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Variations in Recharge at the Hanford Site

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Abstract

Recharge from meteoric sources (rain and snowmelt) is an important hydrologic variable. A knowledge of recharge rates is needed in the assessment of potential groundwater contamination problems at the U.S. Department of Energy's Hanford Site, near Richland, Washington. Lysimeter data, collected at a number of locations at Hanford over a period of 20 yrs, indicate that recharge rates vary widely, ranging from more than 100 mm/yr to rates near zero (i.e., no measurable drainage). This wide range in recharge is attributed to variations in precipitation, vegetative cover, and surface soil-type. Coarse-textured soils without plants yield the most recharge, fine-textured soils with or without plants yield the least. Deep-rooted plants, such as sagebrush, are generally successful in limiting recharge on all soils at Hanford to near-zero amounts, but shallow-rooted plants such as cheatgrass appear unable to prevent recharge. Drainage (i.e., recharge) from a cheatgrass-covered lysimeter, backfilled with sandy soil, averaged 62 mm/yr (35% of the annual precipitation) during a 3-yr test (1984 to 1986).

The time required for contaminants to travel through the thick unsaturated zone at Hanford is estimated to range from thousands of years, for recharge rates below 1 mm/yr, to tens of years, for recharge rates above 50 mm/yr. The implications of these findings to environmental cleanup and management at Hanford are significant. Present practices that replace surface soils with coarse sands and gravels and prevent or limit vegetative growth are inducing significant recharge that may contribute to contaminant migration. Remediation, such as covering waste sites with a silt-loam soil layer, may be required to limit recharge to negligible amounts, thus ensuring long-term protection of groundwater.

Introduction

Isolation of radioactive wastes in dry sediments high above the water table (i.e., in the vadose zone), has been considered a viable disposal option for Hanford's defense wastes (USDOE 1987). Public acceptance of an in-place disposal option depends, in part, on clearly demonstrating that the wastes will remain hydrologically isolated for thousands of years because some waste components (e.g., technetium, iodine) have very long half-lives. To be hydrologically isolated, the waste zone must be located where meteoric water does not penetrate below the plant root zone and travel to the water table. Such water is termed recharge and serves as a mechanism for transporting soluble contaminants to the groundwater.

Just how much water from meteoric sources penetrates below the plant root zone? This question has been asked repeatedly over the past 47 years. A committee of the National Research Council (National Academy of Sciences) was formed in 1955 to address issues related to disposing of radioactive wastes in the ground. The committee reviewed the scientific basis for waste disposal activities at Hanford and other arid sites and expressed concerns about the assumption that all precipitation was returned to the atmosphere (via evaporation) and none percolated downward to the water table at such sites. In 1966, this committee reiterated its earlier concerns by stating, "the Council is dubious about the concept that in arid and semiarid lands meteoric water does not percolate downward as far as the water table but instead is lost entirely by evaporation and plant transpiration" (NAS 1966). The committee recommended that vadose zone water movement should be thoroughly studied, particularly with reference to questions about percolation of rain and snowmelt to the water table.

In 1985, a panel of university and government experts on hydrology reviewed the recharge question at Hanford (Gee 1987). They shared the concerns expressed previously by the National Academy of Sciences and stated further: "Notwithstanding the general aridity of the climate at the Hanford Site and the absence of deep percolation in 'normal years', it is entirely possible that some recharge of groundwater may indeed occur following episodes of high precipitation. Such occurrences are particularly likely under topographic depressions where surface water might accumulate, in places underlain by very coarse and highly permeable deposits, and when the land is denuded of vegetation (as by fire, by overgrazing, or by mechanical clearing)."

In a recent paper, Routson and Johnson (1990) concluded that recharge on the Hanford Site 200 Areas Plateau (where most of the nuclear wastes are stored) is negligibly small (0 ± 2 mm/yr). The basis for this conclusion rests mainly on water storage data obtained from one location. At other

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locations on the 200 Areas Plateau and elsewhere on the Hanford Site there is mounting evidence that recharge can be large (exceeding 100 mm/yr) under certain circumstances (Gee 1987, Gee *et al.* 1989a, Rockhold *et al.* 1990, Waugh *et al.* 1991).

In this paper, we address the reasons why recharge is so highly variable at Hanford, review the recharge studies published to date, then use recharge estimates to predict the time expected for mobile contaminants to travel through the vadose zone to the underlying water table. We conclude by discussing the implications of recharge variation on waste management practices.

General Considerations

Recharge is controlled by three major factors: climate, soil and vegetation. The assessment of recharge at waste sites at Hanford requires an understanding of the interaction of the three major factors, both under natural site conditions and under conditions that have been disturbed or modified by site operations. Topographical relief can also affect recharge, but most waste processing sites at Hanford are located on nearly flat terrain, and runoff (or runon) is infrequent, thus topography is considered of secondary importance.

Climate

At the Hanford Site the 79-yr-average precipitation is 162 mm/yr. Winters are cool and wet with summers hot and dry (Stone *et al.* 1983). Changes in total precipitation as well as seasonal distribution significantly affect recharge. Since 1970, annual precipitation has varied widely, ranging from 76 mm in 1976 to 281 mm in 1983. In spite of these variations, the 20-yr average of 168 mm is just slightly more than the 79-yr average. Periods exceeding 65 days without rain have been recorded twice in the last 4 yrs (1988 and 1991), while storm events such as thundershowers (with intensities greater than 11 mm in 10 min) have also been recorded in the recent past (1991).

Under Hanford climate, most of the water available for recharge comes in the winter months, during periods of low evaporation. In addition to winter rains, snowmelt can be an important contributor to recharge at Hanford. Rapid snowmelt has been observed to cause high rates of water infiltration into soils resulting in significant drainage (recharge). For example, in February 1985, a warm "chinook" wind, gusting to 72 km/hr, melted most of a 200 mm (approx. 8 in.) snow pack in less than one day, causing significant runoff in some locations and infiltration in others (Gee and Hillel 1988).

