose Rock as Biobarriers in Shallow Land Burial." *Health Phys.* 39:497-504.

Downs, J. L., W. H. Rickard, C. A. Brandt, L. L. Cadwell, C. E. Cushing, D. R. Geist, R. M. Mazaika, D. A. Neitzel, L. E. Rogers, M. R. Sackschewsky, and J. J. Nugent. 1993. *Habitat Types on the Hanford Site: Wildlife and Plant Species of Concern.* PNL-8942, Pacific Northwest Laboratory, Richland, Washington.

Enfield, C. G., J. J. C. Hsieh, and A. W. Warrick. 1973. "Evaluation of Water Flux Above a Deep Water Table Using Thermocouple Psychrometers." *Soil Sci. Soc. Am. Proc.* 37:968-970.

Fayer, M. J., and G. W. Gee. 1992. "Predicted Drainage at a Semiarid Site: Sensitivity to Hydraulic Property Description and Vapor Flow." In M. Th. van Genuchten et al. (eds.) *Proceedings of the International Conference on Indirect Methods for Estimating the Hydraulic Properties of Unsaturated Soils*, October 11-13, 1989, University of California, Riverside.

Fayer, M. J., and T. L. Jones. 1990. *UNSAT-H Version 2.0: Unsaturated Soil Water and Heat Flow Model.* PNL-6779, Pacific Northwest Laboratory, Richland, Washington.

Fayer, M. J., and T. B. Walters. 1995. *Estimated Recharge Rates at the Hanford Site.* PNL-10285, Pacific Northwest Laboratory, Richland, Washington.

Fayer, M. J., M. L. Rockhold, and M. D. Campbell. 1992. "Hydrologic Modeling of Protective Barriers: Comparison of Field Data and Simulation Results." *Soil Sci. Soc. Amer. J.* 56:690-700.

Galley, J. E., C. W. Brown, G. B. Maxey, J. C. Maxwell, C. Meyer, R. C. Scott, C. V. Theis, and A. F. Van Everdingen. 1966. *Report of Committee on Geologic Aspects of Radioactive Waste Disposal.* National Academy of Sciences, National Research Council, Washington, D.C.

Gaylord, D. R., L. D. Stetler, G. D. Smith, and R. W. Mars. 1993. *Summary of 1990 Eolian Characterization Studies, Hanford Site, Washington.* PNL-8862, Pacific Northwest Laboratory, Richland, Washington.

Gee, G. W., and D. Hillel. 1988. "Groundwater Recharge in Arid Regions: Review and Critique of Estimation Methods." *Hydrol. Processes.* 2:255-266.

Gee, G. W., M. L. Rockhold, and J. L. Downs. 1989. *Status of FY 1988 Soil-Water Balance Studies on the Hanford Site.* PNL-6750, Pacific Northwest Laboratory, Richland, Washington.

Gee, G.W., M. J. Fayer, M. L. Rockhold, and M. D. Campbell. 1992. "Variations in Recharge at the Hanford Site." *Northwest Sci.* 66:237-250.

Gee, G. W., P. J. Wierenga, B. J. Andraski, M. H. Young, M. J. Fayer, and M. L. Rockhold. 1994. "Variations in Water Balance and Recharge Potential at Three Western Desert Sites." *Soil Sci. Soc. Am. J.* 58:63-72.

Hajek, B. F. 1966. *Soil Survey Hanford Project in Benton County, Washington.* BNWL-243, Pacific Northwest Laboratory, Richland, Washington.

Hanford Future Site Uses Working Group (HFSUWG). 1992. "The Future for Hanford: Uses and Cleanup." Eastern Washington University, Cheney, Washington.

Klepper, E. L., K. A. Gano, and L. L. Cadwell. 1985. *Rooting Depth and Distributions of Deep-Rooted Plants in the 200 Area Control Zone of the Hanford Site.* PNL-5247, Pacific Northwest Laboratory, Richland, Washington.

Leopold, A. 1949. "A Sand County Almanac." 269 pp. Oxford University Press, New York.

Lindsey, K. A., B. N. Bjornstad, and M. P. Connelly. 1991. *Geologic Setting of the 200 West Area: An Update.* WHC-SD-EN-TI-008, Rev. 0, Westinghouse Hanford Company, Richland, Washington.

Link, S. O., G. W. Gee, and J. L. Downs. 1990. "The Effect of Water Stress on Phenological and Ecophysiological Characteristics of Cheatgrass and Sandberg's Bluegrass." *J. Range Manage.* 43(6):506-513.

Mualem, Y. 1976. "A New Model for Predicting the Hydraulic Conductivity of Unsaturated Porous Media." *Water Resour. Res.* 12:513-522.

Murphy, E. M., J. E. Szecsody, and S. J. Phillips. 1991. *A Study Plan for Determining Recharge Rates at the Hanford Site Using Environmental Tracers.* PNL-7626, Pacific Northwest Laboratory, Richland, Washington.

National Research Council (NRC). 1957. *The Disposal of Radioactive Waste on Land.* Committee on Waste Disposal Division of Earth Sciences. Washington, D.C. National Academy of Sciences, Springfield, Virginia.

Petersen, K. L. 1993. "Appendix B, Meteorology and Projection of Potential Future Climate for the Grout Project," In *Performance Assessment of Grouted Double-Shell Tank Waste Disposal at Hanford*, PNL-8988, Vol. 2, Pacific Northwest Laboratory, Richland, Washington.

Philip, J. R., and D. A. De Vries. 1957. "Moisture Movement in Porous Materials under Temperature Gradients." *Trans. Am. Geophys. Union* 38:222-232.

Prych, E. A. 1995. *Using Chloride and Chlorine-36 as Soil-Water Tracers to Estimate Deep Percolation at Selected Locations on the U.S. Department of Energy Hanford Site, Washington. Open-File Report 94-514*, U.S. Geological Survey, Denver, Colorado.

Rickard, W. H. and B. E. Vaughan. 1988. "Plant Community Characteristics and Responses." In *Shrub-Steppe Balance and Change in a Semi-Arid Terrestrial ecosystem.* W. H. Richard et al., ed., Developments in Agricultural and Managed-Forest Ecology 20, Elsevier Science Publishers, New York.

Rockhold, M. L., M. J. Fayer, and G. W. Gee. 1988. *Characterization of Unsaturated Hydraulic Conductivity at the Hanford Site.* PNL-6488, Pacific Northwest Laboratory, Richland, Washington.

Schreckhise, R. G., and J. F. Cline. 1979. "Comparative Uptake and Distribution of Plutonium, Americium, Curium, and Neptunium in Four Plant Species." *In* W. C. Hanson (ed.), *Transuranic Elements in the Environment.* Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Selders, A. A. 1950. *The Adsorption and Translocation of Fission Elements by Russian Thistle.* HW–18034, General Electric Company, Richland, Washington.

Sonnichsen, J. C. 1986. *Summary Report: Hanford Groundwater Recharge Workshop (October 14, 15, 1985).* SD-WM-PRS-004, Rockwell Hanford Operations, Richland, Washington.

Stone, W. A., J. M. Thorpe, O. P. Gifford, and D. J. Hoitink. 1983. *Climatological Summary for the Hanford Area.* PNL-4622, Pacific Northwest Laboratory, Richland, Washington.

Tallman, A. M., K. R. Fecht, M. C. Marratt, and G. V. Last. 1979. *Geology of the Separation Areas, Hanford Site, South-Central Washington.* RHO-ST-23, Rockwell Hanford Operations, Richland, Washington.

U.S. Department of Agriculture (USDA). 1971. *Soil Survey, Benton County Area, Washington.* U.S. Government Printing Office, Washington, D.C.

U.S. Department of Energy (DOE). 1987. *Disposal of Hanford Defense High-Level, Transuranic and Tank Wastes.* DOE/EIS-0113, U.S. Department of Energy, Richland, Washington.

U.S. General Accounting Office (GAO). 1989. "DOE's Management of Single-Shell Tanks at Hanford, Washington." GAO/RCED-89-157. U.S. General Accounting Office, Washington, D.C.

van Genuchten, M. Th. 1980. "Predicting the Hydraulic Conductivity of Unsaturated Soils." *Soil Sci. Soc. Am. Proc. 44*:892-898.

Westinghouse Hanford Company (WHC). 1993. *Performance Assessment of Grouted Double-Shell Tank Waste Disposal at Hanford.* WHC-SD-WM-EE-004, Rev. 0, Westinghouse Hanford Company, Richland, Washington.

Wing, N. R. 1994. *Permanent Isolation Surface Barrier Development Plan.* WHC-EP-0673, Westinghouse Hanford Company, Richland, Washington.

Yates, S. R., M. Th. van Genuchten, A. W. Warrick, and F. J. Leij. 1992. "Analysis of Measured, Predicted, and Estimated Hydraulic Conductivity Using the RETC Computer Code." *Soil Sci. Soc. Am. J.* 56:347-354.

Appendix A

Recharge Estimation Methods

Appendix A

Recharge Estimation Methods

The various methods that are available for estimating natural ground water recharge are based on quantifying water flow and solute transport processes in the unsaturated zone. In this section, the fundamental principles and governing equations that are used to describe unsaturated flow and solute transport are briefly reviewed, followed by descriptions of methods that have been used for estimating natural ground water recharge rates at Hanford.

A.1 Fundamental Concepts and Governing Equations

Water flow and solute transport processes in the unsaturated zone are complex and multi-dimensional, and generally occur under nonisothermal conditions, with multiple fluid phases (i.e., liquid water and water vapor). For brevity, the following discussion will be limited to the description of isothermal, single-phase (liquid water) flow and solute transport, in one dimension (the vertical direction). Additional details are provided elsewhere in this report, where needed, to address non-isothermal conditions and multiphase flow effects.

Water moves from regions of higher to lower potential energy. This potential energy (H) can be expressed as

$$H = h_p + h_o + h_m + h_z \tag{A.1}$$

where h_p = gas pressure potential
h_o = osmotic potential
h_m = matric potential
h_z = gravitational potential.

Gas pressure potential represents the difference between the external gas pressure and atmospheric pressure. Osmotic potential (i.e., solute potential) represents the potential energy lowering caused by the presence of solutes. Matric potential consists of hydrostatic pressure and the capillary and adsorptive forces that attract and bind water to the soil matrix. Gravitational potential is the energy associated with the location of water in the Earth's gravitational field, measured with respect to some reference point such as the ground surface or the water table.

Gas pressure and osmotic potentials are generally considered to be negligible, so that the total potential is simply taken to be the sum of the matric potential and the gravitational potential. This sum, when expressed on an equivalent height-of-water basis, is commonly referred to as the hydraulic head, or H. The matric potential is also referred to as the soil water pressure head, which is negative for unsaturated conditions. Corey and Klute (1985) provide a detailed discussion on the application of the potential energy concept to soil water equilibrium and flow.

The flux (q) of water through soil is proportional to the hydraulic head gradient (dH/dz) where z is depth, measured positive downward from the soil surface. For saturated systems, the flux can be determined with the Darcy flow equation

$$q = -K_s \frac{dH}{dz} \tag{A.2}$$

where K_s is the saturated hydraulic conductivity. For unsaturated soils, the hydraulic conductivity is nonlinearly related to the pressure head or water content. Therefore, Equation A.2 is usually modified as

$$q = -K(\theta)\frac{dH}{dz} \tag{A.3}$$

where K is the flux of water per unit gradient of hydraulic head and θ is the volumetric water content, or volume of water per unit bulk volume of soil.

To describe transient water flow in the vertical direction, Equation A.3 is combined with the equation of continuity,

$$\frac{\partial\theta}{\partial t} = -\frac{\partial q}{\partial z} + u \tag{A.4}$$

where t is time, z is depth and u is a source or sink term used to account for water uptake by plant roots to give

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}\left[K(\theta)\frac{\partial H}{\partial z}\right] + u \tag{A.5}$$

Equation A.5 is known as the Richards equation (Richards 1931) and forms the basis for most process-based descriptions of water movement in the unsaturated zone. Equation A.5 can also be expressed as

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}\left[K(h_m)\frac{\partial h_m}{\partial z} - K(h_m)\right] + u \tag{A.6}$$

The advective-dispersive solute transport equation can be written as

$$\frac{\partial(\rho s)}{\partial t} + \frac{\partial(\theta c)}{\partial t} = \frac{\partial}{\partial z}\left(\theta D\frac{\partial c}{\partial z} - qc\right) + \phi \tag{A.7}$$

where s = solute concentration associated with the solid phase of the soil
ρ = soil bulk density
c = solute concentration of the fluid phase
D = solute hydrodynamic dispersion coefficient
ϕ = source or sink for solute.

If the source or sink terms in Equations A.6 and A.7 are neglected, and the adsorbed concentration is related to the solution concentration through the linear equilibrium sorption isotherm, (i.e., $s = k_d c$), Equation A.7 reduces to the standard advection-dispersion equation

$$R \frac{\partial c}{\partial t} = D \frac{\partial^2 c}{\partial z^2} - v \frac{\partial c}{\partial z} \tag{A.8}$$

where $v = q/\theta$ is the average pore water velocity, and $R = 1 + pk_d/\theta$ is the solute retardation factor. The hydrodynamic dispersion coefficient can be defined as

$$D = \tau D_m + \alpha |v| \tag{A.9}$$

where τ is a tortuosity factor, D_m (L^2/T) is the coefficient of molecular diffusion in the pore fluid, and α (L) is the dispersivity. The tortuosity factor can be written as a function of θ using a relationship such as that of Millington and Quirk (1961),

$$\tau = \theta^{10/3} / \theta_s^2 \tag{A.10}$$

where θ_s is the saturated water content.

Equations A.3, A.6, A.7, and A.8, or variants of these equations, form the mathematical basis for most of methods used to estimate natural ground water recharge. Some of these methods are described below.

A.2 Soil Water Balance

Estimating natural ground water recharge using the soil water balance method requires quantification of the terms in the following water balance equation:

$$\Delta S = P + I - ET - D \pm R \tag{A.11}$$

where ΔS = change in soil water storage (L/T)
P = natural precipitation (L/T)
I = irrigation (L/T)
ET = evapotranspiration (L/T)
D = drainage below root zone (i.e., recharge or net residual flux) (L/T)
R = net overland flow (i.e., runoff or runon) (L/T).

The water-balance components in Equation A.11 are depicted in Figure A.1. The units of measurement for these components are generally expressed as the volume of water per unit area per unit time. Therefore, units of equivalent water depth (cm or mm) per unit time are used throughout this report. The methods used to measure or calculate each of these water-balance components are described in the following sections.

A.2.1 Soil Water Storage

Soil water storage is the total quantity of water in the soil zone of interest. Soil water storage is calculated by integrating water content measurements made at different depths within the soil profile. Changes in calculated storage over a selected time interval represent the ΔS term in Equation A.11.

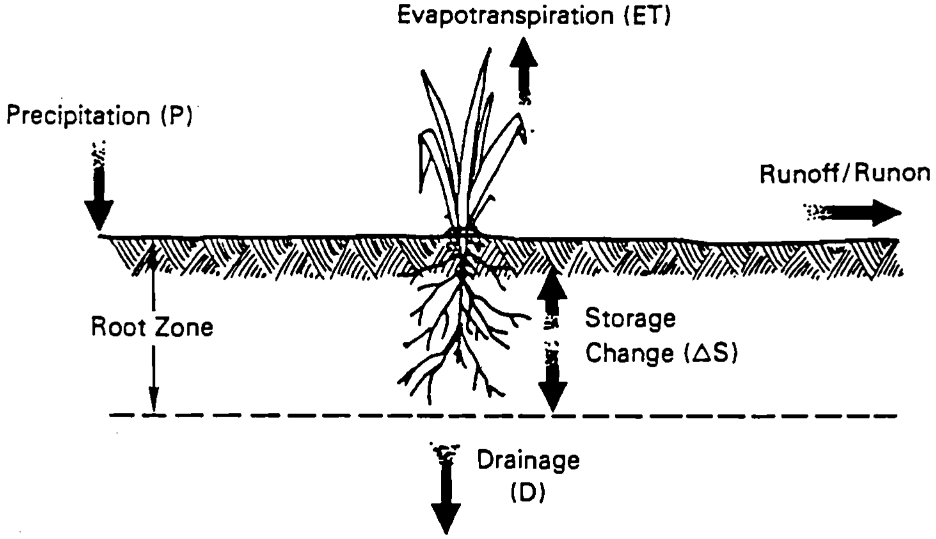


Figure A.1. Water-Balance Components

Water contents in surface soils are determined at most of the field sites at Hanford using the neutron probe or gravimetric sampling techniques. Neutron probes are calibrated by linear regression of measured volumetric water contents and corresponding neutron probe counts or count ratios. The technical procedure used for monitoring water contents using the neutron probe is described by Gee et al. (1989). Gravimetric water contents are converted to volumetric water contents by multiplying by the soil bulk density.

In an analysis of neutron probe data collected from lysimeters at the Hanford Site, Jones (1978) reported that the accuracy of measurements of volumetric water content made using the neutron probe cannot be expected to be better than about $\pm 0.005 \text{ cm}^3/\text{cm}^3$. Reginato and Nakayama (1988) report average errors in volumetric water contents determined using neutron probes in agricultural soils of up to $\pm 0.01 \text{ cm}^3/\text{cm}^3$. A detailed description of the estimation of errors in volumetric water content measurements made using the neutron probe and the uncertainties in the associated calibration curve is given by Haverkamp et al. (1977).

A.2.2 Precipitation

Precipitation and other weather data are recorded at the HMS, located between the 200-East and 200-West Areas (see Figure 1.1). The HMS was constructed as part of the Manhattan Project in 1944. Hourly observations began on December 7, 1944 (Stone et al. 1983). However, complete records were not compiled for several years and only since January 1947 have hourly records been available on a continuous basis (Hoitink and Burk 1994). These data are available on magnetic tape at least as far back as 1957.

The HMS collects hourly data on precipitation (i.e., rain and snow), air and soil temperatures, wind speed and direction, solar radiation, relative humidity, atmospheric pressure, cloud cover, etc. (Stone et al. 1983; Hoitink and Burk 1994). Precipitation is also recorded at several other water balance study locations and lysimeter facilities using tipping bucket and standard collection rain gauges. Tipping bucket rain gauges typically measure precipitation to within 0.3 mm. Precipitation can also be calculated from weighing lysimeters from the weight changes, as described later in Section A.3.

A.2.3 Irrigation

Irrigation is a significant part of several experimental studies at Hanford (Freeman and Gee 1989; Waugh et al. 1990; Sackshewsky et al. 1991; Gee et al. 1993). The study described by Gee et al. (1993) uses irrigation to create artificial rainfall conditions on lysimeters to test the performance of capillary barriers under total precipitation rates ranging from 32 to 48 cm/yr (2 to 3 times the long-term average). These irrigation treatments represent potential climate/land use change scenarios.

A.2.4 Evapotranspiration

Evapotranspiration (ET) represents the combined processes of plant transpiration and evaporation. ET can be determined from lysimeter weight changes or from the solution of Equation A.11 after the other water balance components have been determined. Bowen ratio and eddy correlation techniques have also been used to estimate evapotranspiration rates at Hanford (Kirkham 1993), and whole plant gas exchange systems have recently been developed for measuring ET rates on vegetated lysimeters (Link et al. 1992a,b).

ET can also be estimated as some fraction of PET, which is a measure of the maximum amount of water that can be absorbed into the atmosphere given the atmospheric vapor density and radiant energy condition (Jones et al. 1984). PET at the Hanford Site is generally calculated from solar radiation, wind speed, and other climate data using the Penman equation in Doorenbos and Pruitt (1977). PET can be used to empirically estimate actual evaporation and transpiration without describing any controlling physical processes such as diffusion and convection. In the absence of plants, only evaporation is considered for the ET component in Equation A.11.

A.2.5 Drainage

Drainage below the root zone is also referred to as recharge, net percolation, or net residual flux (Phillips 1994). This component of the water balance is usually calculated using Equation A.11 (and measurements or estimates of the other terms) unless it can be measured directly using lysimeters. This water balance component can be negative, indicating upward flow, and can be induced by thermal gradients and capillary imbibition. Upward flow may occur, for example, when a water table is located near the soil surface. This particular example is generally not applicable for most of the Hanford Site because the water table is sufficiently deep [10 to 100 m or more below the ground surface (Gee 1987)] to be well below the plant root zone.

A.2.6 Net Overland Flow

Runoff or runon is generally considered to be negligible for most of the Hanford Site because the surface soils are typically coarse-textured and the Site is relatively flat. However, this water balance component may be significant when the soil is frozen and when rapid snowmelt occurs, especially on terrain with a significant slope.

A.3 Lysimetry

The water balance method is classified as an indirect physical method because drainage or recharge is not directly measured. The only method available for directly measuring drainage or recharge is lysimetry. One of the strengths of lysimetry is that it provides a control volume in which a number of water balance components can be measured directly, thus providing the necessary data to calibrate numerical models that can then be used to forecast recharge.

The Hanford Site has one of the most extensive networks of lysimeters in the world. Descriptions of various lysimeters in use at Hanford are provided by Kirkham et al. (1991), Gee and Jones (1985), Gee et al. (1989), and Freeman and Gee (1989). Two principal types of lysimeters are used at Hanford: drainage lysimeters and weighing lysimeters. The drainage lysimeters consist of cylindrical, soil-filled containers instrumented with neutron probe access tubes or sampling ports that allow for the measurement of water contents at different depths. Some of these lysimeters have closed bottoms to prevent water from draining out of the lysimeters. These closed-bottom lysimeters are more accurately referred to as "collection" lysimeters. Others have suction candles and drainage systems that allow water draining out of the bottom of the lysimeter to be measured directly.

Most of the lysimeters drain via gravity flow. Drainage water is collected periodically and weighed to document drainage rates (Gee et al. 1993). The bottom of some of the lysimeters contain suction candles. Water removal (drainage) can be initiated by applying a vacuum (up to 100 cm of water) to the suction candles. A schematic of a suction-candle vacuum system is shown by Gee et al. (1989).

The weighing lysimeters consist of soil-filled containers, 1.5 m on a side, and approximately 1.5 m deep, resting on platform scales that have a 9,090-kg capacity. The scales are connected to dataloggers that record voltage changes corresponding to lysimeter weight changes. Design specifications for the weighing lysimeters are given by Kirkham et al. (1991).

Lysimeter weight changes are calculated using a linear regression of weight-voltage data for the calibration range of each scale. Periodic calibration of the scales is required to ensure that deviations from any measured weight do not exceed the manufacturer's published tolerance of ± 0.02% of the loaded value (Weigh-Tronix, Inc., Fairmont, Minnesota). Lysimeter weight changes result from water-storage changes, which are caused by precipitation, irrigation, evapotranspiration, and drainage. Weight changes, expressed in terms of equivalent units of water depth, are determined by dividing the lysimeter weight changes by the area of the lysimeter. According to Campbell et al. (1990), the lysimeter scales have a resolution of ± 50 g (0.02 mm).

Although they provide the only direct means of measuring recharge, lysimeters have several disadvantages, compared to some other indirect methods. Lysimeters are usually fixed in space and are, therefore, limited in their ability to quantify the effects of spatial variability. The soils filling many (but not all) of the lysimeters at Hanford represent composite samples of the surrounding sediments. Therefore, the natural stratification or layering is usually not preserved. The length of data record that is available from lysimeters is also relatively short, so that meaningful long-term averages are difficult to obtain from lysimeter records.

A.4 Zero-Flux Plane

The zero-flux plane method for estimating recharge relies on determining the location of a plane of zero hydraulic gradient in the soil profile (Wellings 1984). The location of this plane can be directly determined using sensors to measure soil suction or capillary pressure (e.g., tensiometers, heat dissipation sensors, thermocouple psychrometers). Recharge for a given duration is calculated by integrating water-content measurements below the zero-flux plane to determine the change in total water stored in the profile. A decrease in total storage below this plane over the time period is assumed to be recharge. Unfortunately, this zero-flux plane is not always stationary, and the method cannot be used during periods of high infiltration if the hydraulic gradient becomes positive downward throughout the profile.

A.5 Unit Hydraulic Gradient

While studying drainage losses from lysimeters, Black et al. (1969) noted that a "unit gradient" condition often occurred. This condition arises for fairly uniform (homogeneous) soils when the water content is nearly constant with depth, and results in $dH/dz \approx 1$. For unit gradient conditions, Equation A.3 reduces to $q = -K(\theta)$ and the flux of water moving through the soil is equal to the unsaturated hydraulic conductivity of the soil. Unit gradient conditions have been observed in some lysimeters and at some water balance study locations on the Hanford Site (Rockhold et al. 1988; Gee et al. 1989). For unit gradient conditions, recharge rates can be estimated from the measured (or estimated) unsaturated hydraulic conductivities and the volumetric water content of the soil below the plant root zone (Nimmo et al. 1994).