Soils

Surface soils on the 200 Areas Plateau at Hanford are predominantly coarse-textured alluvial sands, covered by a variably thick mantle of wind-deposited fine sands (Hajek 1966), and are associated with the Quincy soil series (mixed, mesic Xeric Torripsamments). These surface soils have high infiltration capacities, thus rains infiltrate readily with little or no surface runoff. Subsurface sediments are well-drained coarse sands and gravels of glacial-fluvial (flood) origin (classed informally as the Hanford formation). These sediments overlay compacted silts and clays of the Ringold Formation (Tallman *et al.* 1979). On the 200 Areas Plateau (Figure 1) the water table (located near the top of the Ringold Formation) is as much as 100 m below the land surface (USDOE 1987).

Vegetation

Vegetation consists of shrub-steppe plant communities composed of winter and summer annual grasses and perennial grasses and shrubs (Rickard and Vaughan 1988). This desert vegetation, because of its mixture of shallow and deep-rooted plants, is generally very efficient in utilizing soil water. 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). While winter annuals are efficient in competing for water stored near the soil surface, they cannot access water below their shallow roots. Lack of water coupled with increased temperature cause these grasses to produce seed and die in late spring. A mantle of dead biomass (leaves, stems, etc.) from these grasses persists as ground cover during summer and fall and contributes to frequent and extensive wildfires at Hanford (Rickard and Vaughan 1988).

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* Tausch) and bursage (*Ambrosia acanthicarpa* L.) are common to the site and have extensive root systems (Klepper *et al.* 1985). The perennial shrubs and summer annuals suffer summer water stress but generally survive during the summer months, utilizing both summer rains and water stored at depth in the soil profile from winter precipitation.

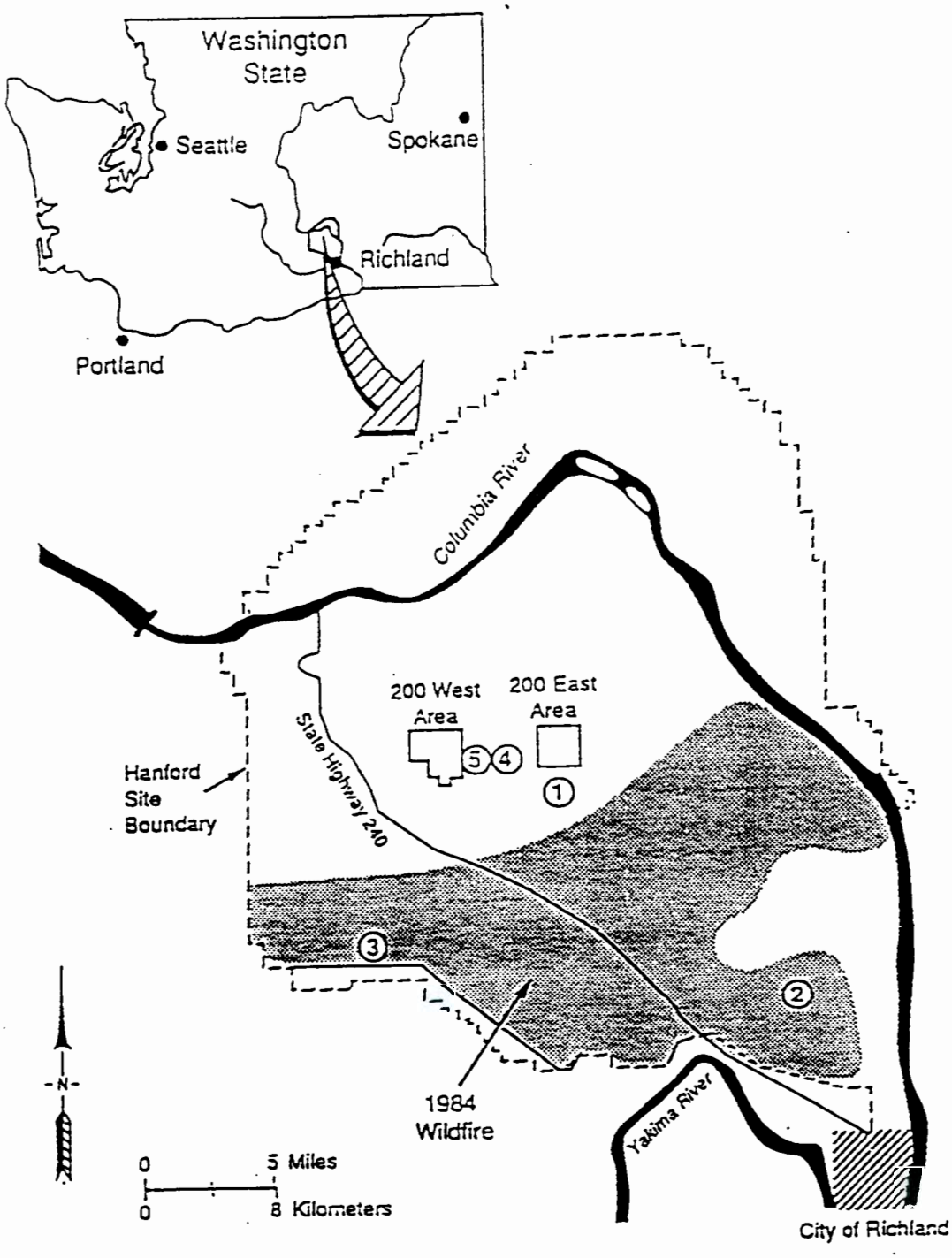

Figure 1. Hanford Site map. Numbered circles represent lysimeter locations. Shaded area represents extent of August 1984 wildfire.

Climate/Vegetation Interactions

Vegetation changes in response to climate at Hanford are relatively common. Over the years there have been periods of drought and periods of excess winter precipitation which have affected species composition. In addition, there have been numerous wildfires which have dramatically altered plant communities at Hanford (Rickard and Vaughan 1988). For example, as shown in Figure 1, a wildfire in 1984 swept over Rattlesnake Mountain and eastward to the Columbia River, burning more than 518 km^2 (over one-third of the entire Hanford Site) (Price *et al.* 1986). Sagebrush does not resprout after fires, so for the past 8 yrs a significant part of the burned area has remained shrubless, covered primarily with cheatgrass. In the burned area it is expected that recharge potential has increased, since water stored at depth from winter rains has likely drained below the root zone of the shallow-rooted grasses.

Surface Disturbances

Site operations have had a significant impact on recharge through changing the surface soil and vegetative conditions at specific waste sites. As an example, since 1947, many large storage tanks (ranging in size from 55 thousand- to 1 million-gallon capacity) have been buried in the 200 Areas at locations called "tank farms" (USGAO 1989). During excavation of the tank farms, both vegetation and surface soil were removed. Backfill, which now covers the tanks to a depth of about 2.5 m, consists of very coarse sands and gravels (Smoot *et al.* 1990). The coarse-textured surface combined with an absence of vegetation (via herbicide application) optimizes conditions for recharge.

At other locations in the 200 Areas, where liquid and solid wastes have been buried, the surfaces often have been covered with soil and revegetated, primarily with a variety of grasses (Fuchs and Cox 1983). There are no detailed studies of soil type or plant rooting depth at these waste sites, so it is difficult to estimate recharge conditions at these sites. However, the transplanted grasses at these sites have, in general, shallower roots than the original cover (shrubs, etc.), thus we would expect the recharge potential to have increased.

Recharge Methodology

The wide range of changing surface conditions has given rise to a wide range of recharge that is only now being documented. Quantification of recharge can only be indirect since the deep water table and lack of surface water (streams, etc.) preclude direct measurements. Tracer techniques and lysimeters are two approaches that have been used to estimate recharge conditions on the 200 Areas Plateau and elsewhere at the Hanford Site.

Initial Studies

There were several research studies initiated at the Hanford Site in the late 1960s and early 1970s designed to address the question of natural (meteoric) recharge in the 200 Areas. One of the studies measured bomb-pulse tritium distributions in the soil. Another study focused on water balance measurements in lysimeters.

Tritium Profiles

From 1953 to 1969, significant quantities of tritium were released to the environment during atmospheric testing of thermonuclear weapons (i.e., hydrogen bombs). Tritium removed from the atmosphere during precipitation events was deposited on the land surface in pulses in the 1950s and 1960s. The downward migration of these tritium pulses should indicate the depth of penetration of recent recharge. Based on consistently elevated levels of tritium found in near-surface sediments (Brownell 1971), there is an indication that meteoric water moved to depths of about 5 m during a 16-year period. However, the tritium fallout study was marred by nonreplicated sampling, possible cross-contamination, and poor vertical resolution.

Lysimeter Studies

Lysimeters are simply soil-filled containers of various sizes and configurations which can be used to measure water (and solute) flow through soil. Lysimeters, as used under field conditions, are generally set vertically in the ground with the top open and flush with the surrounding soil surface. The lysimeter soil responds to the precipitation incident on it and the water balance (i.e., precipitation balanced against evapotranspiration, water storage, and drainage) reflects the surface conditions of the lysimeter. Under appropriate circumstances lysimeter data can be useful in estimating recharge (Gee and Jones 1985). Generally, the larger (and deeper) the lysimeter, and the more similar the lysimeter surface soil and vegetation are to the surroundings, the better the estimate of recharge.

The first study of recharge using lysimeters was conducted at the Hanford Site in 1971 (Hsieh *et al.* 1973). Two 18-m-deep lysimeters, one closed at the bottom, the other open, were installed on the 200 Areas Plateau in a location that is about 2 km directly south of the 200-East Area (Figures 1 and 2). To our knowledge these are the deepest lysimeters in the world. As indicated by Brownell *et al.* (1975), "the general plan of the lysimeter experiment was to use the closed-bottom lysimeter as a container to collect water, if it does indeed tend to percolate to the water table on the 200 Areas Plateau of the Hanford site." Measurements of water content in the closed-bottom lysimeter could then be interpreted as an indication of the presence or absence of recharge. Increased water content in the bottom of the lysimeter would result only if water had percolated to the bottom over the period of the study. Stable or decreasing water contents would indicate lack of recharge.

The lysimeters were filled with sediment which had been excavated from the site and thoroughly mixed using a road construction batch-plant located nearby (Hsieh *et al.* 1973). Gee (1987) reported that the sediment in the closed-bottom lysimeter had a sand texture (87% sand, 10% silt and 3% clay). This is very similar to the texture of core sediments taken from four wells adjacent to the lysimeters (Routson and Johnson 1990). Downwell access tubing was installed for monitoring water content profiles using fast-neutron-moderation techniques. Monitoring of the lysimeters was initiated in early 1972 and continued on a routine basis for a period of about 7 yrs (Brownell *et al.* 1975, Last *et al.* 1976, Jones 1978).

Detailed records of vegetation were not kept for these lysimeters. Routson and Johnson (1990) suggest that the lysimeter surfaces were relatively free of vegetation from 1972 through 1980. However, Gee and Heller (1985) show photographs of the lysimeters taken in 1974 and 1978 with vegetation (presumably tumbleweed) growing on the lysimeter surfaces. We assume from photographic records and periodic visits that some vegetation was present on the lysimeters during much of their history.

Interpretation of the neutron logs by several researchers (Brownell *et al.* 1975, Last *et al.* 1976 and Jones 1978) suggested that if meteoric water was moving deep into the closed-bottom lysimeter, it was doing so very slowly. Below the 5-m depth the water content stayed relatively constant at about 0.06 cm^3/cm^3. Jones (1978) suggested that the constant water content implied a unit hydraulic gradient (i.e., gravity drainage) condition. Jones used the data of Hsieh *et al.* (1973) and calculated the unsaturated hydraulic conductivity at a water content of 0.06 cm^3/cm^3, which he used to estimate a steady-state recharge rate of approximately 5 mm/yr.

Subsequent Studies

Since the 1970s, studies of recharge have continued. Model development and use of additional lysimeter facilities have increased our understanding of recharge processes at Hanford. Figure 1 shows the location of the additional lysimeter studies. Both modeling and lysimeter studies have been used to document recharge under a range of soil and vegetative conditions, including the conditions at the 200-East Lysimeter site.