Both direct and indirect methods are available for measuring or estimating unsaturated hydraulic conductivities (Klute and Dirksen 1986; van Genuchten et al. 1992). However, no single method appears to be suitable for providing reliable estimates of unsaturated hydraulic conductivity over a wide range of conditions for all Hanford soils. Independent measurements and estimates of unsaturated hydraulic conductivities for Hanford soils have been reported by Rockhold et al. (1988); Gee et al. (1991); Connelly et al. (1992a, b); Rockhold et al. (1993); and Wright et al. (1994).

A.6 Tracers

Various chemical and radioactive tracers can be used to estimate natural ground water recharge rates in arid and semiarid environments. As noted by Phillips (1994), these tracers should possess several characteristics. Most importantly, the tracer must be conservative, meaning that it is not adsorbed onto the solid phase and not produced in the soil or taken up by plants through the roots. The rate at which the tracer is introduced into the soil must also be known. Murphy et al. (1991) evaluated the feasibility of using various environmental tracers to estimate recharge rates at Hanford. These tracers included chloride, chlorine-36, and tritium, which are discussed below.

A.6.1 Tritium (^3H)

Large quantities of ^3H were released into the environment by atmospheric nuclear weapons testing, mostly during the early 1960s (Phillips 1994). Some ^3H was also generated from sea-level nuclear weapons testing in the 1950s. This entered the hydrologic cycle as tritiated water vapor, which behaves similarly to water vapor. Therefore, ^3H is an excellent tracer for water movement in both liquid and vapor phases (Phillips 1994). The use of bomb ^3H as an environmental tracer is limited because it has a half-life of approximately 12.45 years (Phillips 1994). Furthermore, there is some question at Hanford (where copious quantities of tritium have been produced) as to the relative contribution of bomb pulse tritium versus Hanford derived tritium in the soil profile.

Allison (1981) described two simple methods for estimating mean annual recharge using bomb-^3H profiles. In the first method, assuming steady-state (with constant water content) and piston flow (no dispersion), and that ^3H moves with the mass fluid flow, recharge is estimated by dividing the total amount of water stored in the profile above the ^3H peak by the time elapsed since the fallout peak. In the second method, local annual recharge or net residual flux (J_r) is estimated by evaluating the ^3H mass balance as

$$J_r = T/T_A \qquad \text{(A.12)}$$

where T is the total quantity of ^3H stored in the soil profile per unit area. T is calculated as

$$T = \int_0^{\ell} T_z \theta_z \, dz \qquad \text{(A.13)}$$

where ℓ = the depth below which the ^3H concentration is negligible
T_z = ^3H concentration at depth z
θ_z = volumetric water content at depth z.

The term T_A is given by

$$T_A = \sum_{i=1}^{n} W_i T_{pi} \exp(-i\lambda) \tag{A.14}$$

where W_i = weighting factor that accounts for year-to-year variations in recharge
T_{pi} = average ^3H concentration in precipitation for year i before sampling
λ = decay constant for ^3H
n = number of years considered prior to sampling.

Allison and Hughes (1978) tested different schemes for estimating the weighting factors (W_i) but determined that using a constant value of 1 was adequate. An application of this method for estimating natural ground water recharge in a semiarid region of New Mexico is described by Mattick et al. (1987). Both of the methods described above require the 1962 to 1965 bomb-^3H peak to be clearly identified in the soil profile.

A.6.2 Chlorine-36 (^{36}Cl)

^{36}Cl is produced naturally in the atmosphere but was also produced indirectly, as a byproduct of nuclear weapons testing, by thermal neutron irradiation of chloride in sea water (Phillips 1994). This bomb ^{36}Cl was released in measurable amounts only during the sea-level tests in the 1950s, rather than during the stratospheric tests of the 1960s (Bentley et al. 1982; Elmore et al. 1982). Therefore, the maximum fallout of ^{36}Cl preceded the maximum ^3H fallout by about 10 years (Phillips 1994). The average estimated ^3H and ^{36}Cl fallout resulting from nuclear weapons testing for the northern hemisphere is shown in Figure A.2.

The ^{36}Cl fallout entered the hydrologic cycle as chloride anion, dissolved in precipitation and as dry fallout (Phillips 1994). The natural $^{36}Cl/Cl$ ratio in precipitation and dry fallout for eastern Washington has been estimated to be 150 x 10^{-15} to 200 x 10^{-15} (Bentley et al. 1986). ^{36}Cl is conservative, chemically stable, and nonvolatile. Therefore, unlike ^3H, it is a tracer for the transport of solutes only in the liquid phase. The half-life of ^{36}Cl is approximately 301,000 years (Phillips 1994).

The methods used to estimate natural ground water recharge from $^{36}Cl/Cl$ ratios are essentially the same as those described previously for ^3H. Since ^3H moves in both the liquid and vapor phases, it can move faster than ^{36}Cl. This suggests that estimating recharge from the bomb ^{36}Cl pulse could underestimate actual recharge rates but might be better for predicting the movement of other nonvolatile solutes. There is also some uncertainty about the local influence Hanford Site operations may have had on the time-dependent concentrations of both ^{36}Cl and ^3H in precipitation falling on the Site. A summary of Site operations that may have affected the concentrations of these tracers is given by Murphy et al. (1991).

A.6.3 Chloride

Meteoric chloride (Cl^-) originates primarily from sea salts and is continuously deposited on the land surface by precipitation and as dry fallout. This Cl^- moves into the soil profile with infiltrating precipitation. Cl^- is conservative and nonvolatile, and is almost completely retained in the soil when water evaporates or is transpired by plants (Phillips 1994). Therefore Cl^-, like many other tracers, may concentrate in the root zone as a result of evapotranspiration. The Cl^- mass balance method has become a relatively popular method for estimating recharge rates. A brief description of this method is given in the following paragraphs.

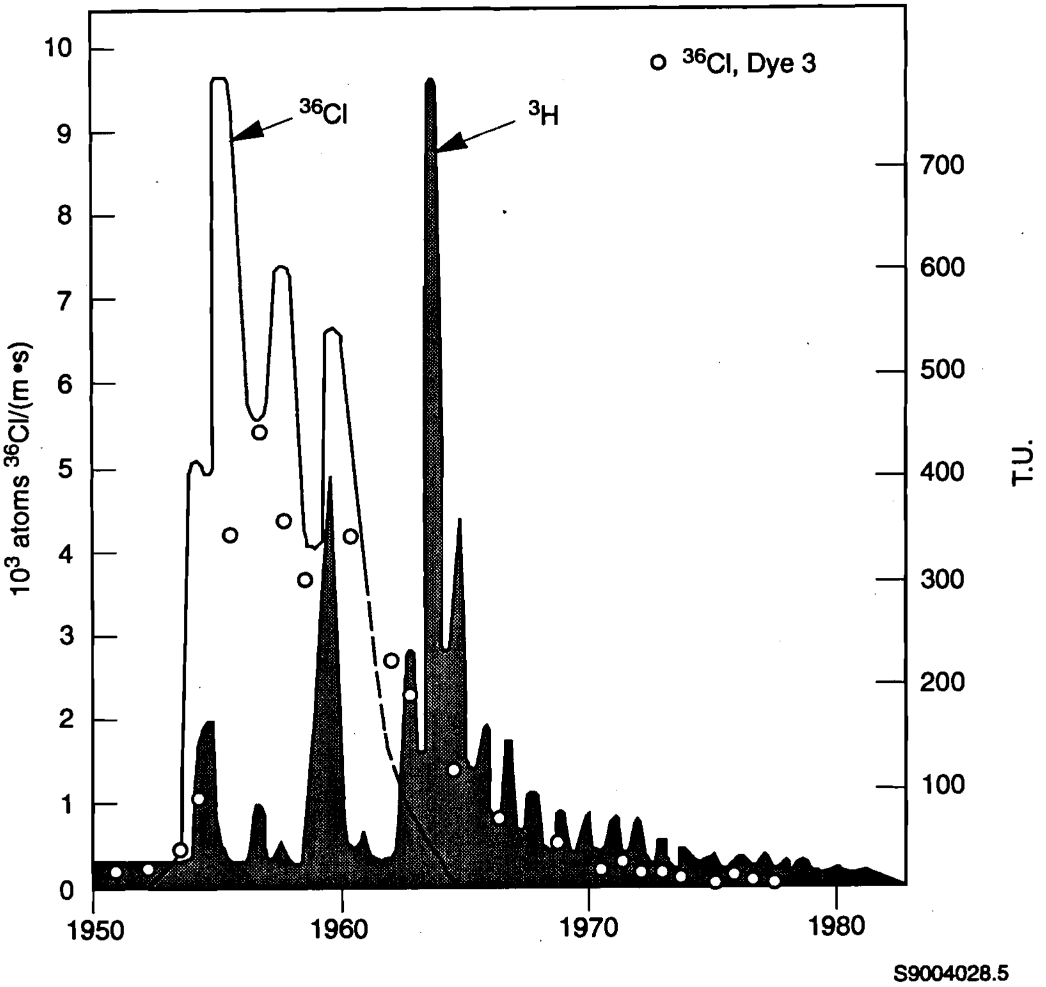


Figure A.2. Average Northern Hemisphere ^{3}H and ^{36}Cl Fallout Corrected to 1985 (Phillips et al. 1988)

Assuming one-dimensional piston flow (no dispersion), recharge or net residual water flux can be calculated from Cl^- measured in a soil profile as

$$J_r = D_{cl}/C_{cl} \tag{A.15}$$

where J_r is the net downward residual water flux at the depth of measurement (L/T), D_{cl} is the Cl deposition rate (M/L^2 T), and C_{cl} is the measured Cl concentration in the soil water (M/L^3). The value of C_{cl} can be determined by plotting cumulative Cl content with depth against cumulative water content at the same depths. The slopes of straight line segments correspond to C_{cl} for the depth interval (Phillips 1994). Changes in the slopes of different line segments, corresponding to the different depth intervals, can represent temporal variability of recharge rates.

In soils with high pH and high adsorption of other anions, anion exclusion can result in faster movement of Cl^- than ^{3}H. Previous studies have shown a direct correlation between clay content and anion exclusion (Warrick et al. 1971). Most of the sandy soils on the Hanford Site have relatively low percentages of clay, so the effects of anion exclusion in these soils should be relatively minor. James and Rubin (1986) reported an increase in the velocities of Cl^- over pore water velocities of about 10% in columns containing sandy soils. This increase in velocities was directly attributed to anion exclusion.

Phillips (1994) suggests that systematic uncertainties in estimated Cl^- deposition rates (D_{cl}) can be as great as 20% if the Cl^- mass balance technique is extended to estimate recharge rates prior to the Holocene epoch (approximately 10,000 years before present). Errors in estimated deposition rates linearly propagate into the recharge estimates made using the Cl^- mass balance method. However, it is generally assumed that there is no Cl^- mass balance signature in Hanford sediments that can be interpreted beyond 13,000 - 14,000 years ago because the Hanford Site was covered by glacial water during cataclysmic flooding at that time. Therefore, the uncertainty in Cl^- deposition rates at the Hanford Site should be less than 20%.

The major uncertainty in the use of chloride is the application of this tracer technique at disturbed sites, where recharge rates may have changed drastically. Under these conditions, chloride and other tracers' estimates of recharge should be used with extreme caution.

Murphy et al. (1991) evaluated the feasibility of using several other radioactive tracers to estimate recharge at Hanford. Significant quantities of some radioactive tracers such as iodine-129 were generated during site operations. Some of these tracers may also be useful for estimating recharge during the past 40 to 50 years on the 200 Area Plateau.

A.7 Numerical Simulation

If sufficient data are available,.Equations A.6 and A.7, or variants of these equations, can be used to simulate soil-water dynamics and solute transport in response to observed or estimated weather data and tracer deposition rates. Scanlon (1992) recently used simulations of this type to estimate recharge rates in the Chihuahuan Desert of Texas. This is the most data-intensive method for estimating natural ground water recharge rates and probably yields recharge estimates that have the most uncertainty. Nevertheless, numerical simulation has several unique advantages over the other methods.

Numerical simulation is useful for investigating "what if" questions. For example, how do predicted recharge rates change if precipitation doubles or triples as a result of climate change? Also, how do predicted recharge rates change if the dominant vegetation changes from deep-rooted sagebrush to shallow-rooted grasses as a result of range fires? These types of questions either cannot be answered or require an impractical amount of data to answer using lysimetry or tracer techniques. Numerical simulation can also be used to evaluate the sensitivity of recharge estimates to different parameters. Such a sensitivity analysis can help focus future data collection activities on the areas or parameters that have the greatest influence on the system.

Although numerical simulation is the only practical tool that can be used to forecast recharge rates for future climate and land use scenarios, it relies on the use of numerous parameters estimated from data to represent climate, soils, and vegetation characteristics. Lysimeter data are useful for testing numerical simulation models, and for refining the mechanistic descriptions of various processes in these models.

As noted in Section 5.0 of this report, the 1985 recharge workshop peer-review panel made several recommendations regarding improvements that could be made in modeling capabilities for simulating soil-plant-atmosphere systems and estimating recharge at Hanford. These included the incorporation of a mechanistic formulation of nonisothermal processes, and a capability for assessing the importance of hysteresis. UNSAT-H is the primary computer code used to estimate natural ground water recharge rates at Hanford. The capability for modeling nonisothermal water flow processes in the liquid and vapor phases and hysteresis in the soil hydraulic properties has been recently added to UNSAT-H (Fayer and Jones 1990). This code has been extensively tested using data from several of the lysimeter experiments at Hanford and other sites since the 1985 recharge workshop (Fayer and Gee 1992; Fayer et al. 1992; Fayer 1993; Martian and Magnuson 1994).

A.8 References

Allison, G. B. 1981. "The Use of Natural Isotopes for Measurement of Groundwater Recharge - A Review." In *Proc. AWRC Groundwater Recharge Conference. Townsville, July 1980.* AWRC Conf. Series No. 3.

Allison, G. B., and M. W. Hughes. 1978. "The Use of Environmental Chloride and Tritium to Estimate Total Recharge to an Unconfined Aquifer." *Aust. J. Soil Res.* 16:181-195.

Bentley, H. W., F. M. Phillips, S. N. Davis, S. Gifford, D. Elmore, L. Tubbs, and H. E. Gove. 1982. "The Thermonuclear 36C1 Pulse in Natural Water." *Nature.* London. 300:100:737-740.

Bentley, H. W., F. M. Phillips, and S. N. Davis. 1986. "Chlorine-36 in the Terrestrial Environment." pp. 427-480. In *Handbook of Environmental Isotope Geochemistry, Vol. 2B,* P. Fritz and J. Ch. Fontes (eds). The Terrestrial Environment, Elsevier, Amsterdam.

Black, T. A., W. R. Gardner, G. W. Thurtell. 1969. "The Prediction of Evaporation, Drainage, and Soil Water Storage for a Bare Soil." *Soil Sci. Soc. Am Proc.* 33:655-660.

Campbell, M. D., G. W. Gee, M. J. Kanyid, and M. L. Rockhold. 1990. *Field Lysimeter Test Facility: Second Year (FY 1989) Test Results.* PNL-7209, Pacific Northwest Laboratory, Richland, Washington.

Connelly, M. P., B. H. Ford, and J. V. Borghese. 1992a. *Hydrogeologic Model for the 200 West Groundwater Aggregate Area.* WHC-SD-EN-TI-014, Westinghouse Hanford Company, Richland, Washington.

Connelly, M. P., B. H. Ford, J. V. Borghese, S. Trent, and J. Lindberg. 1992b. *Hydrogeologic Model for the 200 East Groundwater Aggregate Area.* WHC-SD-EN-TI-019, Westinghouse Hanford Company, Richland, Washington.

Corey, A. T., and A. Klute. 1985. "Application of the Potential Energy Concept to Soil Water Equilibrium and Transport." *Soil Sci. Soc. Am. J.* 49:3-11.

Doorenbos, J., and W. O. Pruitt. 1977. *Guidelines for Predicting Crop Water Requirements.* FAO Irrigation Paper No. 24, Food and Agriculture Organization of the United Nations, Rome, Italy pp. 1-107.

Elmore, D., L. E. Tubbs, D. Newman, X. Z. Ma, R. Finkel, K. Nishiizumi, J. Beer, H. Oeschger, and M. Andree. 1982. "Bomb Pulse Measured in Shallow Ice Core from Dye-3, Greenland." *Nature,* London 300:735-737.

Fayer, M. J. 1993. *Model Assessment of Protective Barriers: Part IV, Status of FY 1992 Work.* PNL-8498, Pacific Northwest Laboratory, Richland, Washington.

Fayer, M. J., and G. W. Gee. 1992. "Predicted Drainage at a Semiarid Site: Sensitivity to Hydraulic Property Description and Vapor Flow." In M. Th. van Genuchten et al. (eds.) *Proceedings of the International Conference on Indirect Methods for Estimating the Hydraulic Properties of Unsaturated Soils,* October 11-13, 1989, University of California, Riverside.

Fayer, M. J., and T. L. Jones. 1990. *UNSAT-H Version 2.0: Unsaturated Soil Water and Heat Flow Model.* PNL-6779, Pacific Northwest Laboratory, Richland, Washington.

Fayer, M. J., M. L. Rockhold, and M. D. Campbell. 1992. "Hydrologic Modeling of Protective Barriers: Comparison of Field Data and Simulation Results." *Soil Sci. Soc. Amer. J.* 56:690-700.

Freeman, H. D., and G. W. Gee. 1989. *Hanford Protective Barriers Program Asphalt Barrier Studies - FY 1988.* PNL-6874, Pacific Northwest Laboratory, Richland, Washington.

Gee, G. W. 1987. *Recharge at the Hanford Site: Status Report.* PNL-6403, Pacific Northwest Laboratory, Richland, Washington.

Gee, G. W., and T. L. Jones. 1985. *Lysimeters at the Hanford Site: Present Use and Future Needs.* PNL-5578, Pacific Northwest Laboratory, Richland, Washington.

Gee, G. W., R. R. Kirkham, J. L. Downs, and M. D. Campbell. 1989a. *Field Lysimeter Test Facility (FLTF) at the Hanford Site: Installation and Initial Tests.* PNL-6810, Pacific Northwest Laboratory, Richland, Washington.

Gee, G. W., M. L. Rockhold, and J. L. Downs. 1989b. *Status of FY 1988 Soil-Water Balance Studies on the Hanford Site.* PNL-6750, Pacific Northwest Laboratory, Richland, Washington.

Gee, G. W., M. D. Campbell, and S. O. Link. 1991. "Arid Site Water Balance Using Monolith Lysimeters." In *Proceedings from the ASCE Irrigation Division Conference on Lysimeters for Evapotranspiration and Environmental Measurements (July 23-25, 1991),* Honolulu, Hawaii, pp. 219-227.

Gee, G. W., J. L. Downs, D. G. Felmy, M. J. Fayer, J. C. Ritter, R. R. Kirkham, M. D. Campbell, S. O. Link. 1993. *Field Lysimeter Test Facility Status Report IV: FY 1993.* PNL-8911, Pacific Northwest Laboratory, Richland, Washington.

Haverkamp, R., M. Vauclin, J. Touma, P. J. Wierenga, and G. Vachaud. 1977. "A Comparison of Numerical Simulation Models for One-Dimensional Infiltration." *Soil Sci. Soc. Am. J.* 41:285-294.

Hoitink, D. J., and K. W. Burk. 1994. *Climatological Data Summary 1993 with Historical Data.* PNL-9809, Pacific Northwest Laboratory, Richland, Washington.

James, R. V., and J. Rubin. 1986. "Transport of Chloride Ion in a Water-Unsaturated Soil Exhibiting Anion Exclusion." *Soil Sci. Soc. Am. J.* 50:1142-1149.

Jones, T. L. 1978. *Sediment Moisture Relations: Lysimeter Project 1976-1977 Water Year.* RHO-ST-15, Rockwell Hanford Operations, Richland, Washington.

Jones, T. L., G. S. Campbell, and G. W. Gee. 1984. *Water Balance at an Arid Site: A Model Validation Study of Bare Soil Evaporation.* PNL-4896, Pacific Northwest Laboratory, Richland, Washington.

Kirkham, R. R., M. L. Rockhold, G. W. Gee, M. J. Fayer, M. D. Campbell, and L. J. Fritschen. 1991. "Lysimeters: Data Acquisition and Analysis." In *Proceedings of the Conference on Lysimeters for Evapotranspiration and Environmental Measurements, Honolulu, Hawaii, July 23-25, 1991,* Irrigation Division, American Society Civil Engineers, pp 362-370.

Kirkham, R. R. 1993. *Comparison of Surface Energy Fluxes with Satellite-Derived Surface Energy Flux Estimates from a Shrub-Steppe.* PNL-9003, Pacific Northwest Laboratory, Richland, Washington.

Klute, A., and C. Dirksen. 1986. "Hydraulic Conductivity and Diffusivity: Laboratory Methods." pp. 687-734. In *Methods of Soil Analysis.* A. Klute (ed.) Part 1. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WIsconsin.

Link, S. O., J. L. Downs, M. E. Thiede, D. J. Lettau, T. R. Twaddell, and R. A. Black. 1992a. *Evaporation Studies for Protective Barriers: FY 1990 Status Report.* PNL-8032, Pacific Northwest Laboratory, Richland, Washington.

Link, S. O., M. E., Thiede, J. L. Downs, D. J. Lettau, and W. J. Waugh. 1992b. *Evaporation Studies for Protective Barriers: FY 1989 Status Report.* PNL-8033, Pacific Northwest Laboratory, Richland, Washington.

Mattick, J. L., T. A. Duval, and F. M. Phillips. 1987. *Quantification of Groundwater Recharge Rates in New Mexico Using Bomb-^{36}Cl, Bomb-^{3}H, and Chloride as Soil-Water Tracers.* Report No. 220, New Mexico Water Resources Research Institute, Las Cruces, New Mexico.

Martian, P., and S. O. Magnuson. 1994. *A Simulation Study of Infiltration Into Surficial Sediments at the Subsurface Disposal Area, Idaho National Engineering Laboratory.* EGG-WM-11250, Idaho National Engineering Laboratory, Idaho Falls, Idaho.

Millington, R. J., and J. P. Quirk. 1961. "Permeability of Porous Solids." *Trans. Faraday Soc.* 57:1200-1206.

Murphy, E. M., J. E. Szecsody, and S. J. Phillips. 1991. *A Study Plan for Determining Recharge Rates at the Hanford Site Using Environmental Tracers.* PNL-7626, Pacific Northwest Laboratory, Richland, Washington.

Nimmo, J. R., D. A. Stonestrom, and K. C. Akstin. 1994. "The Feasibility of Recharge Rate Determinations Using the Steady-State Centrifuge Method." *Soil Sci. Soc. Am. J.* 58(1):49-56.

Philip, J. R., and D. A. De Vries. 1957. "Moisture Movement in Porous Materials under Temperature Gradients." *Trans. Am. Geophys. Union* 38:222-232.

Phillips, F. M. 1994. "Environmental Tracers for Water Movement in Desert Soils of the American Southwest." *Soil Sci. Soc. Am. J.* 58:15-24.

Phillips, F. M., J. L. Mattick, T. A. Duval, D. Elmore, and P. W. Kubik. 1988. "Chlorine-36 and Tritium from Nuclear-Weapons Fallout as Tracers for Long-Term Liquid and Vapor Movement in Desert Soils." *Water Resour. Res.* 24:1877-1891.

Reginato, R. J., and F. S. Nakayama. 1988. "Neutron Probe Calibration Based on Plastic Transfer Standards." *Soil Sci.* 145:381-384.

Richards, L. A. 1931. "Capillary Conduction of Liquids in Porous Mediums." *Physics* 1:318-333.

Rockhold, M. L., M. J. Fayer, and G. W. Gee. 1988. *Characterization of Unsaturated Hydraulic Conductivity at the Hanford Site.* PNL-6488, Pacific Northwest Laboratory, Richland, Washington.

Rockhold, M. L., M. J. Fayer, and P. R. Heller. 1993. *Physical and Hydraulic Properties of Sediments and Engineered Materials Associated with Grouted Double-Shell Tank Waste Disposal at Hanford.* PNL-8813, Pacific Northwest Laboratory, Richland, Washington

Sackschewsky, M. R., C. J. Kemp, L. L. Cadwell, M. E. Thiede, and W. J. Waugh. 1991. *Status Report for the Small-Tube Lysimeter Facility Fiscal Year 1990.* WHC-EP-0381, Westinghouse Hanford Company, Richland, Washington.

Scanlon, B. R. 1992. "Evaluation of Liquid and Water Vapor Flow in Desert Soils Based on Chlorine-36 and Tritium Tracers and Nonisothermal Flow Simulations." *Water Resour. Res.* 28:285-298.

Stone, W. A., J. M. Thorpe, O. P. Gifford, and D. J. Hoitink. 1983. *Climatological Summary for the Hanford Area*. PNL-4622, Pacific Northwest Laboratory, Richland, Washington.

van Genuchten, M. Th., F. J. Leij, and L. J. Lund. (eds). 1992. *Proceedings of the International Workshop on Indirect Methods for Estimating the Hydraulic Properties of Unsaturated Soils*. October 11-13, 1989. University of California, Riverside. .718 pp.

Warrick, A. W., J. W. Biggar, and D. R. Nielsen. 1971. "Simultaneous Solute and Water Transfer for an Unsaturated Soil." *Water Resour. Res.* 7:1216-1225.

Waugh W. J., M. E. Thiede, C. J. Kemp, L. L. Cadwell, and S. O. Link. 1990. *Field Study of Gravel Admix, Vegetation, and Soil Water Interactions: Protective Barrier Program Status Report - FY 1989*. PNL-7440. Pacific Northwest Laboratory, Richland, Washington.

Wellings, S. R. 1984. "Recharge of the Upper Chalk Aquifer at a Site in Hampshire, England: Water Balance and Unsaturated Flow." *J. Hydrol.* 69:259-273.

Wright, J., J. L. Conca, and X. Chen. 1994. *Hydrostratigraphy and Recharge Distributions from Direct Measurements of Hydraulic Conductivity Using the UFA Method.* PNL-9424, Pacific Northwest Laboratory, Richland, Washington.

Appendix B

Review of Previous Work

Appendix B

Review of Previous Work

In this appendix, several water balance and recharge studies that have been conducted on the Hanford Site are briefly reviewed, and the purpose and outcome of the associated research are summarized. The recharge studies are grouped initially by Hanford Site area. This review is followed by brief discussions on studies related to surface protective barriers and model-based recharge predictions. The locations of various study sites referred to in this appendix are shown in Figure B.1.

B.1 200 Areas

B.1.1 Deep Well Test Site

Several recharge and water balance studies have been conducted in the 200 Areas. Starting in June 1969, 4 wells were drilled at Hanford coordinates 32-49 specifically for the purpose of providing data for evaluating recharge fluxes on the 200 Area Plateau. These wells were located within about 15 m of each other (Hsieh et al. 1973), and about 1.6 km south of the 200 East Area (see Figure B.1). The predominant vegetation in the area is sagebrush and cheatgrass. The soil is a relatively uniform sand to sandy loam, with some gravel.

Well 32-49A was drilled in June 1969, to a depth of about 76.3 m. Coarse gravel and cobbles were encountered at this depth and prevented further drilling. Sediment samples were collected during drilling to determine field water contents and water retention characteristics. Neutron probe data were also collected after the well casing was installed to measure volumetric water contents. These data were reported by Brownell (1971) and Routsen and Fecht (1979).

A second well, number 32-49B was installed approximately 12.5 m east-northeast of well number 32-49A, in October 1969 (Brownell 1971). This well was drilled to the water table, located at a depth of about 94 m below the ground surface. Samples collected during the drilling of this well were used to measure ^3H concentrations using electrolytic enrichment with gas counting (Isaacson et al. 1974). The method of tritium analysis was reported to provide ^3H data as low as 3 to 5 tritium units (T.U.) with an accuracy of ± 0.5 T.U. (Tadmor 1973; Isaacson et al. 1974). One T.U. is defined as 1 ^3H atom per 10^{18} H atoms.

A third "well", identified as 32-49C, was hand-augered to a depth of approximately 4.4 m at a location approximately 24 m south of the second well, in March 1970 (Brownell 1971; Enfield and Hsieh 1971). Thermocouple psychometers and temperature sensors were placed in the well hole and the hole was then backfilled. These sensors were installed to measure diurnal and seasonal temperature and matric potential gradients to estimate the rates and direction of water flow. Data from these sensors are reported by Enfield and Hsieh (1971).

The fourth well, number 32-49D, was drilled in June 1970, approximately 16.8 m south-southeast of well number 32-49A (Brownell 1971). This well was drilled from the ground surface to the water table, located approximately 95 m below the soil surface (Hsieh et al. 1973). An instrumented cable of thermocouple psychrometers and diode temperature transducers was installed at specific depth intervals in the well hole down to the water table (Hsieh et al. 1973). The well was then backfilled around the instrumented cable.

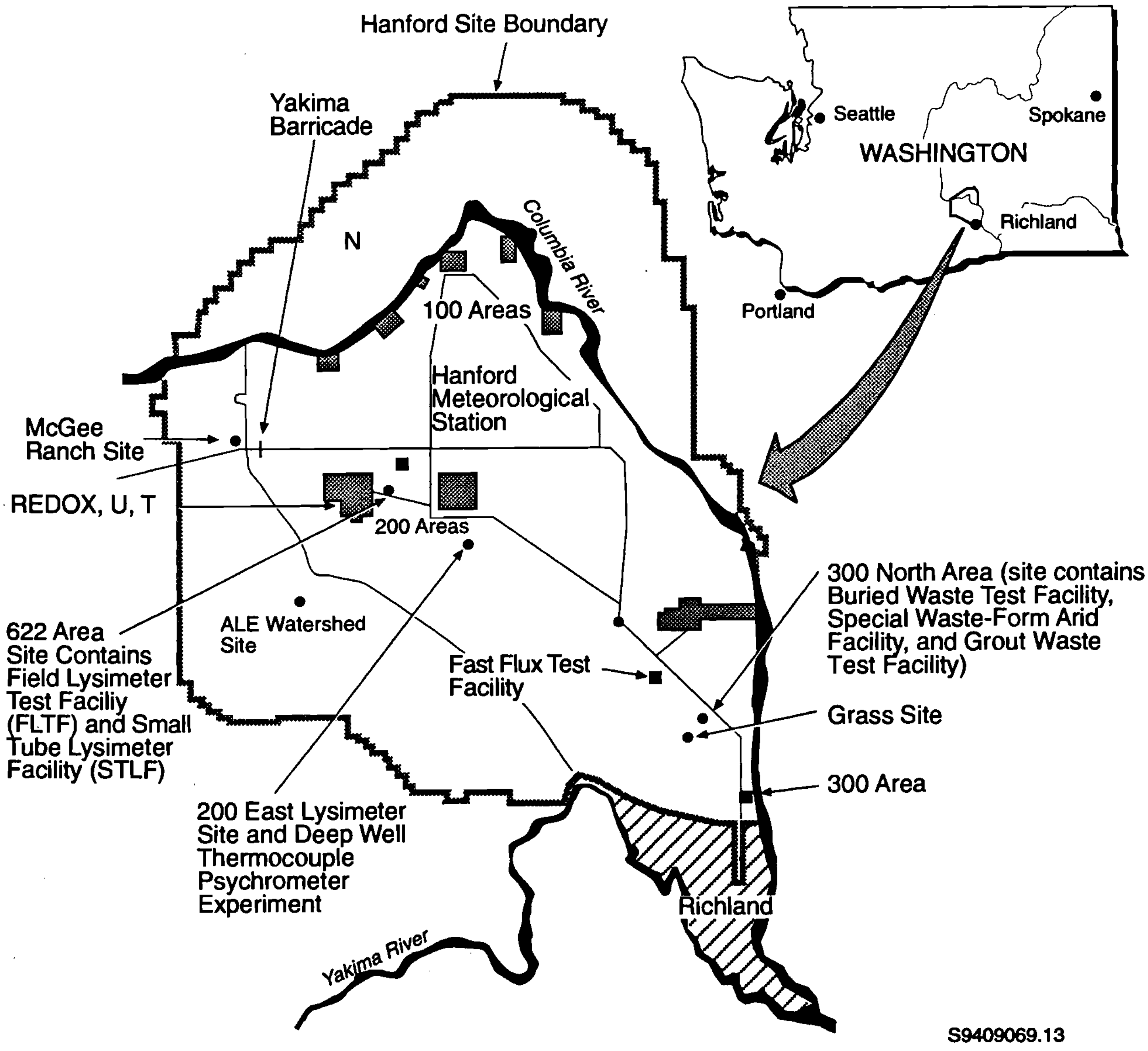


Figure B.1. Water Balance and Recharge Study Locations at the Hanford Site

Soil samples were collected during the drilling of well 32-49D to determine ^3H concentrations, and to measure or calculate hydraulic properties for different soil horizons. Unsaturated hydraulic conductivities were estimated using the method of Millington and Quirk (1959, 1960, 1961), with the matching factor of Jackson et al. (1965).

A fifth well, number 19-47B, was drilled during that time at a site located approximately 4 km south of the 32-49 coordinates. This well was also sampled for ^3H.

The volumetric water contents from well 32-49A and the ^3H data from wells 32-49B, 32-49D, and 19-47B are plotted in Figure B.2. The ^3H profiles were considered to be classic examples of vertical ^3H distributions in undisturbed areas of the vadose zone at Hanford (Brownell 1971). The high surface values of ^3H were thought to be influenced by the ^3H concentration in recent precipitation that occurred prior to sampling. Note that the higher ^3H values at depth are influenced by the groundwater. Unfortunately, recharge fluxes cannot be accurately estimated from the ^3H profiles shown in Figure B.2 because the sampling interval for the wells was relatively coarse (1.5 m), and the

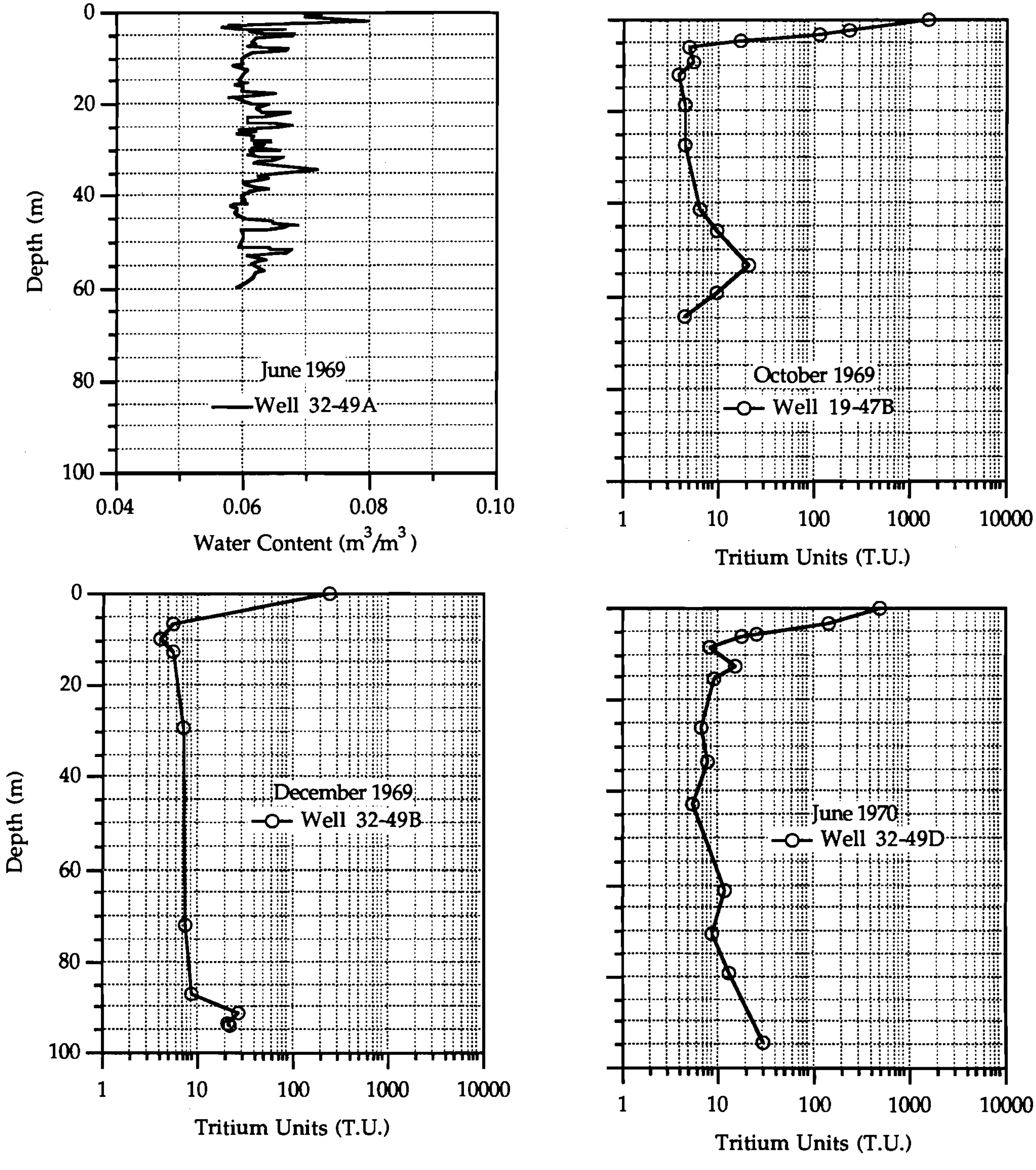


Figure B.2. Neutron Probe Log of Volumetric Water Contents and Tritium Profiles for Wells 32-49A, 32-49B, 32-49D, and 19-47B peak ^{3}H concentration occurred at (or above) the first measurement depth. As noted previously, there is also some uncertainty about the local influence Hanford site operations may have had on the time-dependent concentrations of ^{3}H in precipitation falling on the site. Note that the surface (0 to 1.5 m sampling depth) ^{3}H concentration of 1490 T.U. for well 19-47B is considerably greater than the average peak ^{3}H fallout for the northern hemisphere reported by Phillips et al. (1988) (see Figure A.2).

The thermocouple psychrometer data were intended to provide field measurements of temperatures and matric potentials from the land surface to the water table. These profiles should define the direction of soil water movement in response to annual cycles of precipitation and temperature. Thermocouple psychrometer data collected from well number 32-49C in May 1970, indicated an upward flux of water above the 3-m depth, and a downward flux below 3 m (Enfield and Hsieh 1971). The upward fluxes were attenuated with depth, being higher near the soil surface as a result of the greater evaporative demand, and water uptake by plant roots. Data from well number 32-49D show similar behavior, with a sinusoidal temperature pulse from seasonal temperature variations propagating as deep as 6 m (Hsieh et al. 1973).

Enfield et al. (1973) used averaged thermocouple psychrometer and diode temperature transducer data from well number 32-49D, with estimates of the soil hydraulic properties, to evaluate the steady-state water flux, q (L/T), in the deep unsaturated zone (below the 6-m depth) using the following equation,

$$q = -K\,\nabla(h_m - z) - D_t\,\nabla T - D_{op}\,\nabla OP \qquad (B.1)$$

where K = unsaturated hydraulic conductivity (L/T)
∇ = vector gradient operator (L^{-1})
h_m = matric potential of soil water (L)
z = depth (L), measured positive downward
D_t = thermal fluid diffusivity or the sum of the thermal liquid diffusivity and the thermal vapor diffusivity (L^2 / T per °K)
D_{op} = osmotic fluid diffusivity (L^2/T per bar)
OP = osmotic potential (bars)
T = absolute temperature (°K)

Equation B.1 accounts for thermal and osmotic pressure effects under steady-state flow conditions.

Electrical conductivities measured from saturated soil paste extracts were less than 0.5 ds/m, so the osmotic potential and the flow induced by an osmotic gradient were assumed negligible (Enfield et al. 1973). The psychrometers were assumed to be in equilibrium with the soil water, and the system was assumed to be at steady state. The method for calculating unsaturated hydraulic conductivities (Millington and Quirk 1959, 1960, 1961; Jackson et al. 1965) was also assumed to be reasonably accurate, and layering of the soil profile was neglected. With these assumptions, equation B.1 reduces to the general differential equation presented by Phillip and de Vries (1957) for one-dimensional vertical flow under combined temperature and matric potential gradients.

Enfield et al. (1973) estimated that the flux due to gravitational and matric potential gradients was 0.3 mm/yr (downward). The flux due to the thermal gradient was estimated to be -0.04 mm/yr (upward). Thus, a net downward flux of 0.26 mm/yr was calculated. Enfield et al. (1973) cautioned that the exact determination of the rates and even the direction of flow is uncertain given the variability of the water retention data, uncertainties in the methods used to calculate the unsaturated hydraulic conductivities and thermal diffusivities, and because the potential affects of osmotic gradients were neglected.

B.1.2 200 East Area Closed-Bottom Lysimeter

A lysimeter facility was designed and constructed in early 1972 to provide a more controlled environment for testing the hypothesis that meteoric water percolates down to the water table beneath the 200 Area Plateau. The facility was located approximately 1 km south of the 200 East Area, also at Hanford coordinates 32-49 (see Figure B.1). It consisted of two 18.5-m deep lysimeters and an instrument room, depicted in Figure B.3. The sediments filling the lysimeters consisted of material that was excavated during construction of the facility. These sediments were sieved and uniformly packed into the lysimeters, creating a much more homogeneous profile than the natural system. The lysimeters at this facility are the oldest at the Hanford Site and may be the deepest in the world.

The lysimeters were instrumented with thermocouple psychometers and temperature sensors, and neutron probe access tubes. One of the lysimeters was constructed with a closed bottom to intercept and collect any water that might otherwise percolate. The purpose of the closed-bottom lysimeter was "to demonstrate beyond all doubt whether or not meteoric water is percolating to the underground water from the surface at the 32-49 Hanford coordinates" (Brownell et al. 1975).

Isaacson et al. (1974) and Brownell et al. (1975) described the facility and its instrumentation, and presented data for the 1971-1972, 1972-1973, and 1973-1974 water years. Last et al. (1976) presented water content profiles based on neutron logs for the 1974-1975 and 1975-1976 water years. Jones (1978) presented lysimeter data and an analysis of the observed water movement for the 1976-1977 water year.

During the early years of monitoring, there was no evidence to suggest that meteoric water was percolating down to the bottom of either of the lysimeters. Seasonal pulses of water from winter precipitation percolated as deep as 4 and 6 m in the closed- and open-bottom lysimeter, respectively (Brownell et al. 1975). These pulses eventually dissipated during the summer in dryer, hotter years (Last et al. 1976; Jones 1978). Therefore, data from the 200 East Lysimeter Facility have been cited as evidence to support the contention that zero, or nearly zero recharge occurs on the 200 Area Plateau (Routsen et al. 1988). Although the soil filling the lysimeters was initially free of vegetation, the presence of plants growing on the lysimeters was not discussed in any of the early reports. While previous investigators had concluded no recharge was occurring, Jones (1978) used the unit gradient method and estimated that recharge rates, based on neutron probe data and associated measurement error, could be up to 5 mm/yr.

During the mid-1980s, the 200-East Area Lysimeter facility was not monitored and the open-bottom lysimeter was excavated. Photographs in Gee and Heller (1985) and Gee et al. (1989) document the presence of plants growing on the closed-bottom lysimeter. Fayer et al. (1986) suggested that plants growing on the lysimeters may have been responsible for the apparent lack of recharge during the early years of monitoring. These references also contend that, without the presence of plants, water would have moved deeper into the lysimeters to eventually become recharge.

The presence or absence of plants, the plant type(s), and the type of surface cover (i.e., gravel versus finer-textured soils) are important with respect to current waste management practices at Hanford. As noted previously, the ground surface overlying buried waste storage tanks in the 200 East and West Area is usually covered with gravel, and herbicide is commonly applied to prevent plant growth so that roots will not penetrate into the waste zones. This condition (no plants and gravel covered surface) is optimal for maximizing recharge.

PNL resumed monitoring of the 200 East Area Closed-Bottom Lysimeter in an attempt to demonstrate the potentially significant and detrimental impacts of current waste management practices in the 200 Areas. In February 1988, vegetation and wind-blown sediment which had accumulated on the surface of the closed-bottom lysimeter were removed and an active monitoring

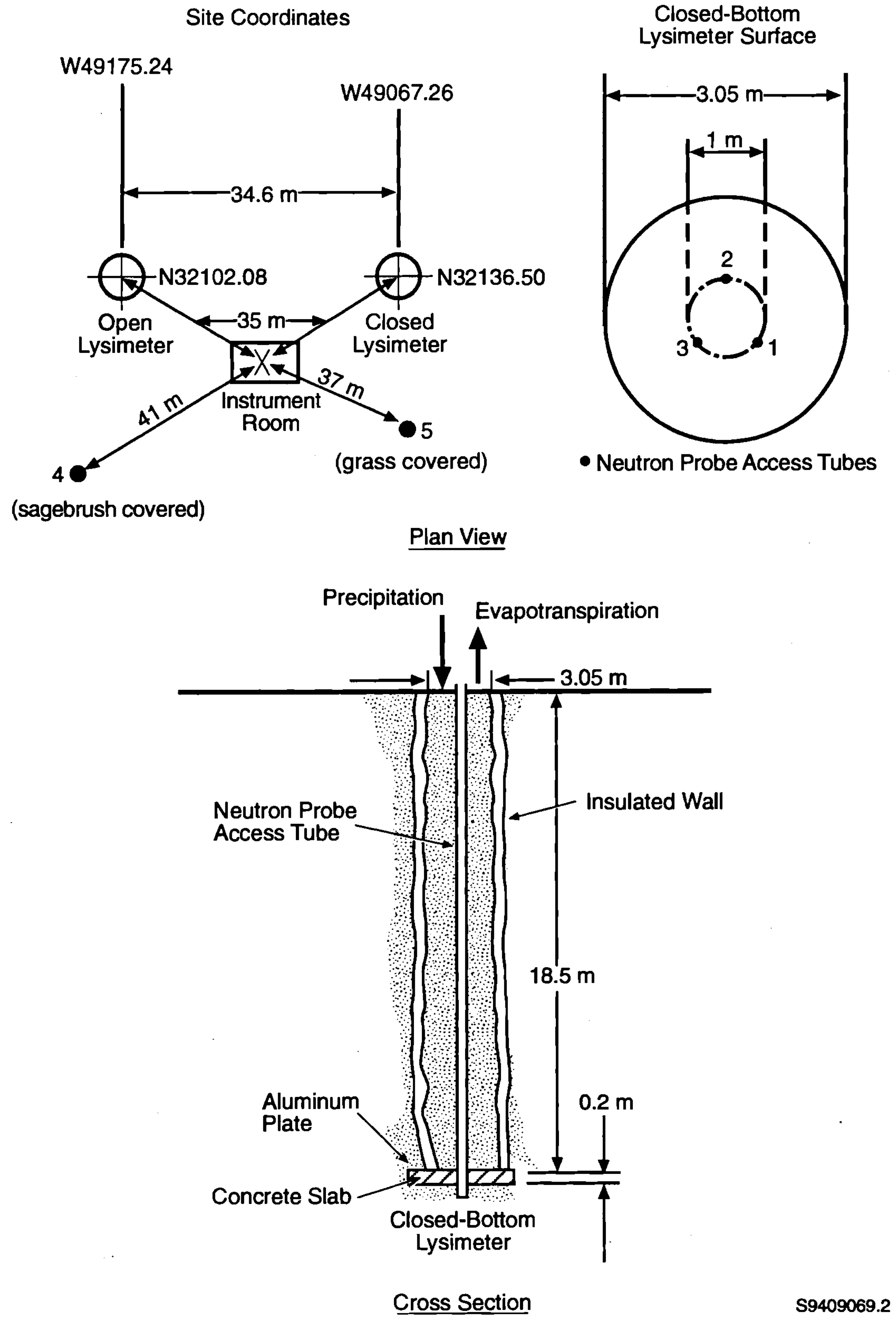


Figure B.3. Plan View and Cross Section of the 200-East Area Closed-Bottom Lysimeter program was initiated (Gee et al. 1989; Gee et al. 1994). The closed-bottom lysimeter, maintained with a bare-soil surface, was monitored for a period of about 3 years (February 1988 to March 1991). Neutron probe data were collected from the 3 access tubes in the lysimeter during most of this time on a biweekly to monthly basis. Two additional neutron probe access tubes were monitored at two adjacent locations during the same time period. One tube was located just southwest of the lysimeter in an area dominated by sagebrush, and the other tube was located directly south of the lysimeter in an area dominated by cheatgrass. The relative locations of the lysimeter and adjacent access tubes are shown in Figure B.3.