Modeling of the Closed-Bottom 200-East Lysimeter

To determine the role of vegetation in controlling water balance, Fayer *et al.* (1986) used the UNSAT-H computer code to model the 200-East closed-bottom lysimeter. The UNSAT-H code embodies a finite-difference model that solves transient, unsaturated water flow problems. With the UNSAT-H code, they simulated the daily water balance of the closed-bottom lysimeter, with and without vegetation, for the 14-yr period from January 1972 to December 1985. Inputs to the model were daily historical weather variables (precipitation, solar radiation, maximum and minimum air temperature, relative humidity, wind speed), soil hydraulic properties, and a plant algorithm that accounted for uptake of water by vegetation. Plant-cover estimates ranged from 0% in 1972 and 1973 to a maximum of 30% in 1978 (based on photographic evidence). Seasonal growth was simulated by initiating water uptake in late spring and summer, and allowing the plant to extend roots to a depth of 3 m over the course of each summer.

Figure 3 shows the simulation results reported by Fayer *et al.* (1986). Simulated water storage increased 175 mm when no plants were present and decreased 28 mm when plants were present. The simulated water storage with plants is in reasonable agreement with the value calculated from the core data obtained in October 1985 and reported by Routson *et al.* (1988).

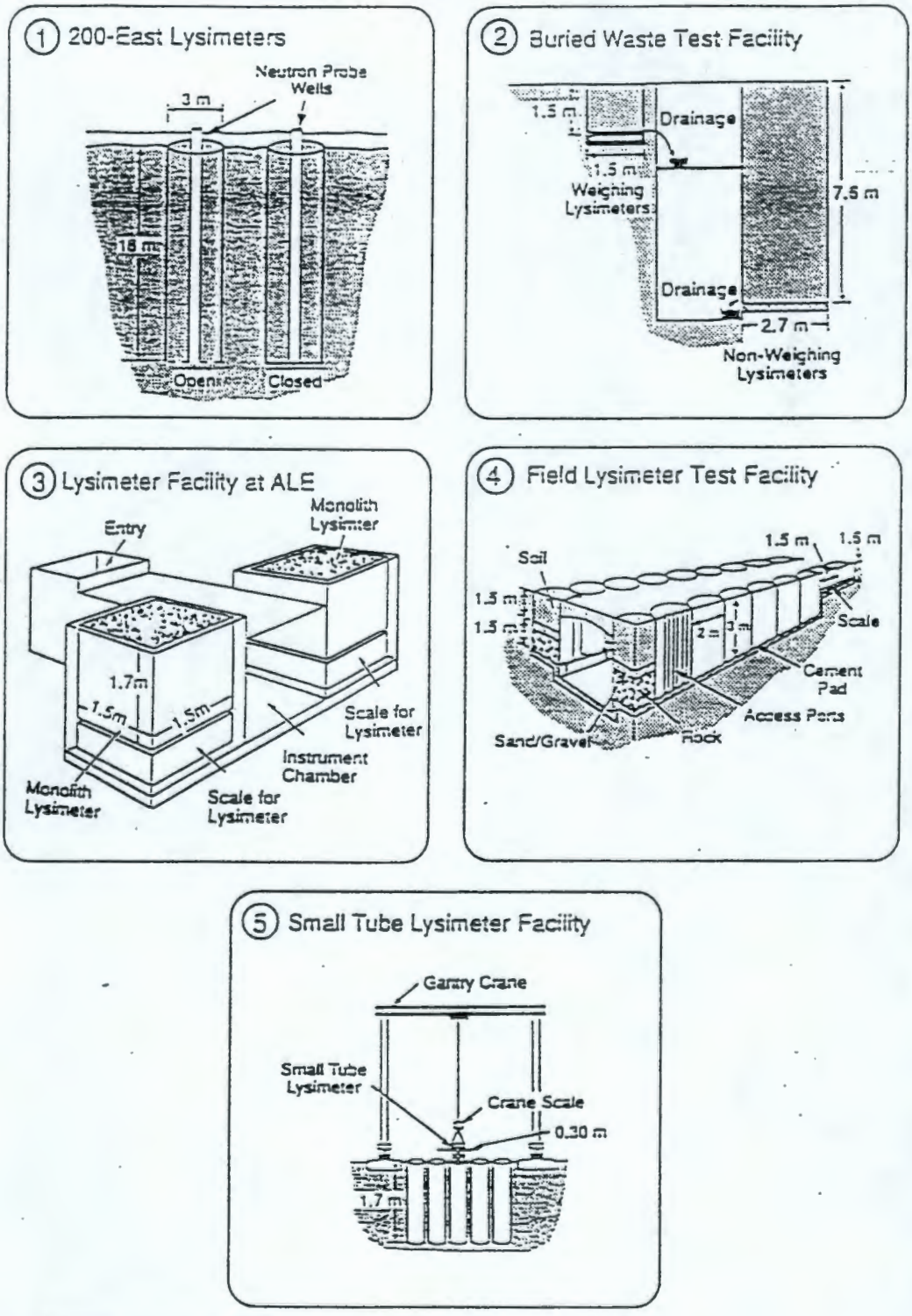

Figure 2. Schematics of lysimeter facilities. Numbered circles are locations shown on Figure 1.

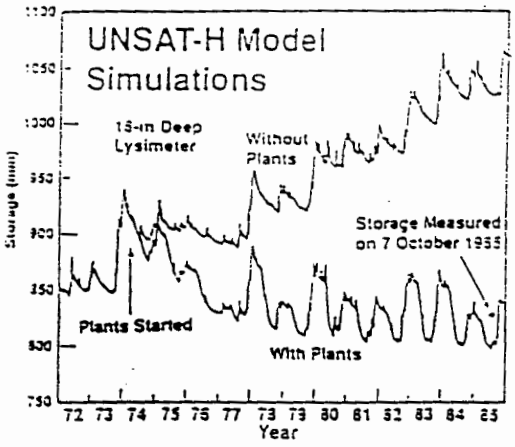

Figure 3. Predicted and observed water storage at the 200-East closed-bottom lysimeter.