Soil-water storage above the 4.9-m depth in the 200-East Area closed-bottom lysimeter and at the adjacent vegetated sites is shown in Figure B.4. Despite precipitation being 15% below normal

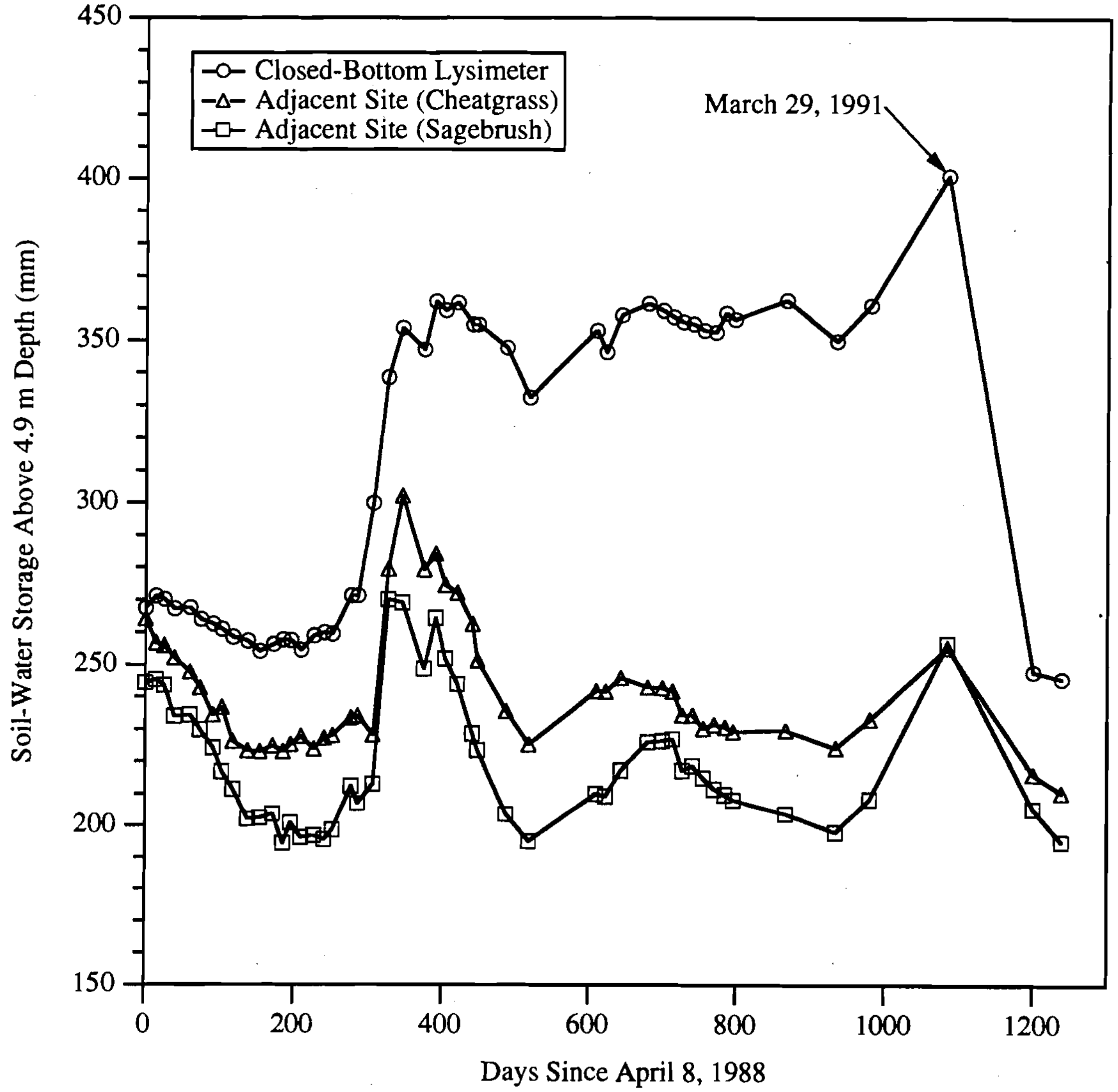


Figure B.4. Soil-Water Storage Above the 4.9-m Depth in the 200-East Area Closed-Botto Lysimeter and at Two Adjacent Vegetated Sites during the 3-year period when the lysimeter was maintained free of vegetation, soil-water storage in the upper 4.9 m increased by 132 mm. No net increase in soil-water storage was evident at the adjacent vegetated sites. Water storage changes below the 4.9-m depth were negligible.

After March 1991, the site was not monitored for several months and plants (mostly tumbleweeds) invaded the lysimeter. By July 1991, the plants had removed all of the water that had accumulated since 1988, effectively reducing the potential recharge to near 0 mm/yr. These results demonstrate the ability of plants to quickly establish themselves on this soil, and to extract water from significant depths. These results also support the supposition by Fayer et al. (1986), that water would have probably moved much deeper into the closed-bottom lysimeter to eventually become recharge if no plants were growing on the lysimeter.

The soil-water dynamics in the 200-East Area closed-bottom lysimeter were simulated from April 8, 1988 through December 31, 1992 using the UNSAT-H computer code (Fayer and Jones 1990) to estimate the potential drainage or recharge rate below the 4.9-m depth. Two sets of simulations were conducted: one without plants, and one with plants. As noted previously, the lysimeter was maintained free of vegetation from February 1988 through March 1991. After March 1991, the site was not monitored for several months and plants (mostly tumbleweeds) invaded the lysimeter. For the simulations reported here, plants were assumed to become active on April 15, 1991.

The data required to estimate plant parameters for use in UNSAT-H are scarce. However, Fayer and Walters (1995) reviewed the available data and literature and estimated representative plant parameters for cheatgrass, bunchgrass, and sagebrush. The parameters estimated by Fayer and Walters (1995) for sagebrush were used to represent the tumbleweeds that were found growing on the lysimeter. A maximum rooting depth of 3 m and a bare fraction of 20% were assumed.

The hydraulic properties for the sand in the lysimeter were represented using the Brooks-Corey (1964) water retention and Burdine (1953) relative permeability models, using parameters reported by Fayer and Gee (1992; Case 3) for a texturally-similar soil. The soil hydraulic properties were assumed to be non-hysteretic. Soil hydraulic properties and plant parameters are listed in the input files contained in Appendix C.

The initial conditions used for the model simulations correspond to the water contents measured on April 8, 1988. These initial water contents were converted to equivalent tensions using the Brooks-Corey water retention parameters given in Appendix C. Initial tensions were assigned for each node of the model grid by linearly interpolating from the tensions corresponding to each water content measurement.

The upper boundary conditions were derived from weather data obtained from the HMS. Hourly precipitation data were used, and snow was treated as equivalent rainfall. Windspeed, cloud cover, relative humidity, solar radiation, and minimum and maximum daily air temperatures were used to calculate PET using the Penman method (Doorenbos and Pruitt 1977). Calculated PET values were set equal to zero on days where snow was reported covering the ground at the HMS. A unit gradient condition was used for the lower boundary.

Figure B.5 shows daily precipitation, soil-water storage, and drainage rates. Without plants, the observed and simulated storage values fluctuated from seasonal variations in precipitation and evaporation, but increased steadily from the initial condition. The observed and simulated storage values decreased soon after plants became active. Although not exact, the storage match is sufficient to demonstrate the effects of water uptake by plant roots. Several attempts were made to calibrate the model parameters to improve the match between observed and simulated water content profiles and storage values. However, the uncalibrated simulation results shown in Figure B.5 matched the observed data as well or better than any of the results that were obtained during calibration attempts.

Figure B.5 shows that the predicted drainage rates increased slowly but continuously for the simulation without plants. For the simulation with plants, the estimated drainage rate increased slowly

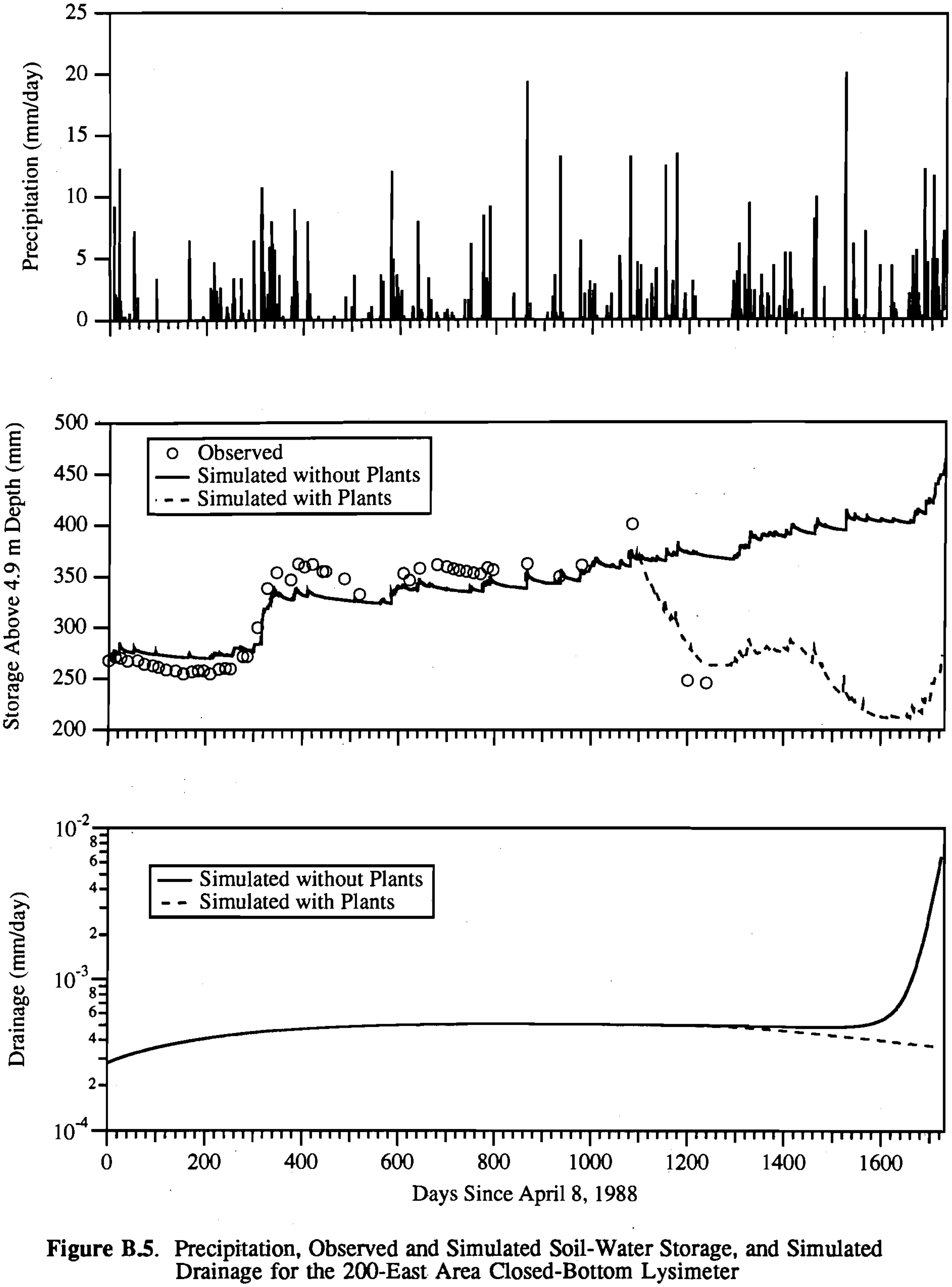


Figure B.5. Precipitation, Observed and Simulated Soil-Water Storage, and Simulated Drainage for the 200-East Area Closed-Bottom Lysimeter and then decreased soon after the plants became active. On the final day of the simulations (December 31, 1992), the estimated drainage rates for the simulations with and without plants were approximately 0.1 and 2.4 mm/yr, respectively. The predicted drainage rate for the simulation without plants was still increasing sharply by the final day of the simulation and would likely be much greater if the simulation was continued into 1993.

This comparison between field data and simulation results demonstrates the ability of the UNSAT-H model to reproduce the observed water balance in lysimeters reasonably well, and improves our confidence in its ability to provide reasonably accurate estimates of recharge rates. Other more detailed comparisons of lysimeter data and model simulation results are reported by Fayer et al. (1992) and Fayer and Gee (1992).

Prych (1995) recently estimated recharge rates at several locations on the Hanford Site using the chloride mass balance and ^{36}Cl bomb-pulse tracer methods. One of his study sites was in the 200 Areas, adjacent to the 200-BP-1 Operable Unit. Alternative interpretations of data from two boreholes yielded estimates of recharge rates ranging from 0.062 to 1.8 mm/yr. These values bracket the recharge rate of 0.26 mm/yr that was estimated by Enfield et al. (1973) using Equation B.1 with soil temperature and hydraulic property data for the 200 East Area deep well test site.

The studies described above indicate that the evaporative demand for water on the 200 Area Plateau is very high, especially during the summer, and that natural vegetation is very efficient at extracting water from deep in the soil profile. The tritium, chloride, and lysimeter data collected during these studies, and the simulation results for the 200-East Area closed-bottom lysimeter all suggest that some very small amounts of natural groundwater recharge may occur (< 10 mm/yr), even when deep-rooted vegetation is present. Exact rates have been difficult to determine due to spatial variability and measurement uncertainties. Some of the other lysimeter studies described below demonstrate that significant quantities of drainage or recharge can occur where the soils are coarse-textured and when vegetation is absent or shallow-rooted.

B.2 300 Area

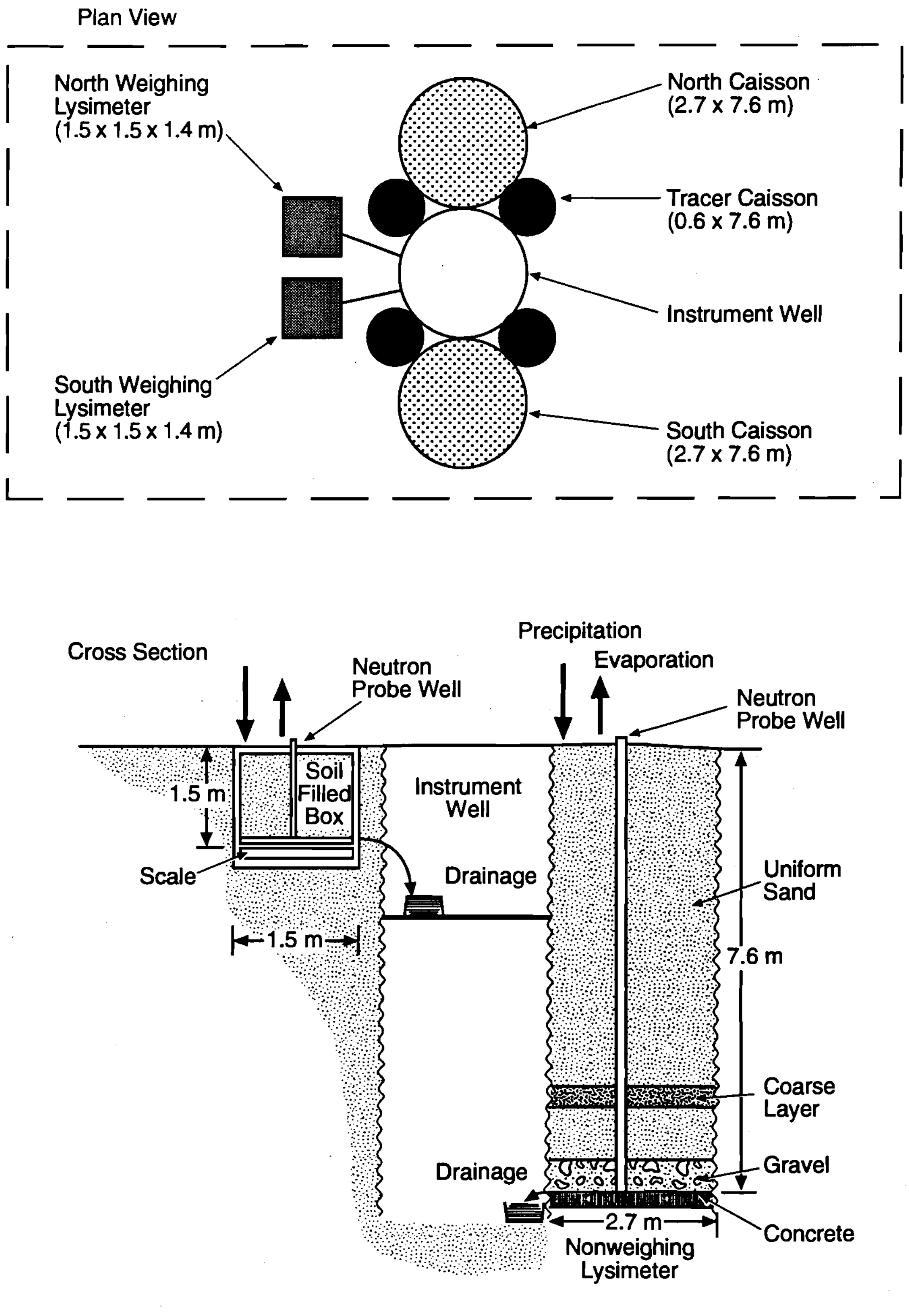
Water balance and recharge data have also been collected from several lysimeter facilities located just north of the 300 Area (see Figure B.1). Although these facilities are a considerable distance from the 200 Area Plateau, the soils and vegetation are similar to those found on the 200 Areas.

B.2.1 Buried Waste Test Facility

The BWTF is located about 6 km northwest of the 300 Area and adjacent to the 300 North Burial Ground. Originally constructed in 1979, this facility was designed for field studies of water balance and radionuclide transport (Phillips et al. 1979; Jones and Gee 1984). More recently, data from this facility have been used for testing water balance models (Fayer and Gee 1992).

The BWTF consists of seven corrugated, galvanized-steel caissons, bolted together in the arrangement shown in Figure B.6, and two weighing lysimeters. These lysimeters are filled with sediment that was excavated from the area. Thermal and hydraulic properties of the sediments are described by Cass et al. (1981) and Rockhold et al. (1988).

The data collected and analyses performed with respect to the BWTF lysimeters differ markedly from the data and analyses obtained from the 200 East closed-bottom lysimeter. Results from the BWTF have shown drainage rates of up to 100 mm/yr through the unvegetated sands and somewhat lower, but significant drainage rates for sands with shallow-rooted grasses (35% of annual precipitation; see Table 3.1). They also indicate that recharge is reduced when deep-rooted plants are present. The BWTF studies have illustrated the complex interactions among vegetation, soil, and climate that influence recharge rates.



S9409069.3

Figure B.6. Plan View and Cross Section of the Buried Waste Test Facility Adjacent to the 300 North Burial Grounds

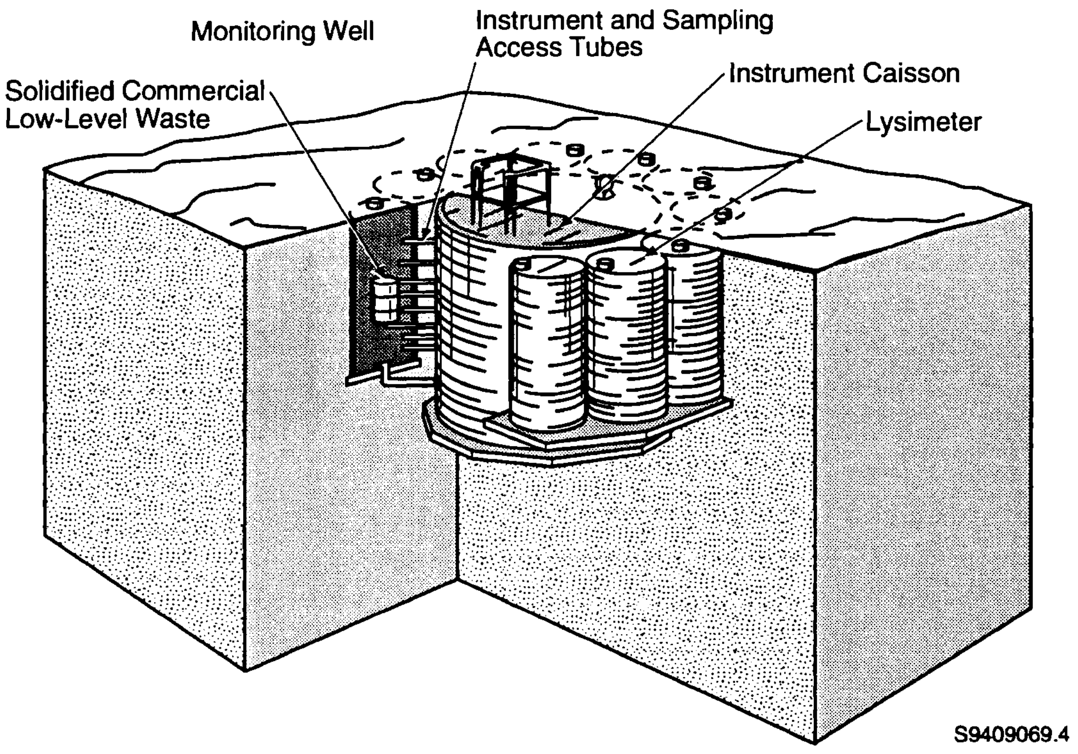


Figure B.7. Schematic of the Special Waste-Form Arid Lysimeter Facility

B.2.2 Special Waste-Form Lysimeters - Arid Facility

The Special Waste-Form Lysimeters-Arid (SWLA) facility, (formerly known as the Commercial Waste Test Facility), is located adjacent to the BWTF. This facility was completed in 1984 (Gee and Jones 1985), and is described in detail by Walter et al. (1984, 1986). The facility consists of 10 lysimeters (caissons) with sealed bottoms. Each caisson is 1.8 m in diameter and 3 m deep (see Figure B.7). The caissons are filled with soil materials very similar to those in the BWTF lysimeters, and are maintained in a vegetation free state.

The purpose of the SWLA facility was to evaluate the leaching of solidified low-level waste in an arid environment. Accordingly, each lysimeter contains a 208-L volume of commercial waste that has been solidified with either bitumen, polymer, or cement. The hydrology of the lysimeters was also studied in order to interpret the leaching and transport characteristics of commercial wastes.

The lysimeters of the SWLA facility all exhibited a distinctive seasonal pattern in water storage (Walter et al. 1986; Jones et al. 1988). Peak water storage occurred during the late winter months, which corresponded with the season of peak precipitation at the site. On average, approximately 30% of precipitation became drainage in the absence of plants. Peak drainage from the lysimeters occurred in the late spring or early summer, implying a travel time through the lysimeters of approximately 5 to 6 months (Jones and Serne 1993). When winters were especially cold, and no significant snowmelt occurred during most of the winter, rapid snowmelt in late winter and early spring produced a sharp peak in storage.

Observations made at the SWLA facility demonstrated the significance of the timing of precipitation events. During the 1985 water year, the facility received 50% more precipitation than in

1986. However, evaporation for the two years was estimated to be quite similar (Jones et al. 1988). This similarity illustrated the complex and dynamic relationships between precipitation, drainage, and evaporation. In the case of the 1985 water year, the additional precipitation came in the form of winter snow, and quickly entered the soil as snow melt when potential evaporation was relatively low. Complete data and a preliminary interpretation of the SWLA study are presented in Jones and Serne (1994). An analysis of the water balance at the SWLA facility is presented in Jones (1989).

B.2.3 Grout Waste Test Facility

A schematic diagram of the Grout Waste Test Facility (GWTF), which was also located in the 300 North Area, adjacent to the BWTF and SWLA, is shown in Figure B.8 (Gee and Jones 1985). The facility consisted of four large field lysimeters. They were designed to test the leaching and migration rates of grout-solidified low-level radioactive wastes generated by Hanford Site operations (Treat 1985, Treat et al. 1985). Each lysimeter was an 8-m deep by 2-m diameter closed bottom caisson. They were placed in the ground so that the upper rim remained just above grade. Two of the lysimeters were used to test grout-solidified wastes; the other two remained empty. The lysimeters were backfilled in March and September of 1985. Routine monitoring and maintenance continued until January 1989, and some drainage samples were collected until December 1992. The facility was decommissioned during the summer of 1994.

Because large scale grout-solidified waste disposal was proposed at a site adjacent to the 200 East Area, soils from that vicinity were used as fill for these lysimeters. Typical of the candidate site, the lower 4 m of each lysimeter was filled with coarse sand and the upper 4 m was filled with very fine sand. A 20-cm-thick gravel layer formed the upper surface of each lysimeter. This material was selected to promote infiltration of meteoric waters and thereby enhance the flux of water past the wastes. Until January 1989 the surfaces were maintained free of vegetation.

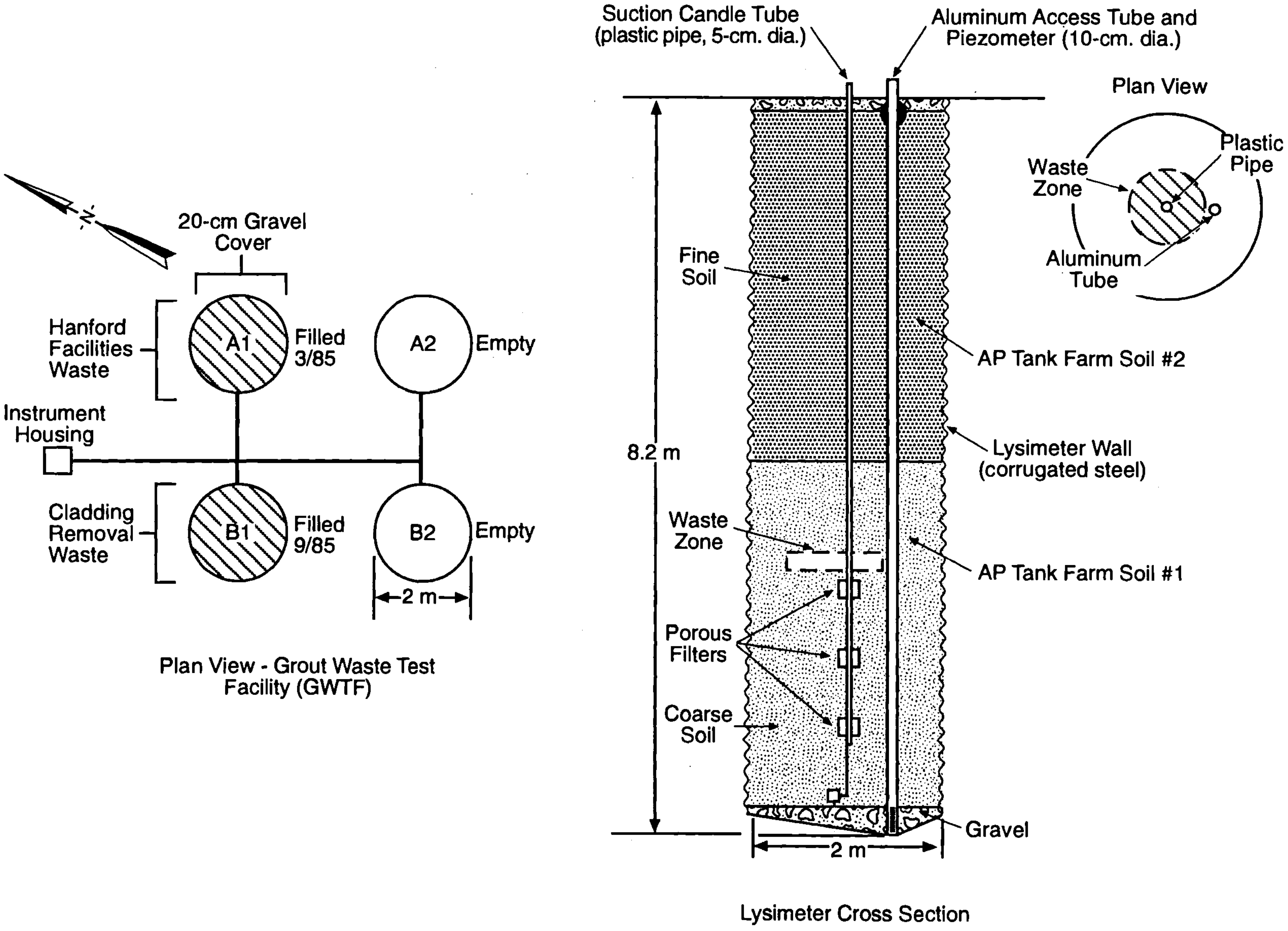
Monitoring of precipitation, water storage and drainage occurred over a 3-year period. The data indicate that it took approximately 2 years for the 8-m deep lysimeters to reach an equilibrium or steady-state flow condition. During the only full water year recorded after equilibrium was reached (i.e., 1987/1988), annual water flux through the well-sealed lysimeter was on the order of one-half of the annual precipitation. This level of deep drainage or recharge is associated with the coarse-gravel and vegetation-free surface condition.

B.3 Grass Site

The Grass Site is located about 5 km northwest of the 300 Area and about 2 km southeast of the 300 North Area (Gee and Kirkham 1984). The site lies in a slight topographic depression approximately 900 m wide and several thousand meters long in a northeast-southwest direction. It is covered with cheatgrass and Sandberg's bluegrass; deep-rooted sagebrush and rabbitbrush cover was burned off before 1983 and again in August 1984 by range fires. The vegetation community of grasses is typical of disturbed areas on the Hanford site where natural revegetation has occurred. Brush species now grow only at the burn area perimeters. This site was of interest to study the water balance response of a site covered with only shallow-rooted vegetation to natural precipitation events (Gee et al. 1989).

In January 1983 a network of 25 neutron access wells were installed at the Grass Site (see Figure B.9). From early 1983 until the summer of 1991, water content data were collected. Other data necessary for assessing the site water balance were also collected, (i.e., precipitation, air temperature, humidity, and wind speed). Estimates of the hydraulic properties of the soils at the Grass Site were reported by Rockhold et al. (1988) and Gee et al. (1991).

Data from Grass Site suggested that significant drainage or recharge was occurring. Early estimates ranged from 40 to 80 mm/yr (Gee and Heller 1985; Gee 1987). Analyses by Rockhold et al. (1990) revealed a zero-flux plane at the 120-cm depth, and a steady decrease in stored water

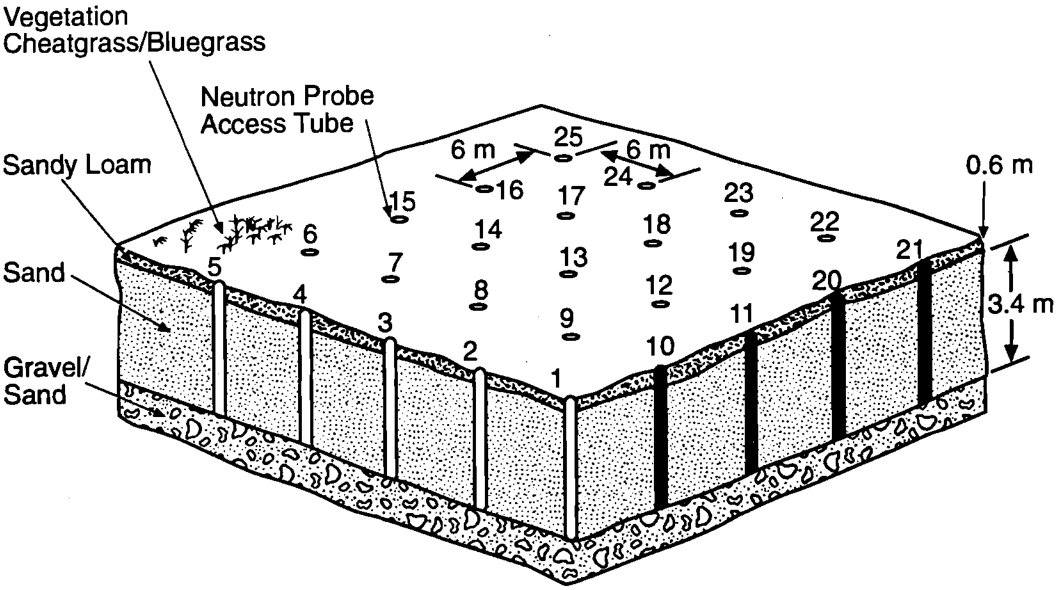


Plan View - Grout Waste Test Facility (GWTF)

Lysimeter Cross Section

Figure B.8. Schematic Diagram of the Grout Waste Test Facility (after Gee and Jones 1985)

S9409069.5



S9409069.6

Figure B.9. Schematic Diagram of Neutron Probe Access Tubes at the Grass Site

below this level since 1986. Based on average water storage changes from July 1988 through June 1989, the zero-flux plane method yielded a recharge estimate of 8.1 mm/yr. Using representative soil hydraulic properties and the average water content below the 120-cm depth, the unit gradient method yielded an estimated recharge rate of 2.2 mm/yr. However, considering the neutron probe measurement uncertainty, the recharge rate was estimated to range anywhere from 0.06 to 28 mm/yr.

Fayer and Walters (1995) reported estimated recharge rates at the Grass Site for an 8-year period. The overall mean value for 19 locations and eight years was 25.4 mm/yr. The data gave some indication of the variability that might be expected in recharge. For the 19 locations, the highest recharge estimate in a given year was anywhere from 2 to 28x the lowest estimate for that year. During the entire eight years, the lowest annual estimate was 3.0 mm/yr and the highest was 143.5 mm/yr.

Prych (1995) used the chloride mass balance and ^{36}Cl bomb pulse tracer techniques to estimate recharge rates using data collected from 4 boreholes at the Grass Site. The estimates of recharge rates obtained using these tracers ranged from 0.39 to 5.1 mm/yr. These values are within the range of values estimated using neutron probe data and the unit gradient and zero-flux plane methods.

B.4 Arid Lands Ecology Reserve

A number of recharge and water balance studies have been conducted on the ALE Reserve. Four weighing lysimeters, containing monoliths of undisturbed soil were constructed in the summer of 1986 (Gee et al. 1991). Lysimeter pairs are located approximately 250 m apart in areas of plant cover representative of two plant communities; bunchgrass, and a combination of sagebrush and bunchgrass. Figure B.10 shows a lysimeter pair; each monolith, excavated onsite from silt loam soil, has a surface area 1.5 m by 1.5 m, is 1.7 m deep and weighs approximately 6 Mg. Each lysimeter is positioned on a 9 Mg capacity platform scale with a resolution of 50 g.

Measurements of evapotranspiration and other water balance parameters have been made using the ALE weighing lysimeters since 1987. Water balances between the two plant communities have

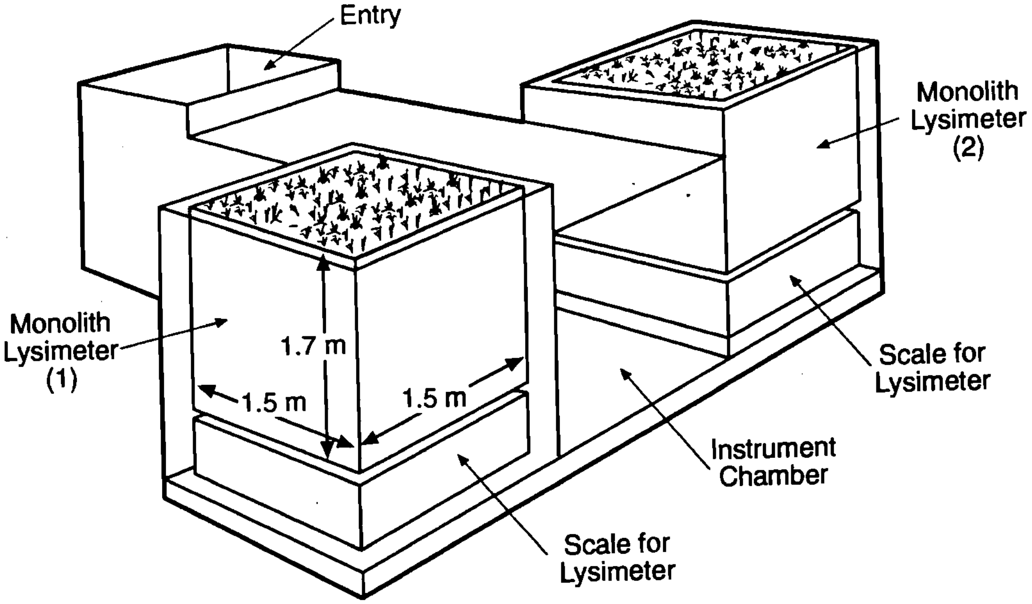


Figure B.10. Schematic Diagram of Weighing Lysimeters at the Arid Lands Ecology Reserve (after Gee et al. 1991)

been found to be comparable. However, the applicability of these lysimeters may be limited by their depth (1.7 m). Depth appears adequate for the bunchgrass plant community. However, it appears to be too shallow for the combination bunchgrass and sagebrush community. For the deep-rooted sagebrush species, this application of weighing lysimetry may be underestimating long-term evapotranspiration and influencing water balance estimates.

Figure B.11 is a schematic diagram of a small weighing lysimeter typical of those used for early water balance studies on the ALE Reserve (Hinds 1973; Cline et al. 1980). These small lysimeters were typically about 13 cm in diameter with lengths of 100 cm or less and made of plastic. Evapotranspiration rates were determined directly from weight changes obtained by removing the lysimeters from the ground and weighing them. Root growth patterns were obtained by destructively sampling the lysimeters (Cline et al. 1980). Quantitative data relating root density to evapotranspiration for cheatgrass at Hanford were also collected using this type of lysimeter (Hinds 1973). The empirical relationships that are currently used to model evapotranspiration from cheatgrass using the UNSAT-H code are based on these data (Gee and Simmons 1979). Disadvantages of these small lysimeters include their size which does not allow deep-rooted species to fully develop, and lack of any drainage measurement (Gee and Jones 1985). While these early data were important for the development of plant transpiration models, larger-scale lysimeter experiments were needed to demonstrate field scale relevance.

Murphy et al. (1991) used moisture content and chloride data from the Warden silt loam soil at the ALE lysimeter site to estimate recharge using the chloride mass balance method. The estimated recharge rate for this site using the chloride mass balance method was < 0.01 mm/yr (Murphy et al. 1991).

B.5 Protective Barrier Studies

Most, if not all, of the LLW disposal facilities in the United States have a surface or near-surface cover system in place to reduce infiltration of meteoric water and to isolate buried wastes from the

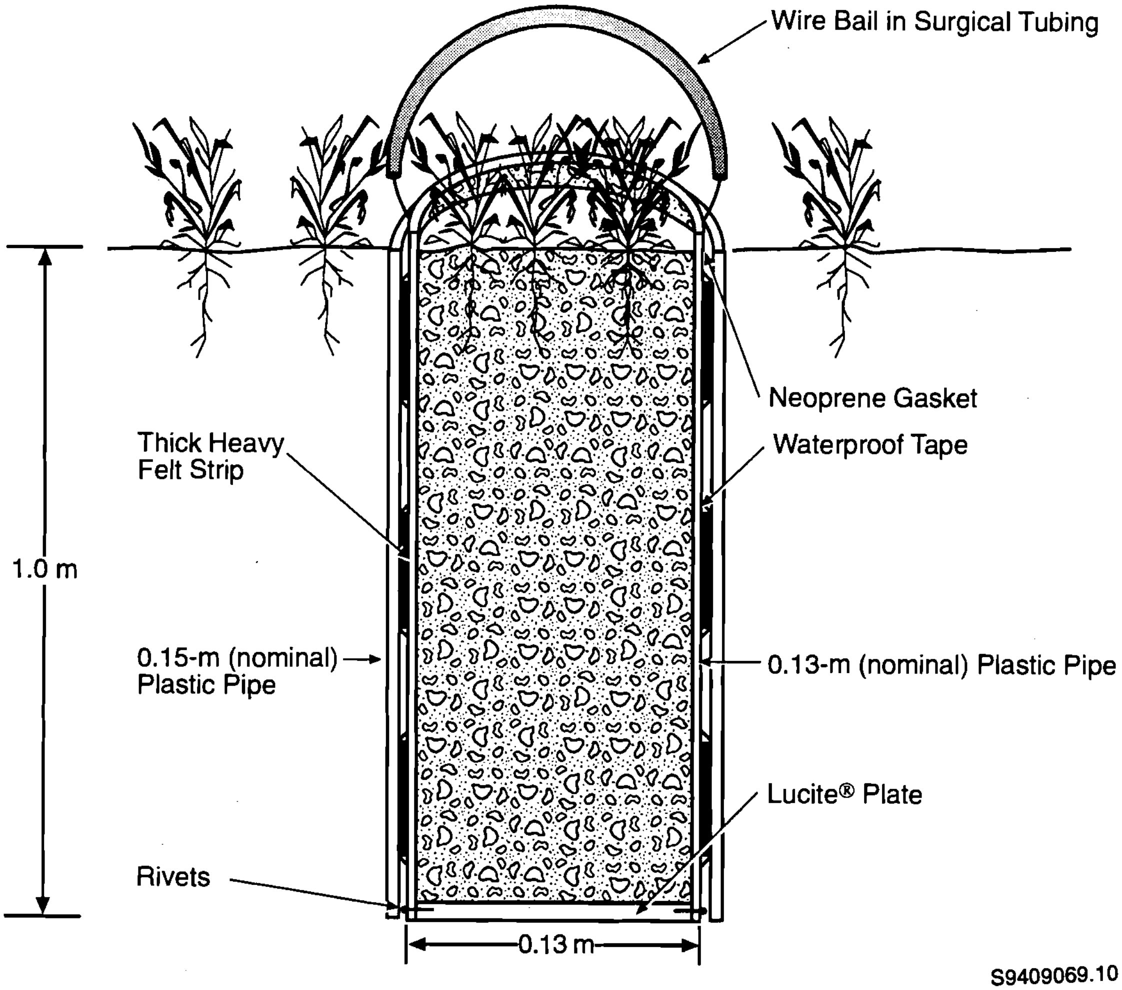


Figure B.11. Schematic Diagram of Small Weighing Lysimeters used for ET Measurements at ALE (after Hinds 1973)

accessible environment (EPA 1986, 1987, and 1991). The proposed facility used for disposal of vitrified wastes from the Hanford tanks will also use a surface or near surface cover system.

The layering sequence used in most of more complex cover designs creates a "capillary barrier" which prevents or limits drainage into the underlying coarser materials until the finer soil is almost saturated at the interface with the coarser material. These capillary barriers systems are highly effective in reducing or even eliminating the percolation of meteoric water into the underlying wastes, especially when the surface soils are vegetated. The capillary barrier causes infiltrating water to temporarily accumulate in the finer-textured soils, from where it can eventually be recycled to the atmosphere via evaporation or plant transpiration. A performance objective of the multilayered engineered barrier at Hanford is to achieve a recharge rate of < 0.5 mm/yr over the 1000-year design life.

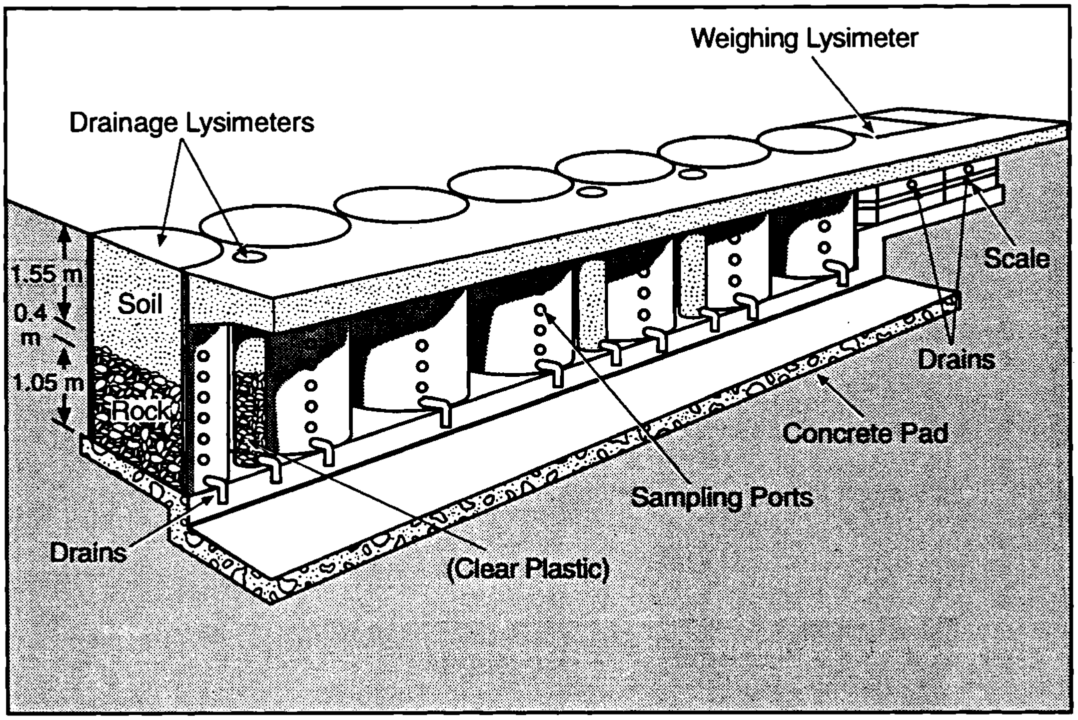
Surface and subsurface cover systems that utilize the capillary barrier concept have been proposed and tested under a variety of climatic conditions throughout the world (Rancon 1980; Nyhan et al. 1986; Cartwright et al. 1987; Anderson and Clausen 1988; Healy 1989; Schultz et al. 1989; Melchior et al. 1993). A prototype protective barrier cover system has also been recently constructed at the Hanford Site (KEH 1993).

B.5.1 Field Lysimeter Test Facility

A field lysimeter test facility (FLTF) was designed and constructed on the Hanford Site to test the performance of capillary barrier cover systems under arid site conditions (Kirkham et al. 1987; Campbell et al. 1990; Gee et al. 1989, 1992, and 1993). The FLTF is located between the 200 East and West Areas, immediately adjacent to the HMS (see Figure B.1). The facility has been operational since 1987. It consists of 24 lysimeters (14 drainage-type, 4 weighing-type, and 6 clear-tube lysimeters). The lysimeters are configured to provide duplicates of 11 different treatments. These treatments consist of different layering sequences and irrigation rates ranging from ambient precipitation to 2 and 3 times the long-term average annual precipitation.

A schematic diagram of the FLTF is shown in Figure B.12. The lysimeters at the FLTF are instrumented with neutron probe access tubes for measuring water contents, tensiometers for monitoring soil-water pressure heads, and thermocouple psychrometers for measuring soil temperatures. The bottoms of the lysimeters are sloped toward ports which are used to collect drainage water. Weighing lysimeter weight changes are recorded on an hourly basis.

Compared with the bare soil lysimeters at the FLTF, those with vegetation have exhibited approximately twice the water loss rates and amounts (ET). Root growth rates of 14 mm/day have been observed in the clear-tube lysimeters for sagebrush. Such rapid growth caused roots to intrude the full depth of the lysimeters in a single growing season. Intrusion was followed by rapid water removal to nearly 8 vol%, which is the plant extraction limit in the silt loam soil. Analysis of barrier treatments has shown that those lysimeters that have drained have not lost water by liquid drainage, but rather by vapor-phase transport. The observed drainage is closely approximated by estimates of downward vapor transport caused by thermal gradients (Campbell and Gee 1990).



S9503018.1

Figure B.12. Schematic Drawing of the Field Lysimeter Test Facility Showing One-Half of the Parallel Configuration of Lysimeters (after Gee et al. 1989)

A record-breaking snowfall of 1425 mm (56.1 in.) occurred during the winter of 1992/1993. This extreme snowfall was more than four times the long-term average reported for the years 1912 to 1980 by Stone et al. (1983). In the spring of 1993, over 30 mm of drainage occurred from the unvegetated lysimeters that had been previously subjected to 3 times the long-term average precipitation. This drainage was the result of spring melt water from the record winter snowfall. No drainage was measured from any of the vegetated or unvegetated lysimeters subjected to ambient precipitation. The occurrence of this extreme event, and the subsequent drainage from the lysimeters, indicates that long-term lysimeter and surface barrier monitoring programs are required for testing different barrier designs and their performance under extreme, but realistic conditions. Extreme events must be accounted for when evaluating the long-term performance of a LLW disposal facility at Hanford.