Additional 200-East Lysimeter Measurements

Routson *et al.* (1988) collected samples for water content analysis by coring the closed-bottom lysimeter in October 1985. They found low water contents that compared favorably with water contents measured during filling operations in 1971. They also observed no increase in water content at the bottom of the lysimeter and only slight changes in water content below the 3-m depth. From the measured differences in water contents between 1971 and 1985, Routson *et al.* (1988) concluded that the drainage (recharge) at this location was negligibly small (0 ± 2 mm/yr).

In January 1988 a visit was made to the 200-East lysimeters. The open-bottom lysimeter had been partially excavated and could not be monitored. We found the rim of the closed-bottom lysimeter buried beneath about 20 cm of soil and the surface vegetated with mostly annual grasses and weeds. While removing the soil down to the lysimeter rim we discovered that the roots of scurf pea (*Psoralea lanceolata* Pursh), a desert lentil with a prolific root system, were abundant in the soil above the lysimeter as well as outside the lysimeter (Gee *et al.* 1989a). Brownell *et al.* (1975) indicated that the rim was buried more than 15 cm beneath the soil surface at least as far back as 1975. Thus, even if plants were specifically removed from the surface directly above the lysimeter, roots from plants outside the lysimeter could have accessed the water within the lysimeter.

Figure 4 shows the observed changes in water storage compared to changes in surrounding

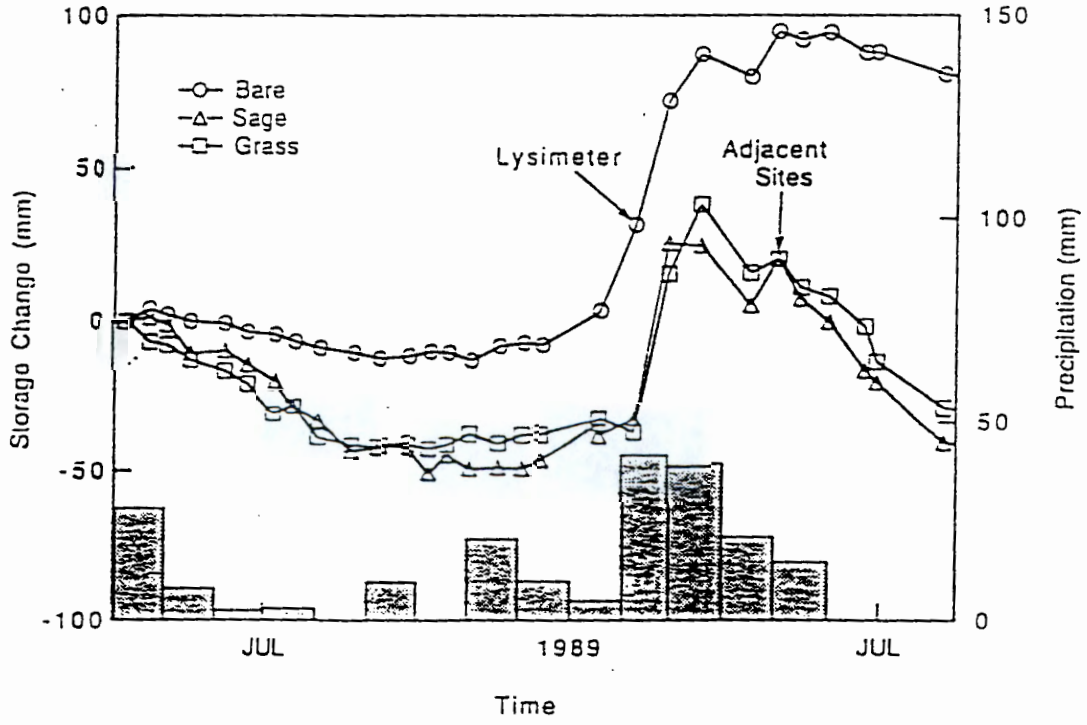

Figure 4. Measured water storage changes at the 200-East closed-bottom lysimeter and adjacent sites. Bar graphs represent monthly precipitation.

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vegetated sites (Rockhold *et al.* 1990). The data clearly show differences in water removal by bare and vegetated surfaces. The data also show the effects of winter rain on water accumulation in the soil. In the bare surface lysimeter the water stored from winter rains in late 1988 and early 1989 are not removed from the profile. At adjacent locations where plants (grass and shrubs) were growing on the soil surface, the winter rains were entirely removed by late spring. The data are in qualitative agreement with the model predictions by Fayer *et al.* (1986). The lack of recharge suggested by the 1985 coring data of Routson *et al.* (1988) does not appear to be due to evaporation alone, but rather to the combination of evaporation and transpiration. If plants are removed from waste sites with soils similar to (or coarser than) the sands found in the 200-East lysimeter, we would expect water storage (and thus recharge) to increase.

Buried Waste Test Facility Lysimeters

Figure 2 shows the configuration of the Buried Waste Test Facility (BWTF) which has been in operation since 1978 (Rockhold *et al.* 1990). A suite of lysimeters at this facility are used to measure the water balance of unvegetated and vegetated sands. Drainage lysimeters (2.7-m dia. by 7.6-m deep) and weighing lysimeters (1.5 m by 1.5 m by 1.5-m deep) have been used to monitor drainage at this site for the past 13 yrs.

Table 1 shows that drainage from the weighing lysimeter with a cheatgrass cover was about 35% of the annual precipitation for a 3-yr period

TABLE 1. Summary of estimated recharge from lysimeter facilities at the Hanford Site.