Alternative models to simulate soil-water dynamics in response to evaporation and transpiration have been investigated using weighing lysimeter data from the FLTF. The SWIM (Ross 1990), SPUR-91 (Carlson and Thurow 1991), and UNSAT-H (Fayer and Jones 1990) computer codes have all been tested using these data. Simulation results from the UNSAT-H code were compared with data from the FLTF by Fayer and Gee (1992). Fayer et al. (1992) concluded that field-measured sorption and hydraulic conductivity data were important to the prediction of drainage. They also referred to needed work in the areas of unsaturated hydraulic conductivity measurements below -20 kPa, hysteresis, snow cover, frozen soil, the calculation of potential evaporation, and the effects of temperature variations on water and vapor flow. They also alluded to the need for conducting long-term comparisons. Longer-term modeling studies are currently underway using data from both the bare and vegetated lysimeters at the FLTF.

B.5.2 Small Tube Lysimeter Facility

The Small Tube Lysimeter Facility (STLF) is located immediately adjacent to the FLTF (Waugh and Link 1988; Waugh et al. 1991). The STLF field experiment was designed to test and quantify whether the use of a gravel mulch at the surface of a protective barrier, which is designed to control erosion, will significantly increase water storage and result in drainage through a multilayer barrier. As a result, a variety of surface covers and precipitation rates have been examined in terms of impacts on storage, drainage and ET. Twenty-one treatment combinations are possible, each with 5 replicates; twenty treatment combinations were studied with 100 of the lysimeters.

The STLF, depicted in Figure B.13, is composed of 105 lysimeters arranged in a 21-by-5 array (Sackschewsky et al. 1993). Each lysimeter is 169-cm long and has a 30.4-cm inside diameter; each is set into a sleeve within the array. The tops of the sleeves and lysimeter tubes are approximately at grade, and the sleeves are set in the steel grating surface of the STLF array and suspended in air. An inflatable rubber insulting collar has been placed in the annulus between each sleeve and its lysimeter to minimize heat transfer with the atmosphere. Each lysimeter has an aluminum collar for lifting and weighing. This collar also serves as a coupling for plant-gas exchange studies on photosynthesis and ET.

The STLF was placed in service in September 1988 and Sackschewsky et al. (1993) report findings through fiscal year 1992. The facility is not currently monitored and is in a standby mode. Experiments involving 80 lysimeters at the STLF examined surface treatment effects, surface sand and gravel effects, and layering sequence effects. Ten of the lysimeters were used to examine alternate subsurface low-permeability barriers composed of clay and grout. Ten others were used to examine the effects of infiltration and root penetration on asphalt barrier integrity.

Initial conditions and results for 90 of the 100 lysimeters are reported by Relyea et al. (1990), Sackschewsky et al. (1991), and Sackschewsky et al. (1993). In general greater amounts of water storage and less ET were found in the gravel mulch lysimeters than in either the gravel admix or plain soil lysimeters (Sackschewsky et al. 1991). The lysimeters subjected to irrigation treatments exhibited increased storage and ET. The vegetated lysimeters showed lower storage and increased ET. The gravel mulch treatments all produced detectable quantities of drainage. A surface sand

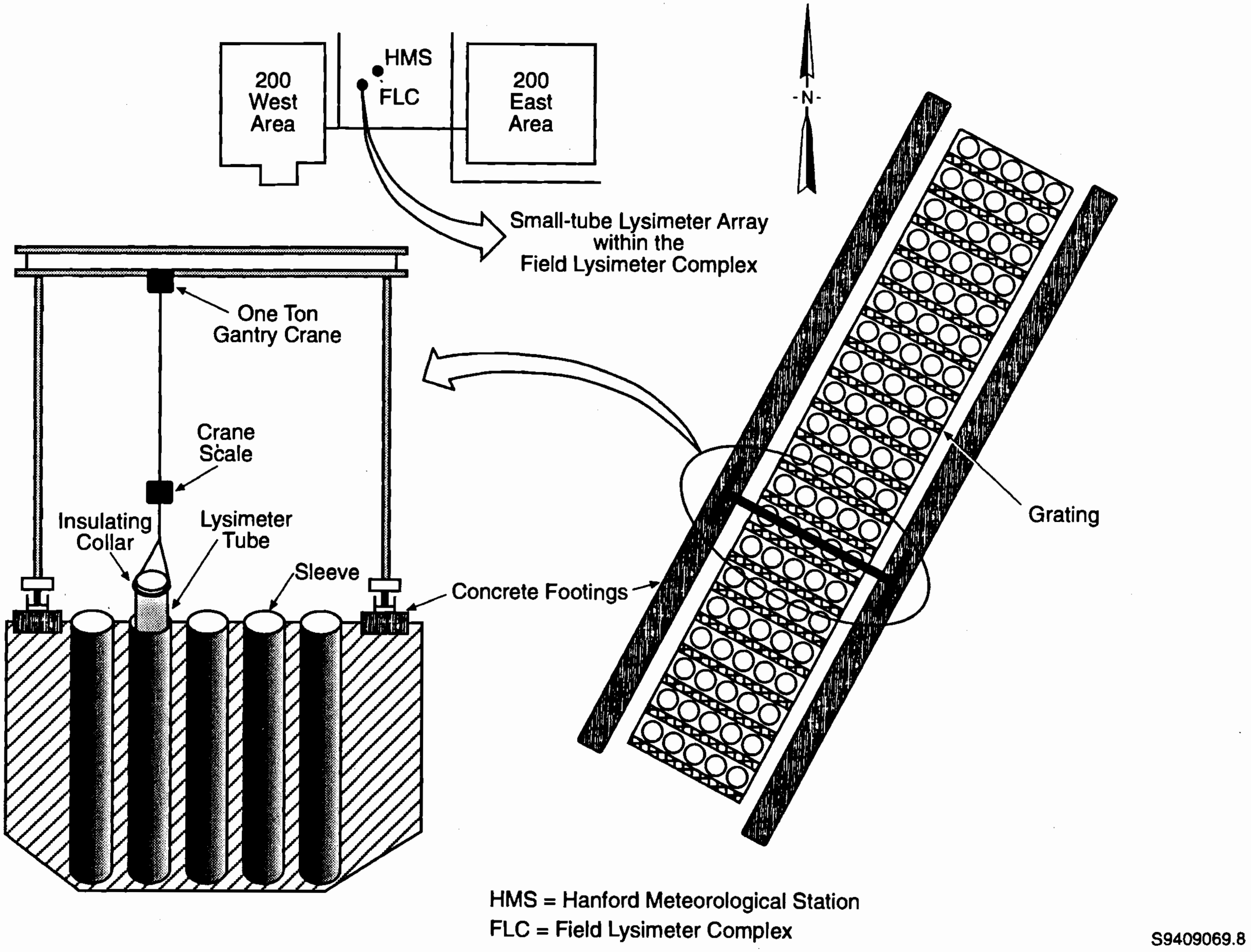


Figure B.13. Lysimeter Array within the Small-Tube Lysimeter Facility (after Sackschewsky et al. 1993) layer was found to behave similarly to a gravel mulch layer with regard to its effects on the soil-column water balance. Drainage was detected from all sand-covered and gravel-covered lysimeters. No significant storage or ET effects were observed in the layering sequence experiments. Clay and grout treatments revealed no significant storage or ET differences and neither treatment produced drainage.

A significant element of the STLF study was the determination of ET for a variety of vegetation treatments. A whole-plant gas exchange system was created which enables quantification of plant dynamics (Link and Waugh 1989, Link et al. 1992a, 1992b). As configured in fiscal year 1989, the device was able to measure evaporation, ET, and carbon dioxide exchange rates from the STLF lysimeters with and without cheatgrass. At the STLF and elsewhere at Hanford, these studies are developing simple models of ET for typical vegetation types such as cheatgrass and sagebrush.

B.5.3 McGee Ranch Study Site

The McGee Ranch Site is located at the intersection of State Highways 24 and 240; across Highway 240 from the Yakima Barricade west of the 200 Areas (see Figure B.1). The soils in this area were classified as Esquatzel and Warden silt loams by Hajek (1966). Near-surface soil texture and other physical properties have been characterized by Last et al. (1995). Site characterization indicated that fine-grained soils range in depth from 3 to 10 m. Therefore, this site was selected as the source area for fine-grained soils which will be used as part of the multilayered surface protective barriers for the shallow-land burial sites at Hanford. Water storage and drainage, and plant characteristics from this site have been monitored to provide data necessary for the assessment of the adequacy of protective barriers. McGee Ranch soils are used in the FLTF and STLF studies.

An unsteady drainage-flux experiment was conducted at this site in 1987 (Rockhold et al. 1988) to define unsaturated hydraulic characteristics of McGee Ranch soils. A 2-m by 2-m study plot was employed in this first experiment, and complete results of soil hydraulic properties are reported in Rockhold et al. (1988). A second experiment on a 4-m by 4-m study plot was used to verify that lateral flow did not occur in the first experiment (Gee et al. 1989). The hydraulic properties determined from these analyses can be used to estimate recharge rates using the unit gradient method.

Prych (1995) estimated recharge rates at two locations on the McGee Ranch Site using chloride mass balance and ^{36}Cl bomb-pulse tracer techniques. The vegetation in the vicinity of the boreholes at the time of sampling was sagebrush and cheatgrass. The estimated recharge rates ranged from 0.024 to < 2.1 mm/yr.

As part of the study conducted at Hanford to design and test the effectiveness of surface protective barriers for waste sites, the concept of using a gravel mulch to control erosion has also been studied at the McGee Ranch Site (Waugh and Link 1988). The conceptual protective barrier consists of coarse materials overlain with fine-textured soil. The fine soil acts like a sponge and stores precipitation until it can be cycled back to the atmosphere by evapotranspiration. Maintaining the fine soil layer is critical to barrier performance, and, therefore, minimizing erosion from wind or runoff is a critical issue. Mixing a given size and relative volume of gravel into the upper layer of soil has been studied as a means of creating a desert pavement which would protect underlying soils or waste deposits. Field studies at the McGee Ranch Site were designed to study optimum gravel size and relative volume, and plant community response to armored surfaces. Field plots (see Figure B.14) were used to test the effects of 12 different combinations of gravel mulch, vegetation, and precipitation on soil water storage and plant abundance. A gravel admix study (Waugh 1989; Waugh et al. 1990, 1994; Link et al. 1990, 1994) revealed that additions of gravel (15 and 30% by weight) mixed into the topsoil (upper 20-cm) layer did not significantly influence plant species composition or abundance. However, doubling precipitation influenced both plant species composition and cover.

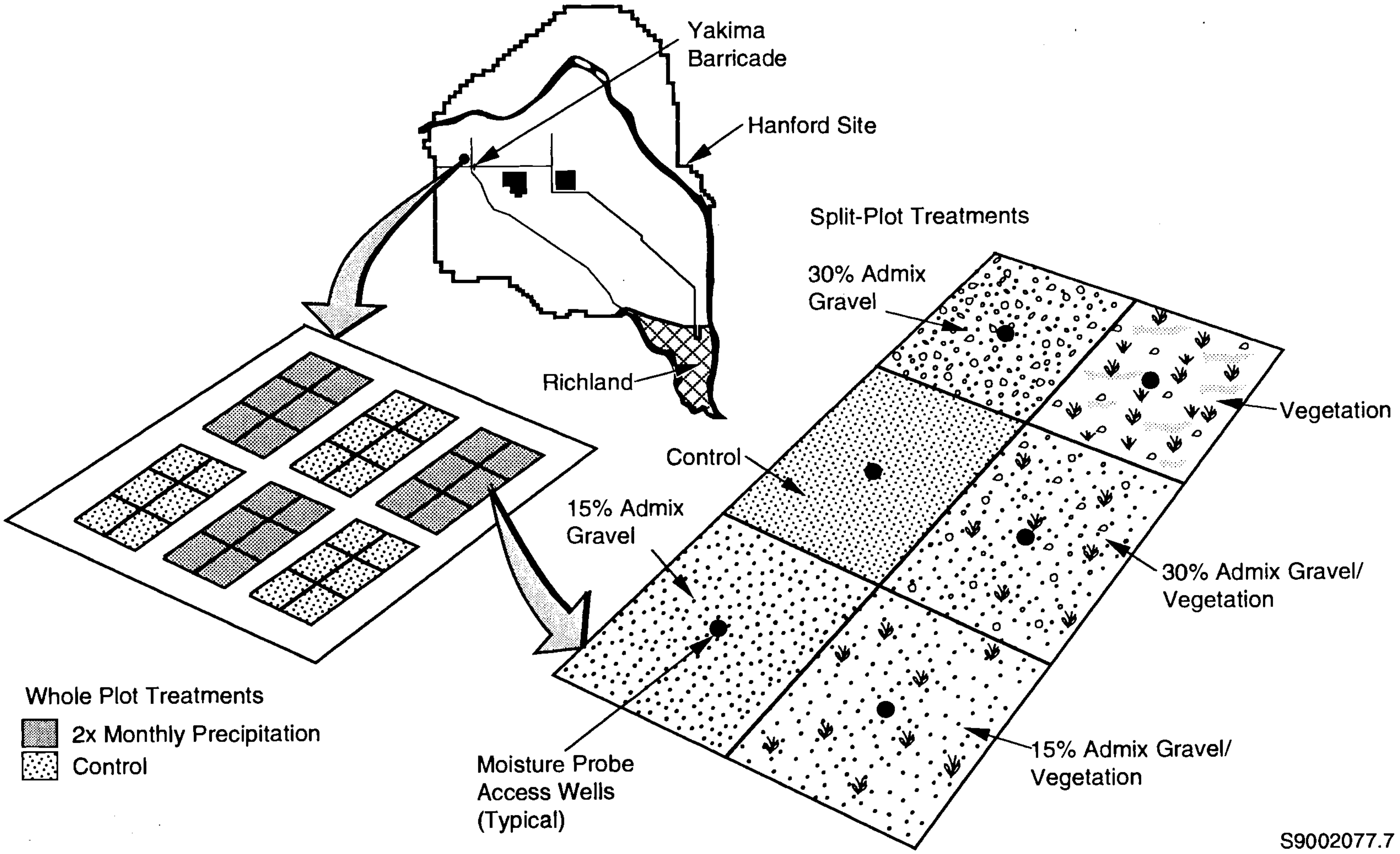


Figure B.14. Plot Design for the Gravel Admix Field Experiment at the McGee Ranch Site (after Waugh et al. 1991)

B.6 Model-Based Estimates of Recharge

B.6.1 Early Hanford Modeling

Wallace (1978) used the Morton model (Morton 1975, 1976) to produce the first estimates of actual ET at Hanford and a simple water balance model to estimate recharge. In addition to latitude and annual average atmospheric pressure, the model calls for weekly or monthly mean values of air temperature, dew point, precipitation, relative humidity, sky cover, barometric pressure, wind speed, solar radiation, and the ratio of observed to maximum possible sunshine duration. Using long-term monthly average data from the Hanford Meteorological Station, Wallace calculated the long-term average recharge rate to be 12 mm/yr. Gee (1987) observed an illogical trend in the Morton model relationship between precipitation and ET, and questioned whether the use of long-term averages was appropriate in arid or semi-arid regions where climate, and in particular precipitation, was so complex (e.g., timing, frequency, intensity).

Smoot et al. (1989) modeled the deep infiltration of meteoric water at sites covered with coarse backfill and maintained free of vegetation. Using the UNSAT-H code (Fayer and Jones 1990), daily meteorological data and soil hydraulic properties typical of coarse soils, they estimated that approximately 77 percent (131 mm/yr) of annual precipitation infiltrates below a depth of 2 meters. Order of magnitude changes in hydraulic conductivity resulted in changes in estimates of drainage of ±9 percent. This was judged to be a reasonable variability in recharge to tolerate in subsequent analyses of water flow and contaminant migration given the potential spatial variability of hydraulic conductivity in surface sediments and covers at operational facilities at Hanford.

The first numerical models of the unconfined aquifer beneath the Hanford Site assumed no surface recharge and consequently neglected the distributed surface recharge (Kipp et al. 1976; Reisenauer 1979). While these models applied boundary fluxes derived from runoff from basalt formations and recharge from the upgradient Cold Creek and Dry Creek drainages, they did not admit any recharge of the aquifer from above through the silt, sand and gravel formations.

As the Hanford Site Surveillance Program began to update their modeling of the unconfined aquifer in the mid-1980s, an estimate of the spatial distribution of recharge was incorporated (Jacobson and Freshley 1990). Figure B.15 shows the distribution of recharge applied in the calibration of their model. This recharge map was based on the known distribution of surface soils, vegetation, and climate in the mid-1980s. The spatial distribution shown represents one possible interpretation; it was not assumed to be definitive. This recharge map was used in simulations of the unconfined aquifer which were incorporated in performance assessment simulations in support of the grout-solidified low-level radioactive waste form (Kincaid et al. 1993).

B.6.2 USGS Study

Bauer and Vaccaro (1990) estimated groundwater recharge to the Columbia Plateau regional aquifer system. The unconfined aquifer beneath Hanford is part of this aquifer system which underlies portions of Idaho, Oregon and Washington. They used their deep-percolation model (Bauer and Vaccaro 1987) to estimate the spatial distribution of recharge. Their model used precipitation, temperature, streamflow, soils, land-use, and altitude information to compute transpiration, evaporation, snow accumulation, snowmelt and sublimation. Daily changes in soil moisture, plant interception, snowpack and deep percolation were computed on computational cells that ranged in size from 0.6 to 2.6 km^2. To perform the calculations and present results, the cells were aggregated into 53 zones covering the 131,000 km^2 of the Columbia Plateau aquifer system. A relatively fine scale map of recharge for zones 4 and 8 of the Bauer and Vaccaro (1990) study is shown in Figure B.16. This work indicated that the timing of precipitation events in relation to soil moisture conditions and climate are critical to recharge estimates. Unusually short but intense periods of precipitation in an arid environment will result in a much greater quantity of recharge than would occur under normal

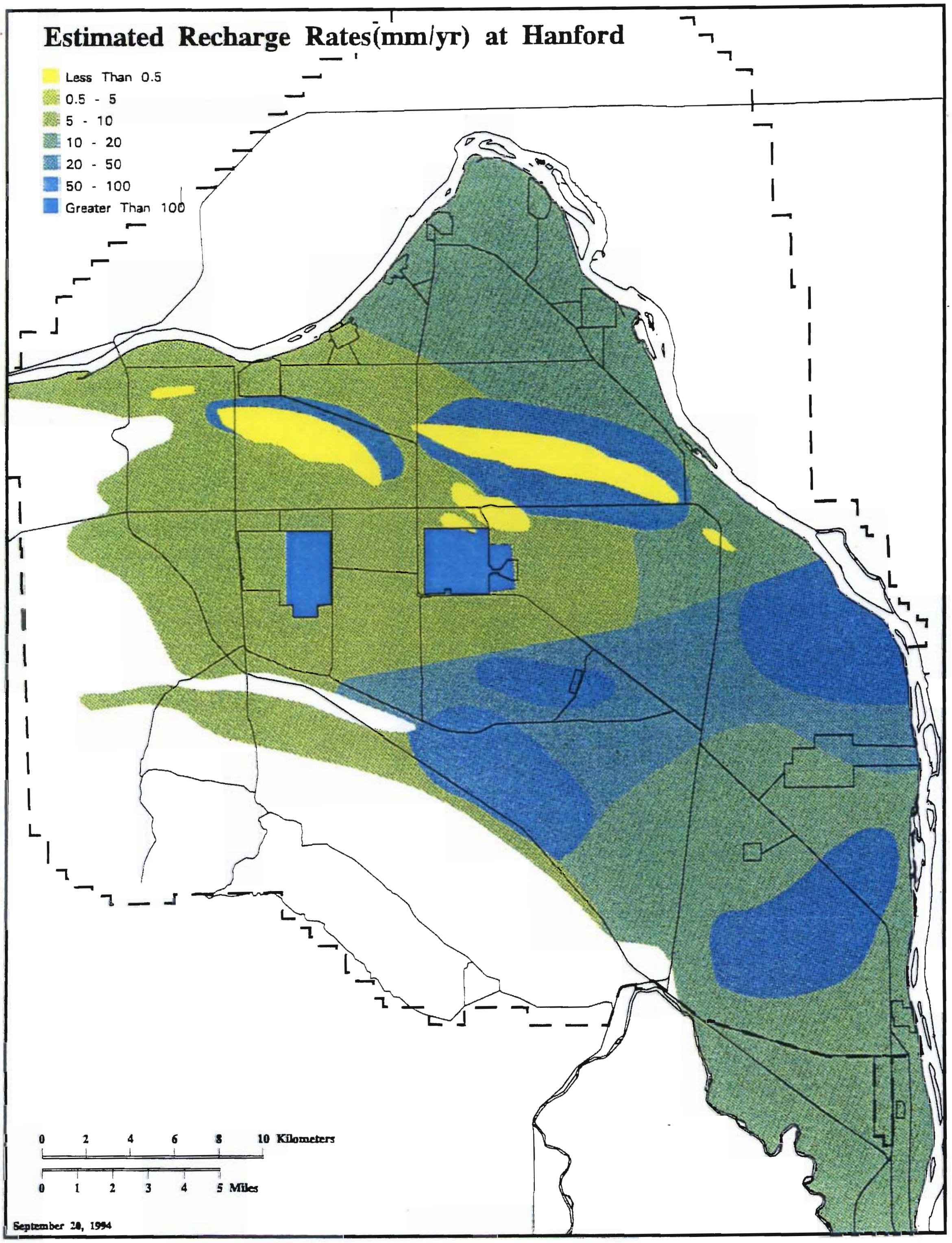


Figure B.15. Estimated Distribution of Areal Recharge to the Unconfined Aquifer (after Jacobson and Freshley 1990)

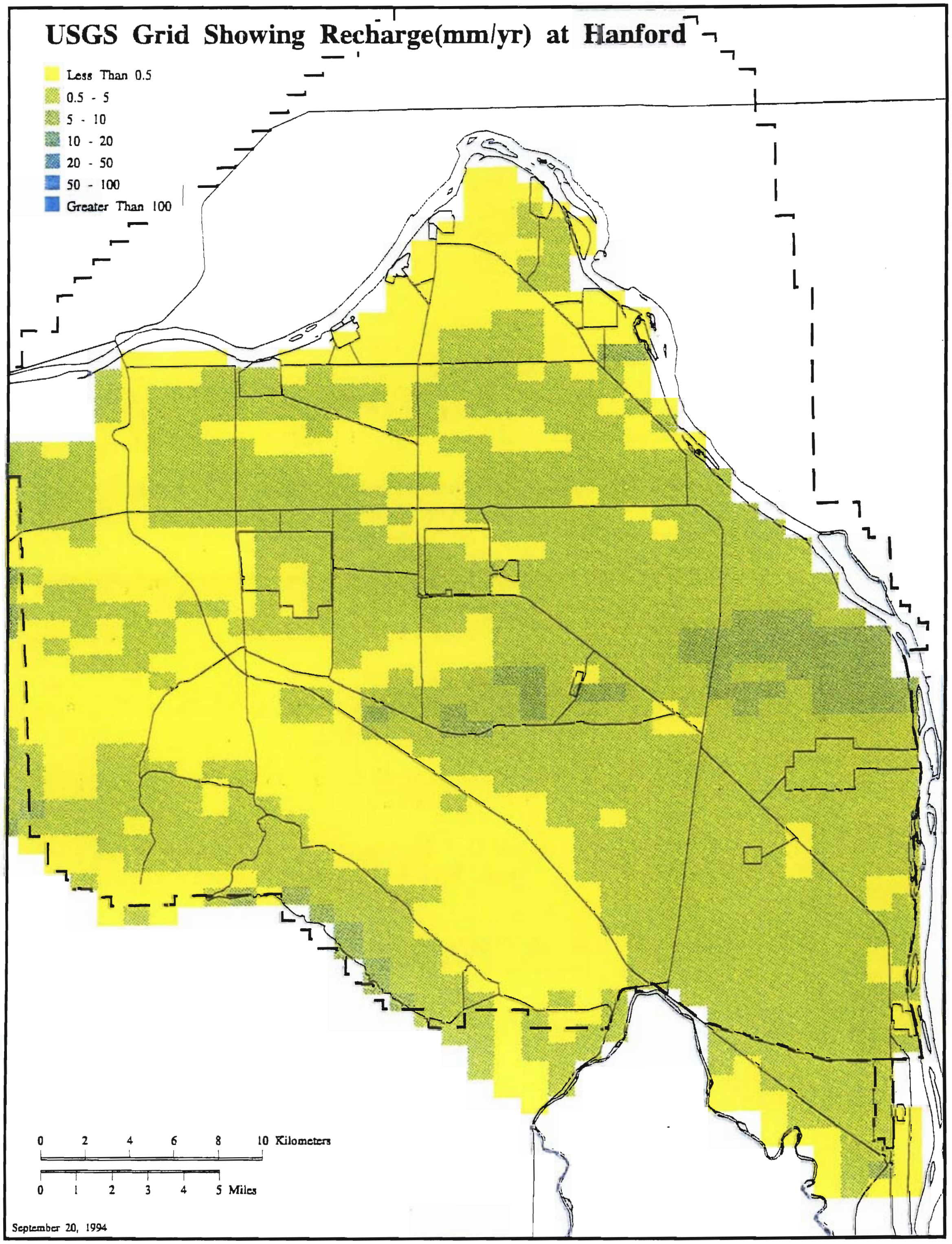


Figure B.16. USGS-Modeled Recharge for the Hanford Site (after Bauer and Vaccaro 1990) weather conditions. Thus, annual precipitation is not as meaningful in arid regions, and the timing, intensity and frequency of storm events significantly affects estimates of recharge (Gee and Hillel 1988).

B.6.3 Hanford Groundwater Surveillance Project

Figure B.17 shows the latest recharge map that has been generated for the Hanford Site (Fayer and Walters 1995). This map was generated for the Hanford Groundwater Surveillance Project to provide distributed surface recharge rates for PNL's site-wide groundwater flow model. The map was generated by combining information about land use, vegetation and soil types, data from the previously mentioned lysimeter and tracer studies, and numerical simulation results, using a GIS. This map will continue to be updated as more data are collected.

B.7 References

Andersen, L. J., and E. V. Clausen. 1988. "The Capillary-Barrier Test Field in Botterup, Denmark." In *Hydrology and Safety of Radioactive and Industrial Waste Disposal, International Symposium,* Vol. 1, pp. 1-4. Communications International Association of Hydrogeologists, Orleans, France.

Bauer, H. H., and J. J. Vaccaro. 1987. *Documentation of a Deep Percolation Model for Estimating Ground-Water Recharge.* U.S. Geological Survey Open-File Report 86-536, 180 pp., U.S. Geological Survey, Tacoma, Washington.

Bauer, H. H., and J. J. Vaccaro. 1990. *Estimates of Ground-Water Recharge to the Columbia Plateau Regional Aquifer System, Washington, Oregon, and Idaho, for Predevelopment and Current Land-Use Conditions.* Water-Resources Investigations Report 88-4108. U.S. Geological Survey, Tacoma, Washington.

Brooks, R. H., and A. T. Corey. 1964. "Hydraulic Properties of Porous Media. Colorado State University." *Hydrol. Paper No. 3,* pp. 27.

Brownell, L. E. 1971. *Soil Moisture Studies Based on Wells at 32-49 Coordinates.* ARH-1888, Atlantic Richfield Hanford Company, Richland, Washington.

Brownell, L. E., J. G. Backer, R. E. Isaacson, and D. J. Brown. 1975. *Soil Moisture Transport in Arid Site Vadose Zones, Part II.* ARH-ST-123, Atlantic Richfield Hanford Company, Richland, Washington.

Burdine, N. T. 1953. "Relative Permeability Calculations from Pore Size Distribution Data." *Petroleum Trans.*, Am. Inst. Mining Eng. 198:71-77.

Campbell, M. D., and G. W. Gee. 1990. *Field Lysimeter Test Facility: Protective Barrier Test Results (FY 1990, the Third Year).* PNL-7558, Pacific Northwest Laboratory, Richland, Washington.

Campbell, M. D., G. W. Gee, M. J. Kanyid, and M. L. Rockhold. 1990. *Field Lysimeter Test Facility: Second Year (FY1989) Test Results.* PNL-7209, Pacific Northwest Laboratory, Richland, Washington.

Carlson, D. H., and T. L. Thurow. 1991. *Workbook and Guide: 1991 Update of the Simulation of Production and Utilization of Rangelands Model.* Texas A&M University, College Station, Texas.

Cartwright, K., T. H. Larson, B. L. Herzog, T. M. Johnson, K. A. Albrecht, D. L. Moffett, D. A. Keefer, and C. J. Stohr. 1987. *A Study of Trench Covers in Minimize Infiltration at Waste Disposal Sites.* NUREG/CR-2478, Vol. 3, U.S. Nuclear Regulatory Commission, Washington, D.C.

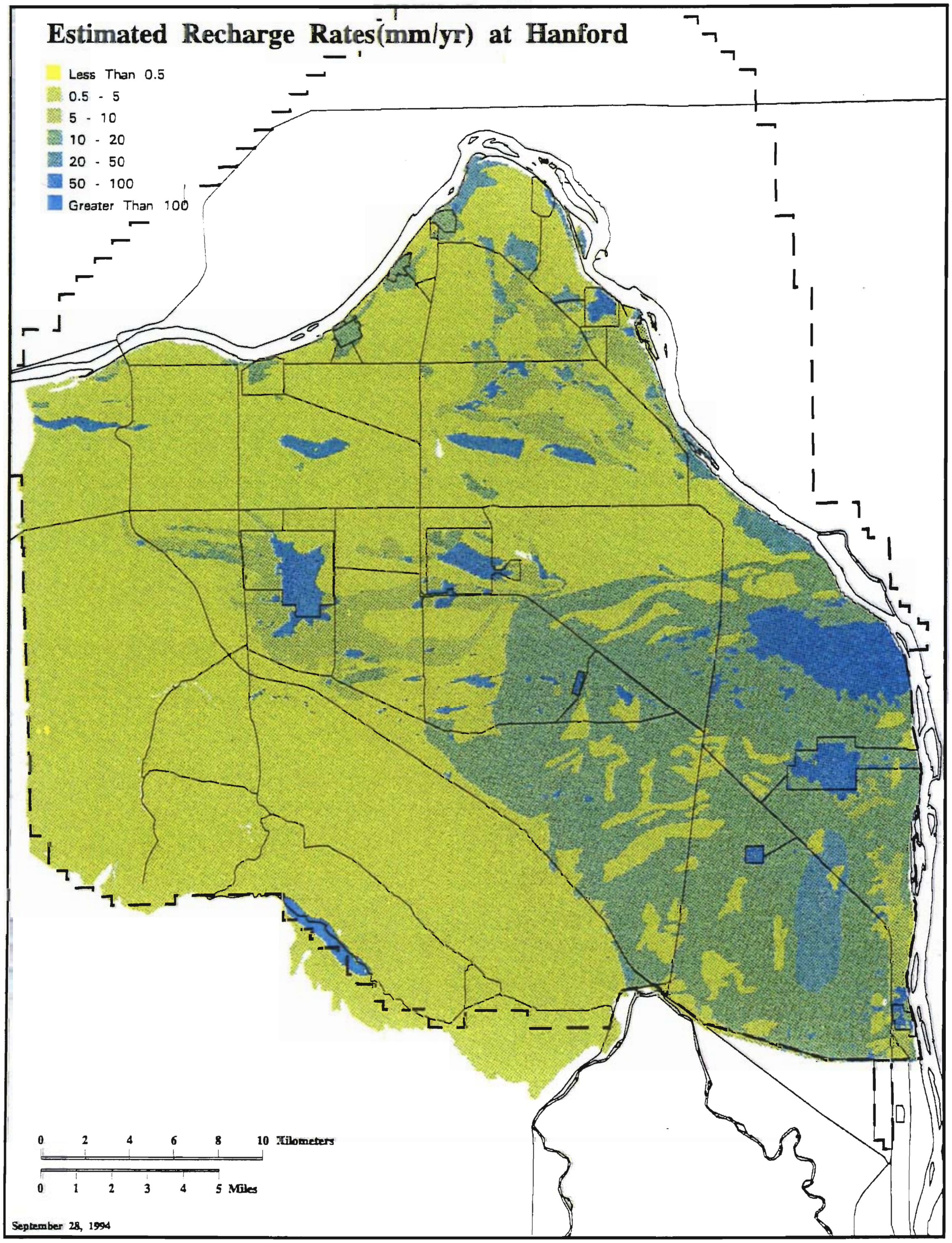


Figure B.17. Estimated Recharge Rates at Hanford Determined from an Integrated Assessment of Lysimeter Data, Tracer Studies, Soil and Plant Distributions, Land Use, and Model Simulations (from Fayer and Walters 1995)

Cass A., G. S. Campbell, and T. L. Jones. 1981. *Hydraulic and Thermal Properties of Soil Samples from the Buried Waste Test Facility.* PNL-4015, Pacific Northwest Laboratory, Richland, Washington.

Cline, J. F., K. A. Gano, and L. E. Rogers. 1980. "Loose Rock as Biobarriers in Shallow Land Burial." *Health Phys.* 39:497-504.

Doorenbos, J., and W. O. Pruitt. 1977. *Guidelines for Predicting Crop Water Requirements.* FAO Irrigation Paper No. 24, Food and Agriculture Organization of the United Nations, Rome, Italy pp. 1–107.

Enfield, C. G., and J. J. C. Hsieh. 1971. "Application of Thermocouple Psychrometers to Soil Water Transport." *Water Resour. Res.* 7:1349-1353.

Enfield, C. G., J. J. C. Hsieh, and A. W. Warrick. 1973. "Evaluation of Water Flux Above a Deep Water Table Using Thermocouple Psychrometers." *Soil Sci. Soc. Am. Proc.* 37:968-970.

EPA (U.S. Environmental Protection Agency). 1986. *Covers for Uncontrolled Hazardous Waste Sites.* EPA/540/2-85/002, U.S. Environmental Protection Agency, Cincinnati, Ohio.

EPA (U.S. Environmental Protection Agency). 1987. *Minimum Technology Guidance on Final Covers for Landfills and Surface Impoundments.* U.S. Environmental Protection Agency, Washington, D.C.

EPA (U.S. Environmental Protection Agency). 1991. *Design and Construction of RCRA/CERCLA Final Covers.* U.S. Environmental Protection Agency, Washington, D.C.

Fayer, M. J., and G. W. Gee. 1992. "Predicted Drainage at a Semiarid Site: Sensitivity to Hydraulic Property Description and Vapor Flow." In *Proceedings of the International Conference on Indirect Methods for Estimating the Hydraulic Properties of Unsaturated Soils*, eds., M. Th. van Genuchten et al., October 11-13, 1989, University of California, Riverside.

Fayer, M. J., and T. L. Jones. 1990. *UNSAT-H Version 2.0: Unsaturated Soil Water and Heat Flow Model.* PNL-6779, Pacific Northwest Laboratory, Richland, Washington.

Fayer, M. J., and T. B. Walters. 1995. *Estimated Recharge Rates at the Hanford Site.* PNL-10285, Pacific Northwest Laboratory, Richland, Washington.

Fayer, M. J., G. W. Gee, and T. L. Jones. 1986. *UNSAT-H Version 1.0: Unsaturated Flow Code Documentation and Applications for the Hanford Site.* PNL-5899, Pacific Northwest Laboratory, Richland, Washington.

Fayer, M. J., M. L. Rockhold, and M. D. Campbell. 1992. "Hydrologic Modeling of Protective Barriers: Comparison of Field Data and Simulation Results." *Soil Sci. Soc. Amer. J.* 56:690-700.

Gee, G. W. 1987. *Recharge at the Hanford Site: Status Report.* PNL-6403, Pacific Northwest Laboratory, Richland, Washington.

Gee, G. W., and P. R. Heller. 1985. *Unsaturated Water Flow at the Hanford Site: A Review of Literature and Annotated Bibliography.* PNL-5428, Pacific Northwest Laboratory, Richland, Washington.

Gee, G. W., and T. L. Jones. 1985. *Lysimeters at the Hanford Site: Present Use and Future Needs.* PNL-5578, Pacific Northwest Laboratory, Richland, Washington.

Gee, G. W., and R. R. Kirkham. 1984. *Arid Site Water Balance: Evapotranspiration Modeling and Measurements.* PNL-5177, Pacific Northwest Laboratory, Richland, Washington.

Gee, G. W., and C. S. Simmons. 1979. *Characterization of the Hanford 300 Area Burial Grounds. Task III - Fluid Transport and Modeling*. PNL-2921, Pacific Northwest Laboratory, Richland, Washington.

Gee, G. W., M. L. Rockhold, and J. L. Downs. 1989. *Status of FY 1988 Soil-Water Balance Studies on the Hanford Site*. PNL-6750, Pacific Northwest Laboratory, Richland, Washington.

Gee, G. W., M. D. Campbell, and S. O. Link. 1991. "Arid Site Water Balance Using Monolith Lysimeters," *Proceedings from the ASCE Irrigation Division Conference on Lysimeters for Evapotranspiration and Environmental Measurements (July 23-25, 1991)*, Honolulu, Hawaii, pp. 219-227.

Gee, G. W., M. J. Fayer, M. L. Rockhold, and M. D. Campbell. 1992. "Variations in Recharge at the Hanford Site." *Northwest Sci.* 66:237-250.

Gee, G. W., J. L. Downs, D. G. Felmy, M. J. Fayer, J. C. Ritter, R. R. Kirkham, M. D. Campbell, S. O. Link. 1993. *Field Lysimeter Test Facility Status Report IV: FY 1993*. PNL-8911, Pacific Northwest Laboratory, Richland, Washington.

Hajek, B. F. 1966. *Soil Survey Hanford Project in Benton County, Washington*. BNWL-243, Pacific Northwest Laboratory, Richland, Washington.

Healy, R. W. 1989. "Seepage Through a Hazardous-Waste Trench Cover." *J. Hydrol.* 108:213–234.

Hinds, W. T. 1973. "Small Lysimeters for Measurement of Water Use and Herbage Yield." *J. Range Mgmtl.* 26(4):304-306.

Hsieh, J. J. C., L. E. Brownell, and A. E. Reisenauer. 1973. *Lysimeter Experiment Description and Progress Report on Neutron Measurements*. BNWL-1711, Battelle Pacific Northwest Laboratories, Richland, Washington.

Isaacson, R. E., L. E. Brownell, and J. C. Hanson. 1974. *Soil Moisture Transport in Arid Site Vadose Zones*. ARH-2983, Atlantic Richfield Hanford Company, Richland, Washington.

Jackson, R. D., R. J. Reginato, and C. H. M. van Bavel. 1965. "Comparison of Measured and Calculated Hydraulic Conductivities of Unsaturated Soil." *Water Resour. Res.* 1:375-380.

Jacobson, E. A., and M. D. Freshley. 1990. *An Initial Inverse Calibration of the Ground-Water Flow Model for the Hanford Unconfined Aquifer*. PNL-7144, Pacific Northwest Laboratory, Richland, Washington.

Jones, T. L. 1978. *Sediment Moisture Relations: Lysimeter Project 1976-1977 Water Year.* RHO-ST-15, Rockwell Hanford Operations, Richland, Washington.

Jones, T. L. 1989. *Simulating the Water Balance of an Arid Site*. PNL-SA-17633, Pacific Northwest Laboratory, Richland, Washington, Ph.D. Dissertation, Washington State University, Pullman, Washington.

Jones, T. L., and G. W. Gee. 1984. *Assessment of Unsaturated Zone Transport for Shallow Land Burial of Radioactive Waste: Summary Report of Technology Needs, Model Verification, and Measurement Efforts (FY 78-FY 83)*. PNL-4747, Pacific Northwest Laboratory, Richland, Washington.

Jones, T. L., and R. J. Serne. 1994. *Special Waste-Form Lysimeters - Arid; 1984-1992 Data Summary and Preliminary Interpretation.* PNL-8955, Pacific Northwest Laboratory, Richland, Washington.

Jones T. L, R. J. Serne, and A. P. Toste. 1988. *Special Waste-Form Lysimeters-Arid: Three-Year Monitoring Report.* PNL-6400, Pacific Northwest Laboratory, Richland, Washington.

Kaiser Engineers Hanford. 1993. *Prototype Surface Barrier at 200-BP-1 Operable Unit.* WHC-SD-EN-TI-142, Rev. 0. Prepared by Kaiser Engineers Hanford for Westinghouse Hanford Company, Richland, Washington.

Kincaid, C. T., J. W. Shade, G. A. Whyatt, M. G. Piepho, K. Rhoads, J. A. Voogd, J. H. Westsik, Jr., M. D. Freshley, K. A. Blanchard, and B. G. Lauzon. 1993. *Performance Assessment of Grouted Double-Shell Tank Waste Disposal at Hanford.* WHC-SD-WM-EE-004, Rev. 0, Volumes 1 and 2. Westinghouse Hanford Company, Richland, Washington.

Kipp, K. L., A. E. Reisenauer, C. R. Cole, and C. A. Bryan. 1976. *Variable Thickness Transient Groundwater Flow Model Theory and Numerical Implementation.* BNWL-1703, Battelle, Pacific Northwest Laboratory, Richland, Washington.

Kirkham, R. R., G. W. Gee, and J. L. Downs. 1987. *Field Lysimeter Test Facility for Protective Barriers: Experimental Plan.* PNL-6351, Pacific Northwest Laboratory, Richland, Washington.

Kirkham, R. R., M. L. Rockhold, G. W. Gee, M. J. Fayer, M. D. Campbell, and L. J. Fritschen. 1991. "Lysimeters: Data Acquisition and Analysis." In *Proceedings of the Conference on Lysimeters for Evapotranspiration and Environmental Measurements, Honolulu, Hawaii, July 23-25, 1991*, Irrigation Division, American Society Civil Engineers, pp. 362-370.

Last, G. V., P. G. Easley, and D. J. Brown. 1976. *Soil Moisture Transport During the 1974-1975 and 1975-1976 Water Years.* ARH-ST-146, Atlantic Richfield Hanford Company, Richland, Washington.

Last, G. V., R. J. Serne, and V. L. Legore. 1995. *Field Lysimeter Studies for Performance Evaluations of Grouted Hanford Defense Wastes.* PNL-10166, Pacific Northwest Laboratory, Richland, Washington.

Link, S. O., and W. J. Waugh. 1989. *Evaporation Studies for Protective Barriers: Experimental Plans.* PNL-6899, Pacific Northwest Laboratory, Richland, Washington.

Link, S. O., G. W. Gee, M. E. Thiede, and P. A. Beedlow. 1990. "Response of a Shrub-Steppe Ecosystem to Fire: Soil Water and Vegetational Change." *Arid Soil Res. and Rehab.* 4:163-172.

Link, S. O., J. L. Downs, M. E. Thiede, D. J. Lettau, T. R. Twaddell, and R. A. Black. 1992a. *Evaporation Studies for Protective Barriers: FY 1990 Status Report.* PNL-8032, Pacific Northwest Laboratory, Richland, Washington.

Link, S. O., M. E., Thiede, J. L. Downs, D. J. Lettau, and W. J. Waugh. 1992b. *Evaporation Studies for Protective Barriers: FY 1989 Status Report.* PNL-8033, Pacific Northwest Laboratory, Richland, Washington.

Link, S. O., W. J. Waugh, J. L. Downs, M. E. Thiede, J. C. Chatters, and G. W. Gee. 1994. "Effects of Coppice Dune Topography and Vegetation on Soil Water Dynamics in a Cold-Sert Ecosystem. *J. Arid Environments* 27:265-278.

Melchoir, S., K. Beger, B. Vielhaber, and G. Miehlich. 1993. "Water Balance and Efficiency of Different Landfill Cover Systems." In *Proceedings of the International Symposium on Geology and Confinement of Toxic Wastes. Geoconfine '93,* eds M. Arnould, M. Barres, and B. Come, pp. 325–330. June 8-11, 1993, Montpelier, France.

Millington, R. J., and J. P. Quirk. 1959. "Permeability of Porous Media." *Nature* 183:387-388.

Millington, R. J., and J. P. Quirk. 1960. "Transport in Porous Media." *Int. Congr. Soil Sci. , Trans.* 7th, Madison, Wisconsin, I. 3:97-106.

Millington, R. J., and J. P. Quirk. 1961. "Permeability of Porous Solids." *Trans. Faraday Soc.* 57:1200-1206.

Morton, F. I. 1975. "Estimating Evaporation and Transpiration from Climatological Observations." *J. Appl. Meteorol.* 14(4):488-497.

Morton, F. I. 1976. "Climatological Estimates of Evapotranspiration." *ASCE, J. Hyd. Div.* 102(HY3):275-290.

Murphy, E. M., J. E. Szecsody, and S. J. Phillips. 1991. *A Study Plan for Determining Recharge Rates at the Hanford Site Using Environmental Tracers.* PNL-7626, Pacific Northwest Laboratory, Richland, Washington.

Nyhan, J. W., W. Abeele, T. Hakonson, and E. A. Lopez. 1986. *Technology Development for the Design of Waste Repositories at Arid Sites: Field Studies of Biointrusion and Capillary Barriers.* LA-10574-MS, Los Alamos National Laboratory, Los Alamos, New Mexico.

Philip, J. R., and D. A. De Vries. 1957. "Moisture Movement in Porous Materials under Temperature Gradients." *Trans. Am. Geophys. Union* 38:222-232.

Phillips, F. M., J. L. Mattick, T. A. Duval, D. Elmore, and P. W. Kubik. 1988. "Chlorine-36 and Tritium from Nuclear-Weapons Fallout as Tracers for Long-Term Liquid and Vapor Movement in Desert Soils." *Water Resour. Res.* 24:1877-1891.

Phillips, S. J., A. C. Campbell, M. D. Campbell, G. W. Gee, H. H. Hoober, and K. O. Schwarzmiller. 1979. *A Field Test Facility for Monitoring Water/Radionuclide Transport Through Partially Saturated Geologic Media: Design, Construction, and Preliminary Description.* PNL-3226, Pacific Northwest Laboratory, Richland, Washington.

Prych, E. A. 1995. *Using Chloride and Chlorine-36 as Soil-Water Tracers to Estimate Deep Percolation at Selected Locations on the U.S. Department of Energy Hanford Site, Washington.* Open-File Report 94-514, U.S. Geological Survey, Denver, Colorado.

Rancon, D. 1980. "Application of the Capillary Barrier Technique to Storage in Trenches." In *Underground Disposal of Radioactive Wastes*, Vol. 1, pp. 241-265, (French with English Summary). IAEA-SM-243/71, International Atomic Energy Agency, Vienna.

Reisenauer, A. E. 1979. *Variable Thickness Transient Ground-Water Flow Model; Volume 1 Formulation.* PNL-3160-1, Pacific Northwest Laboratory, Richland, Washington

Relyea, J. F., M. R. Sackschewsky, and W. J. Waugh. 1990. *Small-Tube Lysimeter Facility Status Report for Fiscal Year 1989.* WHC-EP-0297, Westinghouse Hanford Company, Richland, Washington.

Rockhold, M. L., M. J. Fayer, and G. W. Gee. 1988. *Characterization of Unsaturated Hydraulic Conductivity at the Hanford Site.* PNL-6488, Pacific Northwest Laboratory, Richland, Washington.

Rockhold, M. L., M. J. Fayer, G. W. Gee, and M. J. Kanyid. 1990. *Natural Groundwater Recharge and Water Balance at the Hanford Site*. PNL-7215, Pacific Northwest Laboratory, Richland, Washington.

Ross, P. J. 1990. *SWIM - A Simulation Model for Soil Water Infiltration and Movement.* CSIRO Division of Soils, Davies Laboratory, Townsville, Queensland, Australia.

Routson, R. C., and K. R. Fecht. 1979. *Soil (Sediment) Properties of Twelve Hanford Wells with Geologic Interpretation.* RHO-LD-82, Rockwell Hanford Operations, Richland, Washington.

Routson, R. C., M. R. Fuchs, and W. A. Jordan. 1988. *Recharge Estimate for the Hanford Site 200 Areas Plateau.* WHC-EP-0046, Westinghouse Hanford Company, Richland, Washington.

Sackschewsky, M. R., C. J. Kemp, L. L. Cadwell, M. E. Thiede, and W. J. Waugh. 1991. *Status Report for the Small-Tube Lysimeter Facility Fiscal Year 1990.* WHC-EP-0381, Westinghouse Hanford Company, Richland, Washington.

Sackschewsky, M. R., C. J. Kemp, and L. L. Cadwell. 1993. *Status Report for the Small-Tube Lysimeter Facility Fiscal Year 1992.* WHC-EP-0597, Westinghouse Hanford Company, Richland, Washington.