Facility[a]	Soil/Vegetation	Irrig.	Time	Recharge Estimate (mm/yr)	Recharge Estimate (% of Precip.)	Ref.[b]
200-East	Sand/Tumbleweed	No	1971-1985	<2	<1	1
200-East	Sand/Bare	No	1988-1989	90	43	2
BWTF	Sand/Bare	No	1985-1986	111	48	2
BWTF	Sand/Bare	No	1986-1987	102	55	2
BWTF	Sand/Bare	No	1987-1988	40	29	2
BWTF	Sand/Bare	No	1988-1989	42	24	2
BWTF	Sand/Cheatgrass	No	1984-1986	62	35	3
BWTF	Sand/Tumbleweed	No	1986-1987	1	5	2
BWTF	Sand/Tumbleweed	No	1987-1988	0[c]	0	2
BWTF	Sand/Tumbleweed	No	1988-1989	10	6	2
ALE	Silt Loam/Sagebrush	No	1986-1990	0[c]	0	4
ALE	Silt Loam/Bunchgrass	No	1986-1990	0[c]	0	4
FLTF	Silt Loam/Bare	Yes	1987-1990	0[c]	0	5
FLTF	Silt Loam/Bare	No	1987-1990	0[c]	0	5
FLTF	Silt Loam/Sagebrush	Yes	1987-1990	0[c]	0	5
FLTF	Silt Loam/Sagebrush	No	1987-1990	0[c]	0	5
STLF	Gravel over Silt/Bare	Yes	1988-1989	204	59	6
STLF	Gravel over Silt/Bare	No	1988-1989	74	48	6

[a] 200-East = 18-m-deep, Closed-Bottom Lysimeter (Figures 1 and 2)
BWTF = Buried Waste Test Facility-300 Area (Figures 1 and 2)
ALE = Arid Lands Ecology Reserve Lysimeters (Figures 1 and 2)
FLTF = Field Lysimeter Test Facility (Figures 1 and 2)
STLF = Small Tube Lysimeter Facility (Figures 1 and 2)

[b] 1—Routson and Johnson (1990)
2—Rockhold *et al.* (1990)
3—Gee (1987)
4—Gee *et al.* (1991)
5—Campbell *et al.* 1991)
6—Waugh *et al.* (1991)

[c] Zero value indicates that no drainage occurred from lysimeter(s).

(1984-1986). Cheatgrass is shallow-rooted (observed rooting depths of less than 1 m under Hanford Site soil conditions) and apparently unable to utilize the winter rains that infiltrated the sandy soil and accumulated below the root zone. The increased storage below the root zone resulted in drainage. In subsequent years, when deeper-rooted plants (e.g., tumbleweed) invaded the lysimeter, water in the lower part of the lysimeter was removed and drainage was reduced significantly. As expected, drainage from lysimeters with no plants was always greater than from the lysimeter with plants. Drainage from bare sand varied with time, ranging from 40 mm/yr to 111 mm/yr, in response to annual fluctuations in precipitation (Table 1).

ALE Lysimeters

Figures 1 and 2 show the location and schematic of four monolith lysimeters that were installed in 1986 at the Arid Lands Ecology (ALE) Site at the north end of Rattlesnake Mountain at an elevation of 300 m above MSL. The monolith lysimeters are boxes approximately 1.5 m on a side, constructed to contain undisturbed, silt loam (mixed, mesic, Xerollic Camborthids) soil (Gee *et al.* 1991). The wildfire of 1984 provided the treatment effect for the lysimeter study of water balance of differing plant communities. Roads in the area acted as a fire break and isolated an undisturbed area adjacent to an area consumed in the burn. One pair of lysimeters contained bunchgrass (*Agropyron spicatum* Pursh.) and were located in the burned area while the other pair contained bunchgrass and sagebrush and were located in the unburned area. Since installation, the lysimeters have been exposed to ambient precipitation which, because of location near Rattlesnake Mountain, is about 230 mm (42% higher than on the 200 Areas Plateau). In spite of plant cover difference and elevated precipitation, none of the lysimeters at the ALE site have drained (Table 1).

Field Lysimeter Test Facility

Figures 1 and 2 show the location and schematic of the Field Lysimeter Test Facility (FLTF), which was constructed near the Hanford Meteorological Station in 1987 to evaluate the use of engineered soil covers (barriers) to limit recharge at waste sites (Gee *et al.* 1989b, Campbell *et al.* 1990). Fourteen of the FLTF lysimeters are 2 m in diameter and 3 m deep. These lysimeters are filled with sediment layers in the following sequence from bottom to top: rock, gravel, sand, and a 1.5-m-thick layer of silt loam soil. The remaining four lysimeters are square boxes (1.5 m x 1.5 m x 1.6 m) filled with 1.5 m of silt loam soil overlying a layer of sand. The boxes rest on large (9.6-Mg-capacity) electronic scales. The soil in the top of all the FLTF lysimeters was excavated from an area about 10 km west of the FLTF, where the soil is classified as Warden silt loam (mixed, mesic Xerollic Camborthids). A typical particle-size distribution for this silt loam is 19 percent sand, 69 percent silt and 12 percent clay.

A series of water balance experiments have been conducted to test various surface conditions, including changes in vegetation (bare soil vs. transplanted shrubs and grasses) and changes in precipitation. The precipitation treatments exposed lysimeters to ambient and enhanced precipitation conditions. The enhanced (320 mm/yr) treatment is twice the annual average precipitation and is higher than any annual amount ever recorded at the Hanford Site. There has been no drainage from treatments with or without plants under ambient or enhanced precipitation (Table 1).

Small Tube Lysimeter Facility

Adjacent to the FLTF there are 105 smaller (0.3-m-diameter by 1.6-m-deep) lysimeters currently in use for water balance studies (Figure 2). These lysimeters, part of the Small Tube Lysimeter Facility (STLF), have been constructed to provide replication of the FLTF treatments and to add additional treatments, including unvegetated, gravel cover to simulate conditions that currently exist at some of the waste sites in the 200 Areas (Waugh *et al.* 1991). The STLF lysimeters, with silt loam soil surfaces, have performed similarly to the larger lysimeters at FLTF; no drainage has occurred from them. The gravel-covered lysimeters have had as much as 50% of the applied water drain through them (Table 1). These data confirm that fine-soil surfaces are effective barriers in preventing drainage under Hanford climate conditions, while coarse soil surfaces are not. Quantification of the rates of drainage continue to be made with these lysimeter facilities. Studies of the effect of significantly increased precipitation (up to three times the annual average) have been initiated and will continue over the next several years to document recharge under conditions of elevated precipitation.