Schultz, R. K., R. W. Ridky, and E. O'Donnell. 1989. *Control of Water Infiltration into Near Surface LLW Disposal Units.* NUREG/CR-4918, Vol. 3, U.S. Nuclear Regulatory Commission, Washington, D.C.

Smoot, J. L., J. E. Szecsody, B. Sagar, G. W. Gee, and C. T. Kincaid. 1989. *Simulations of Infiltration of Meteoric Water and Contaminant Plume Movement in the Vadose Zone at Single-Shell Tank 241-T-106 at the Hanford Site.* WHC-EP-0332, Westinghouse Hanford Company, Richland, Washington.

Stone, W. A., J. M. Thorpe, O. P. Gifford, and D. J. Hoitink. 1983. *Climatological Summary for the Hanford Area.* PNL-4622, Pacific Northwest Laboratory, Richland, Washington.

Tadmor, J. 1973. "Deposition of ^{85}Kr and Tritium Released from a Nuclear Fuel Reprocessing Plant." *Health Phys.* 24:37-42.

Treat, R. L. 1985. "Hanford Grout Technology." In *Nuclear Waste Management Semiannual Progress Report, October 1984 Through March 1985*, eds., J. L. McElroy and J. A. Powell. PNL-4250-7, Pacific Northwest Laboratory, Richland, Washington.

Treat, R. L., R. O. Lokken, S. L. Stein, and C. A. Geffen. 1985. "Operational and Long-Term Performance Assessment for Hanford Grout." In *Waste Management '85, Proceedings of the Symposium on Waste Management, March 24-28, 1985*, Tucson, Arizona, pp. 497-501.

Wallace, R. W. 1978. *A Comparison of Evapotranspiration Estimates Using DOE Hanford Climatological Data.* PNL-2698, Pacific Northwest Laboratory, Richland, Washington.

Walter, M. B., M. J. Graham and G. W. Gee. 1984. *A Field Lysimeter Facility for Evaluating the Performance of Commercial Solidified Low-Level Waste.* PNL-5253, Pacific Northwest Laboratory, Richland, Washington.

Walter, M. B., R. J. Serne, T. L. Jones, and S. B. McLaurine. 1986. *Chemical Characterization, Leach, and Adsorption Studies of Solidified Low-Level Wastes.* PNL-6047, Pacific Northwest Laboratory, Richland, Washington.

Waugh, W. J. 1989. *Gravel Admix, Vegetation, and Soil Water Interactions in Protective Barriers: Experimental Design, Construction, and Initial Conditions*. PNL-6616, Pacific Northwest Laboratory, Richland, Washington.

Waugh, W. J., and S. O. Link. 1988. *Barrier Erosion Control Test Plan: Gravel Mulch, Vegetation, and Soil Water Interactions*. WHC-EP-0067, Westinghouse Hanford Company, Richland, Washington.

Waugh, W. J., M. E. Thiede, C. J. Kemp, L. L. Cadwell, and S. O. Link. 1990. *Field Study of Gravel Admix. Vegetation and Soil Water Interactions: Protective Barrier Program Status Report - FY 1989*. PNL-7440, Pacific Northwest Laboratory, Richland, Washington.

Waugh, W. J., M. E. Thiede, L. L. Cadwell, G. W. Gee, H. D. Freeman, M. R. Sackschewsky, and J. F. Relyea. 1991. "Small Lysimeters for Documenting Arid Site Water Balance." In *Proceedings of the Conference on Lysimeters for Evapotranspiration and Environmental Measurements, Honolulu, Hawaii, July 23-25*, Irrigation Division, American Society Civil Engineers, pp. 151-159.

Waugh, W. J., M. E. Thiede, D. J. Bates, L. L. Cadwell, G. W. Gee, and C. J. Kemp. 1994. "Plant Cover and Water Balance in Gravel Admixtures at an Arid Waste-Burial Site." *J. Environ. Quality*. 23:676-685.

Appendix C

Partial Listings of UNSAT-H Input Files

```
UNSAT-H V.2 Input File for 200 East Area Closed-Bottom Lysimeter Simulation.
    1    1    1    1    0    0     0         iplant,lower,ngrav,iswdif,etc.
    0  365  365    1    0    0         0.0   nprint,dayend,ndays,nyears,etc.
    1    2    0    0    0                    nsurpe,nfhour,itopbc,et_opt,icloud
    3    3    1    0    3    1               kopt,kest,ivapor,sh_opt,inmax,inhmax
       0.0  5.00e+05      0.0        0.0    hirri,hdry,htop,dhmax
   1.0e-05  0.25e+00   1.0e-12       24.0    dmaxba,delmax,delmin,stophr
      0.66     293.0      0.24        1.0    tort,tsoil,vapdif,qhtop
       0.0     293.0       0.0        0.0    tgrad,tsmean,tsamp,qhleak
       0.5       1.8   1.0e-06    1.0e-04    wtf,rfact,rainif,dhfact
   1   40                                    matn,npt
  1       0.0    1 0.1190625   1  0.238125   1  0.47625
  1    0.9525   1     1.905   1      3.81   1      7.62
  1     15.24   1     30.48   1     45.72   1     60.96
  1     76.20   1     91.44   1    106.68   1    121.92
  1    137.16   1    152.40   1    167.64   1    182.88
  1    198.12   1    213.36   1    228.60   1    243.84
  1    259.08   1    274.32   1    289.56   1    304.80
  1    320.04   1    335.28   1    350.52   1    365.76
  1    381.00   1    396.24   1    411.48   1    426.72
  1    441.96   1    457.20   1    472.44   1    487.68
Water Retention Parameters from Fayer and Gee, 1992 (Case 3)
    0.4326    0.0381    9.4004    1.2846             thet,thtl,a,n
Hydraulic Conductivity Parameters from Fayer and Gee, 1992 (Case 3)
         1    35.3      9.4004    1.2846       2.0


Plant Parameters for 1988 - 1990 (Note: BARE = 1.0)
    1    1    1    1   91  366                           leaf,nfroot,nuptak,nfpet,...
    6  1.0                                              npoint,bare
    0  0.0   91  0.0  110  0.4  227  0.4  258  0.0 ngrow,flai
  366  0.0                                              ngrow,flai
     0.217     0.0267     0.0109                        aa,b1,b2
    0    0    0    0    0    0    0    0    0    0 ntroot
    0    0    0    0    0    0    0    0    0    0
    0    0    0    0    0    0    0    0    0    0
    0    0    0    0    0    0  366  366  366  366
   7.0e+04   1.0e+03       20.0                         hw,hd,hn

Plant Parameters for 1991
    1    1    1    1   91  366                           leaf,nfroot,nuptak,nfpet,...
    6  0.2                                              npoint,bare
    0  0.0   91  0.0  110  0.4  227  0.4  258  0.0 ngrow,flai
  366  0.0                                              ngrow,flai
     0.217     0.0267     0.0109                        aa,b1,b2
    0    0    0    0    0    0    0    0    0    0 ntroot
    0    0    0    0    0    0    0    0    0    0
    0    0    0    0    0    0    0    0    0    0
    0    0    0    0    0    0  366  366  366  366
   7.0e+04   1.0e+03       20.0                         hw,hd,hn

Plant Parameters for 1992
    1    1    1    1    0  366                           leaf,nfroot,nuptak,nfpet,...
    6  0.2                                              npoint,bare
    0  0.0   60  0.0   90  0.4  227  0.4  258  0.0 ngrow,flai
  366  0.0                                              ngrow,flai
     0.217     0.0267     0.0109                        aa,b1,b2
    0    0    0    0    0    0    0    0    0    0 ntroot
    0    0    0    0    0    0    0    0    0    0
    0    0    0    0    0    0    0    0    0    0
    0    0    0    0    0    0  366  366  366  366
   7.0e+04   1.0e+03       20.0                         hw,hd,hn
```

```
UNSAT-H V.2 Input File for Sand Simulations.
    1    1    1    1    0    0    0        iplant,lower,ngrav,iswdif,etc.
    0  365  365    1    0    0          0.0  nprint,dayend,ndays,nyears,etc.
    1    2    0    0    0                   nsurpe,nfhour,itopbc,et_opt,icloud
    4    3    1    0    3    1              kopt,kest,ivapor,sh_opt,inmax,inhmax
       0.0  5.00e+05       0.0        0.0  hirri,hdry,htop,dhmax
   1.0e-05  0.25e+00   1.0e-12       24.0  dmaxba,delmax,delmin,stophr
      0.66     293.0      0.24        1.0  tort,tsoil,vapdif,qhtop
       0.0     293.0       0.0        0.0  tgrad,tsmean,tsamp,qhleak
       0.5        1.8   1.0e-06    1.0e-04  wtf,rfact,rainif,dhfact
    1   46                                 matn,npt
   1       0.0   1       0.2   1       0.4   1       0.6
   1       0.8   1       1.0   1       1.4   1       1.8
   1       2.4   1       3.0   1       4.0   1       5.5
   1       7.0   1       9.5   1      13.0   1      18.0
   1      24.0   1      32.0   1      40.0   1      50.0
   1      60.0   1      70.0   1      80.0   1      90.0
   1     100.0   1     110.0   1     125.0   1     140.0
   1     160.0   1     180.0   1     200.0   1     220.0
   1     240.0   1     260.0   1     280.0   1     300.0
   1     320.0   1     340.0   1     360.0   1     380.0
   1     400.0   1     420.0   1     440.0   1     460.0
   1     480.0   1     500.0
Sand Parameters for Data from PNL-6488, p.A.1: Water Retention
    0.4114    0.0000    0.0955    1.5833          thet,tht1,a,n
Conductivity:
         2    131.71    0.0955    1.5833       0.5


Cheatgrass Parameters: Use NFPET = 2
    0    1    1    2   60  166                      leaf,nfroot,nuptak,nfpet,...
     1.170     0.131    0.0206                     aa,b1,b2
    0    0    0    0    0    1    2    2    3    3 ntroot
    4    6    7   10   13   18   24   32   40   50
   60  366  366  366  366  366  366  366  366  366
  366  366  366  366  366  366  366  366  366  366
  366  366  366  366  366  366
   2.0e+04   1.0e+03      30.0                     hw,hd,hn
     220.0       0.5

Bunchgrass Parameters: Use NFPET = 1
    1    1    1    1   60  166                      leaf,nfroot,nuptak,nfpet,...
    6  0.5                                         npoint,bare
    0  0.0   60  0.0   90  0.4  150  0.4  166  0.0 ngrow,flai
  366  0.0                                         ngrow,flai
     0.315    0.0773    0.0755                     aa,b1,b2
    0    0    0    0    0    0    0    0    0    0 ntroot
    0    0    0    0    0    0    0    0    0    0
    0    0    0    0    0  366  366  366  366  366
  366  366  366  366  366  366  366  366  366  366
  366  366  366  366  366  366
   4.0e+04   1.0e+03      20.0                     hw,hd,hn

Sagebrush Parameters: Use NFPET = 1
    1    1    1    1    0  366                      leaf,nfroot,nuptak,nfpet,...
    6  0.8                                         npoint,bare
    0  0.0   60  0.0   90  0.4  227  0.4  258  0.0 ngrow,flai
  366  0.0                                         ngrow,flai
     0.217    0.0267    0.0109                     aa,b1,b2
    0    0    0    0    0    0    0    0    0    0 ntroot
    0    0    0    0    0    0    0    0    0    0
    0    0    0    0    0    0    0    0    0    0
    0    0    0    0    0    0  366  366  366  366
  366  366  366  366  366  366
   7.0e+04   1.0e+03      20.0                     hw,hd,hn
```

```
UNSAT-H V.2 Input File for Silt Loam with No Vegetation.
    0    1    1    1    0    0    0         iplant,lower,ngrav,iswdif,etc.
    0  365  365    1    0    0        0.0   nprint,dayend,ndays,nyears,etc.
    1    2    0    0    0                    nsurpe,nfhour,itopbc,et_opt,icloud
    4    3    1    0    3    1               kopt,kest,ivapor,sh_opt,inmax,inhmax
       0.0  5.00e+05        0.0       0.0   hirri,hdry,htop,dhmax
   1.0e-05  0.25e+00    1.0e-12      24.0   dmaxba,delmax,delmin,stophr
      0.66     293.0       0.24       1.0   tort,tsoil,vapdif,qhtop
       0.0     293.0        0.0       0.0   tgrad,tsmean,tsamp,qhleak
       0.5       1.8    1.0e-06   1.0e-04   wtf,rfact,rainif,dhfact
    1   46                                 matn,npt
   1       0.0   1       0.2   1       0.4   1       0.6
   1       0.8   1       1.0   1       1.4   1       1.8
   1       2.4   1       3.0   1       4.0   1       5.5
   1       7.0   1       9.5   1      13.0   1      18.0
   1      24.0   1      32.0   1      40.0   1      50.0
   1      60.0   1      70.0   1      80.0   1      90.0
   1     100.0   1     110.0   1     125.0   1     140.0
   1     160.0   1     180.0   1     200.0   1     220.0
   1     240.0   1     260.0   1     280.0   1     300.0
   1     320.0   1     340.0   1     360.0   1     380.0
   1     400.0   1     420.0   1     440.0   1     460.0
   1     480.0   1     500.0
Silt Loam Parameters from PNL-6488, p.4.36: Water Retention
    0.4440    0.0000    0.0110    1.7619            thet,tht1,a,n
Conductivity:
         2    4.32      0.0110    1.7619       0.5
```

```
UNSAT-H V.2 Input File for Silt Loam over Sand.
    1    1    1    1    0    0    0         iplant,lower,ngrav,iswdif,etc.
    0  365  365    1    0    0       0.0    nprint,dayend,ndays,nyears,etc.
    1    2    0    0    0                   nsurpe,nfhour,itopbc,et_opt,icloud
    4    3    1    0    3    1              kopt,kest,ivapor,sh_opt,inmax,inhmax
       0.0  5.00e+05       0.0       0.0   hirri,hdry,htop,dhmax
   1.0e-05  0.25e+00   1.0e-12      24.0   dmaxba,delmax,delmin,stophr
      0.66     293.0      0.24       1.0   tort,tsoil,vapdif,qhtop
       0.0     293.0       0.0       0.0   tgrad,tsmean,tsamp,qhleak
       0.5       1.8   1.0e-06   1.0e-04   wtf,rfact,rainif,dhfact
    2   51                                 matn,npt
   1       0.0   1       0.2   1       0.4   1       0.6
   1       0.8   1       1.0   1       1.4   1       1.8
   1       2.4   1       3.0   1       4.0   1       5.5
   1       7.0   1       9.5   1      13.0   1      18.0
   1      21.0   1      24.0   1      27.0   1      29.0
   2      31.0   2      33.0   2      37.0   2      43.0
   2      50.0   2      60.0   2      70.0   2      80.0
   2      90.0   2     100.0   2     110.0   2     125.0
   2     140.0   2     160.0   2     180.0   2     200.0
   2     220.0   2     240.0   2     260.0   2     280.0
   2     300.0   2     320.0   2     340.0   2     360.0
   2     380.0   2     400.0   2     420.0   2     440.0
   2     460.0   2     480.0   2     500.0
Silt Loam Parameters from PNL-6488, p.4.36; Water Retention
    0.4440    0.0000    0.0110    1.7619
Conductivity
         2    4.32      0.0110    1.7619       0.5
Sand Parameters for Data from PNL-6488, p.A.1: Water Retention
    0.4114    0.0000    0.0955    1.5833                thet,thtl,a,n
Conductivity:
         2    131.71    0.0955    1.5833       0.5


Cheatgrass Parameters: Use NFPET = 2
    0    1    1    2   60  166                      leaf,nfroot,nuptak,nfpet,...
     1.170     0.131    0.0206                     aa,b1,b2
    0    0    0    0    0    1    2    2    3    3 ntroot
    4    6    7   10   15   20   25   30   35   40
   45   50   53   56   58   60  366  366  366  366
  366  366  366  366  366  366  366  366  366  366
  366  366  366  366  366  366  366  366  366  366
  366
   2.0e+04   1.0e+03      30.0                     hw,hd,hn
   2.0e+04   1.0e+03      30.0
     220.0       0.5

Bunchgrass Parameters: Use NFPET = 1
    1    1    1    1   60  166                      leaf,nfroot,nuptak,nfpet,...
    6  0.5                                         npoint,bare
    0  0.0   60  0.0   90  0.4  150  0.4  166  0.0 ngrow,flai
  366  0.0                                         ngrow,flai
     0.315    0.0773    0.0755                     aa,b1,b2
    0    0    0    0    0    0    0    0    0    0 ntroot
    0    0    0    0    0    0    0    0    0    0
    0    0    0    0    0  366  366  366  366  366
  366  366  366  366  366  366  366  366  366  366
  366  366  366  366  366  366
   4.0e+04   1.0e+03      20.0                     hw,hd,hn

Sagebrush Prameters: Use NFPET = 1
    1    1    1    1    0  366                      leaf,nfroot,nuptak,nfpet,...
    6  0.8                                         npoint,bare
    0  0.0   60  0.0   90  0.4  227  0.4  258  0.0 ngrow,flai
  366  0.0                                         ngrow,flai
     0.217    0.0267    0.0109                     aa,b1,b2
    0    0    0    0    0    0    0    0    0    0 ntroot
    0    0    0    0    0    0    0    0    0    0
    0    0    0    0    0    0    0    0    0    0
    0    0    0    0    0    0  366  366  366  366
  366  366  366  366  366  366
   7.0e+04   1.0e+03      20.0                     hw,hd,hn
```

Distribution

No. of
Copies

OFFSITE

12 DOE/Office of Scientific and
Technical Information

B. J. Andraski
U.S. Geological Survey
333 W. Nye Lane
Carson City, NV 89706

M. Ankeny
D. B. Stephens & Associates
6020 Academy
NE Suite 100
Albuquerque, NM 87109

B. Blake
133 1st Avenue North
Minneapolis, MN 55401

R. Buck, Jr.
Wanapum Indian Band
P.O. Box 878
Ephrata, WA 98823

R. A. Danielson
Washington State Department of
Health
2 South 45th Ave.
Yakima, WA 98908

B. Drost
U.S. Geological Survey
1201 Pacific Avenue, Suite 600
Tacoma, WA 98402

3 Washington State Department of
Health
Division of Radiation Protection
Airdustrial Center
Building 5, M.S. L-13
Olympia, WA 98503
Attn: J. Erickson (2)
M. M. Dunkleman

2 Department of Geosciences
New Mexico Institute of Mining
and Technology
Socorro, NM 87801
Attn: J. Hendrickx
F. Philips

No. of
Copies

S. Harris
Environmental Restoration/
Waste Management
Nez Perce Tribe
P.O. Box 365
Lapwai, ID 83540-0365

R. Hills
New Mexico State University
Mechanical Engineering
Las Cruces, NM 88003

R. Jim
Yakama Indian Nation
Environmental Restoration/Waste
Management
P.O. Box 151
Toppenish, WA 98948

T. L. Jones
New Mexico State University
Soils Department
Las Cruces, NM 88003

W. E. Kennedy
Rt. 2, Box 2519
Benton City, WA 99320

4 Washington State Department of
Ecology
P.O. Box 1386
Richland, WA 99352
Attn: D. Lundstrom (3)
N. H. Uziemblo

R. J. Luxmoore
Oak Ridge National Laboratory
P.O. Box 2008
Oak Ridge, TN 37831

R. Patt
Oregon State Department of
Water Resources
3850 Portland Road
Salem, OR 97310

D. Prudic
U.S. Geological Society
333 W. Nye Lane
Carson City, NV 89706

No. of
Copies

B. Scanlon
The University of Texas at Austin
Bureau of Economic Geology
Austin, TX 78713-7508

E. Springer
Los Alamos National Laboratory
P.O. Box 1663
Los Alamos, NM 87545

M. J. Sully
Reynolds Electrical Engineering Co.,
Inc.
2626 Losee Rd., MS 966
Las Vegas, NV 89030

S. W. Tyler
Desert Research Institute
Daudini Blvd.
Reno, NV 89506

M. Th. van Genuchten
U.S. Salinity Laboratory
U.S. Department of Agriculture, ARS
4500 Glenwood Drive
Riverside, CA 92501

P. J. Wierenga
University of Arizona
Dept of Soil and Water
429 Shartz Bldg.
Tucson, AZ 85721

J. R. Wilkerson
Environmental Planning/
Rights Protection
Confederated Tribes of the
Umatilla Indian Reservation
P.O. Box 638
Pendleton, OR 97801

5 U.S. Geological Survey
1201 Pacific Ave., Suite 600
Tacoma, WA 98402
Attn: H. H. Bauer
W. R. Bidlake
E. A. Prych
W. Staubitz
J. J. Vaccaro

No. of
Copies

ONSITE

20 **DOE Richland Operations Office**

G. M. Bell	A5-52
R. F. Brich	H4-83
N. R. Brown	S7-53
S. T. Burnum	S7-53
B. L. Foley	H4-83
M. J. Furman	R3-81
J. D. Goodenough	H4-83
J. B. Hall	A5-55
J. P. Hanson	K8-50
R. D. Hildebrand	A5-55
R. G. Holt	A5-15
R. A. Holten	H4-83
L. A. Huffman	S7-53
R. G. McLeod	H4-83
D. Olson	H4-83
P. M. Pak	H4-83
J. C. Peschong	S7-53
R. K. Stewart	H4-83
K. M. Thompson	H4-83
D. Wanek	H4-83

12 **Bechtel Hanford, Inc.**

M. P. Connelly	H6-04
K. R. Fecht	H4-80
B. H. Ford	H4-80
G. L. Kasza	H6-04
A. J. Knepp	H4-80
M. J. Lauterbach	H6-01
W. J. McMahon	H6-04
K. R. Simpson	H6-07
L. C. Swanson	H6-03
S. J. Trent	H4-80
D. C. Weekes	H4-82
S. R. Weil	H4-80

2 **CH2M-Hill**

R. L. Jackson	H6-04
R. E. Peterson	H6-05

2 **U.S. Army Corps of Engineers**

W. L. Greenwald	A5-20
W. D. Perro	A5-19

No. of Copies		
4	**U.S. Environmental Protection Agency**	
	P. R. Beaver	B5-01
	L. E. Gadbois	B5-01
	P. S. Innis	B5-01
	D. R. Sherwood	B5-01
20	**Westinghouse Hanford Company**	
	D. B. Barnett	H6-06
	K. C. Burgard	G6-13
	L. B. Collard	H6-30
	C. R. Eiholzer	H0-36
	J. G. Field	H6-30
	E. A. Fredenburg	S4-53
	R. L. Gibby	H5-27
	M. J. Hartman	H6-06
	V. G. Johnson	H6-06
	R. Khaleel	H0-36
	A. H. Lu	H0-36
	F. M. Mann	H0-36
	R. J. Murkowski	G6-13
	S. P. Reidel	H6-06
	J. S. Schmid	H6-06
	F. A. Schmittroth	H0-35
	A. M. Tallman	H5-57
	J. A. Voogd	G6-13
	G. F. Williamson	G6-13
	Public Reading Room	H2-53
55	**Pacific Northwest Laboratory**	
	M. P. Bergeron	K9-33
	M. A. Chamness	K9-48
	J. M. Creer	K9-80
	J. L. Downs	K6-63
	P. E. Dresel	K6-96
	G. W. Gee (5)	K9-33
	M. J. Fayer (5)	K9-33
	C. J. Freeman	P7-41
	M. D. Freshley	K9-36
	J. H. Holbrook	K9-81
	K. A. Hoover	K9-33
	P. R. Hrma	P8-37
	B. M. Johnson	K9-70
	C. T. Kincaid	K9-33
	R. R. Kirkham	K9-33
	D. E. Larson	K9-80
	S. P. Luttrell	K6-96
	B. P. McGrail	K2-38
	P. D. Meyer	K9-36
	E. M. Murphy	K3-61
	M. L. Rockhold (10)	K9-33
	P. Sliva	P8-44
	P. A. Smith	P7-14
	J. L. Smoot	K9-36
	G. P. Streile	K9-33
	J. E. Szecsody	K9-36
	T. B. Walters	K6-96
	A. L. Ward	K9-33
	J. H. Westsik, Jr.	K9-80
	G. A. Whyatt	P7-19
	S. K. Wurstner	K9-36
	Publishing Coordination	K1-06
	Technical Report Files (5)	
Routing		
	R. W. Bryce	K9-34
	R. M. Ecker	SE-UI
	M. J. Graham	K9-38
	S. A. Rawson	K9-34
	R. L. Skaggs	K9-34
	P. C. Hays (last)	K9-41