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A series of water balance experiments have been conducted to test various surface conditions, including changes in vegetation (bare soil vs. transplanted shrubs and grasses) and changes in precipitation. The precipitation treatments exposed lysimeters to ambient and enhanced precipitation conditions. The enhanced (320 mm/yr) treatment is twice the annual average precipitation and is higher than any annual amount ever recorded at the Hanford Site. There has been no drainage from treatments with or without plants under ambient or enhanced precipitation (Table 1).

Small Tube Lysimeter Facility

Adjacent to the FLTF there are 105 smaller (0.3-m-diameter by 1.6-m-deep) lysimeters currently in use for water balance studies (Figure 2). These lysimeters, part of the Small Tube Lysimeter Facility (STLF), have been constructed to provide replication of the FLTF treatments and to add additional treatments, including unvegetated, gravel cover to simulate conditions that currently exist at some of the waste sites in the 200 Areas (Waugh *et al.* 1991). The STLF lysimeters, with silt loam soil surfaces, have performed similarly to the larger lysimeters at FLTF; no drainage has occurred from them. The gravel-covered lysimeters have had as much as 50% of the applied water drain through them (Table 1). These data confirm that fine-soil surfaces are effective barriers in preventing drainage under Hanford climate conditions, while coarse soil surfaces are not. Quantification of the rates of drainage continue to be made with these lysimeter facilities. Studies of the effect of significantly increased precipitation (up to three times the annual average) have been initiated and will continue over the next several years to document recharge under conditions of elevated precipitation.

Travel-Time Calculations

Knowledge of recharge rates at the Hanford Site is necessary for calculating contaminant travel times through the vadose zone. Using a simple one-dimensional model, the steady-state water velocity in the vadose zone can be related to the recharge rate as follows:

$$v = r/\Theta \quad (1)$$

Where v = water velocity (mm/yr)
r = recharge rate (mm/yr)
Θ = water content (cm^3/cm^3)

The velocity can also be expressed as

$$v = L/T \quad (2)$$

where L is the travel distance (mm) and T is the travel time (yr). Combining Eqs. (1) and (2) yields the expression for travel time

$$T = L\,\Theta/r \quad (3)$$

For the tritium study of Brownell (1971) we can estimate recharge knowing the timing of the initial tritium pulse (1953), the maximum depth of tritium penetration and the water content of the sediments in which the tritium pulse was measured. Based on the reported gravimetric water contents and assuming a typical bulk density of 1.7 g/cm^3 we estimate an average water content for the sediments was 0.047 cm^3/cm^3. Then using Eq. (1) and the estimated depth of tritium penetration of 5 m in 16 yrs (1954 to 1970), we calculate a recharge rate of 14.7 mm/yr. Given that the tritium can also move as a vapor, the calculated recharge rate represents a conservative estimate (i.e., the actual value for liquid flow may be lower).

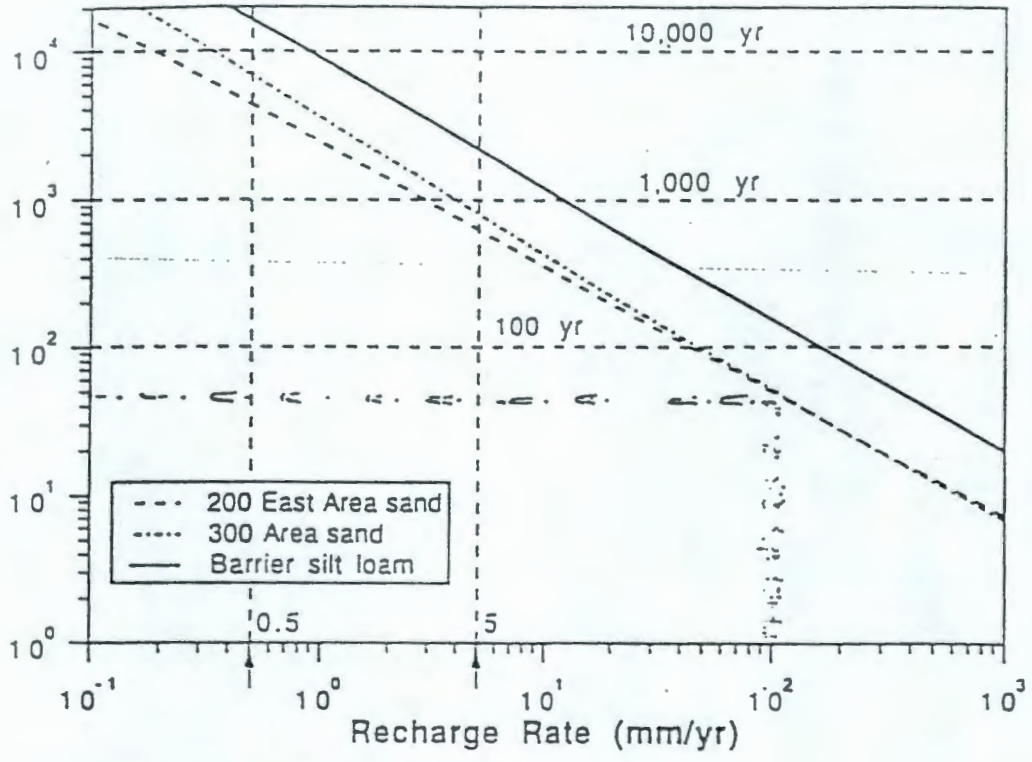
Assuming a 60-m-thick vadose zone above a water table, Eq. (1) can be used to calculate that, under the above conditions, with recharge, r_1 = 14.7 mm/yr and water content, Θ_1 = 0.047 cm^3/cm^3, a non-sorbing contaminant would reach the water table in 192 yrs. Now suppose that below the 5-m depth to which the tritium penetrated, the sediments were coarser, as is often the case at Hanford (Tallman *et al.* 1979). In coarser sediments the water content would be lower; for example, 0.025 cm^3/cm^3. Water contents this low have been found in coarse, well drained sediments at Hanford (Brownell 1971). Heller *et al.* (1985) indicate that for layered sediments, the overall travel time can be computed as a summation of travel times through the various layers of differing water contents. Thus, while the recharge rate is constant throughout the soil profile, the water velocity through various layers will vary according to their volumetric water content. Summing the travel times through the two layers, the total travel time is 110 years. This is 82 years less than (about one-half) the travel time through a profile with no coarse sublayer.

Our simplified (1-dimensional) analysis does not account for lateral spreading in layered sediments, as might occur following a localized injection of water (e.g., flow from a leaking tank and subsequent spreading of the contaminant plume above a caliche layer).

The travel time analysis suggests that a long-lived, mobile contaminant would reach the water table faster in coarser than in finer sediments. In general, the coarser the soil, the shorter the travel time through the vadose zone for the same recharge rate. In addition, there is mounting evidence that unsaturated flow in coarse sediments can be unstable, such that pulses of water might move in preferred channels or paths at rates far in excess of the average water velocity that would occur in uniformly wetted soils (Hillel 1987, Gee and Hillel 1988). The one-dimensional analysis used here does not take preferential flow into account, so it would not predict potential early arrival (faster flow) that could occur if preferential flow occurs in Hanford sediments.

Travel times through a 60-m-deep sediment profile were computed as a function of recharge rate for three Hanford Site sediments (two sands and a silt loam) following procedures described by Heller *et al.* (1985). Hydraulic properties were determined in the laboratory for the three sediments and were used to determine water contents for a given recharge flux. Then Eq. (3) was used to calculate the corresponding travel times (Figure 5).

The computed travel times provide guidance on recharge control. For example, to exceed a 10,000 yr limit in travel time, the recharge rate in the sands must be below 0.5 mm/yr. For the same travel time in silt loam, the recharge rate must be less than 1 mm/yr. This analysis holds for uniform soils that are subjected to areally uniform recharge rates under steady state conditions. A similar analysis has been reported for layered sediments by USDOE (Appendix Q of the Final Environmental Impact Statement-Disposal of Hanford Defense High-Level, Transuranic and Tank Wastes, Hanford Site Richland Washington; USDOE 1987).



ure 5. Travel time as a function of recharge in a 60-m-deep vadose zone.

scussion

.e lysimeter drainage data indicate that, regard-s of location, drainage (recharge) occurred in th sandy and gravel-covered soils (Table 1). The ta indicate that recharge values ranged from ore than 100 mm/yr to less than 2 mm/yr in ndy soils (or those covered with gravel) and was timated to be zero (no measurable drainage) in t loam soils.

oarse-Textured Soil

l lysimeter data collected to date suggest that charge is significant when coarse-textured soils pical of most of the Hanford Site) are kept free vegetation. Recent modeling of water flow and ntaminant migration at a tank farm, where bu-ed single-shell tanks are located, has shown that nual recharge could be more than 110 mm/yr 0% of the long-term annual precipitation) be-use the surfaces of coarse sands and gravels are pt free of vegetation (Smoot *et al.* 1990). These odeling results are consistent with lysimeter sults presented here. Under such high recharge tes, flow around tanks is accelerated, causing mobile contaminants leaking from the tanks to be moved to the water table at accelerated rates. Model simulations (Smoot *et al.* 1990) show that flow to the water table can occur in tens of years at tank farms or other similar sites where surfaces are bare and gravel covered.

The recharge rate in any one year in bare soils depends on the seasonal distribution of precipitation, with maximum recharge events occurring after the wettest winter periods (Figure 4). Data in Table 1 show a variable amount of drainage occurred in bare sand at the Buried Waste Test Facility (BWTF) over a period of 4 yrs (1985 through 1989). Although there is some lag between precipitation and drainage in the 7.6-m-deep lysimeters at the BWTF, the highest drainage rate (111 mm) is associated with the most annual precipitation (231 mm) and the lowest drainage rate (40 mm) with the least precipitation (134 mm). In soils with a deep (i.e., >90 m) water table, as exists in the 200 Areas Plateau at Hanford, such drainage fluctuations would likely be damped considerably. The recharge in deep sediments then would be an average of multiple years of fluctuating drainage. This suggests that lysimeter data should be taken over

a number of years to produce reliable estimates of recharge.

Vegetation

Vegetation produces a dramatic effect on recharge in coarse-textured soils. At the BWTF site, a sand-filled lysimeter, revegetated with cheatgrass, produced significant drainage (62 mm/yr) during 1984 through 1986, while precipitation averaged 177 mm/yr (Table 1). Invasion of tumbleweed on this lysimeter in subsequent years reduced the drainage to small amounts, ranging from 0 to 10 mm/yr. The data suggest that shallow-rooted plants do not reduce recharge to negligible amounts on coarse-textured soils at Hanford. The data also suggest that deep-rooted plants, such as tumbleweed, may not be entirely effective in eliminating recharge in sandy soils, since in 2 of 3 yrs there was measurable drainage in the sand-filled lysimeter when tumbleweed was present.

The intrusion into waste sites by plant roots is a major concern for waste management at the Hanford Site. Radioactive tumbleweeds have been found growing on waste burial grounds (Dabrowski 1973, Marshall 1987). For this reason plants have been removed by non-selective herbicides and soil sterilants from some waste sites (Dabrowski 1973) and relatively shallow-rooted grass species have been planted on other waste sites (Fuchs and Cox 1983). While effectively limiting radionuclide uptake, the removal of vegetation or the modification of plant species (i.e., changes to shallow-rooted species) tends to enhance recharge.

No drainage was observed in the sandy soil in the 200-East closed-bottom lysimeter for nearly 14 yrs (Figure 2, Table 1). The lack of drainage is attributed to the type of vegetation (deep-rooted annuals and perennials) growing on the lysimeter (from at least 1978 through 1988). When plants were removed from the 200-East lysimeter in 1988, water storage stayed relatively constant until the winter of 1988-1989. In response to late winter and early spring rain, water storage increased by nearly 100 mm so that by July, water storage was over 85 mm more than in early 1988 (Figure 3). In contrast, measurements taken in adjacent grass- and shrub-covered soils showed large water storage losses in the summer of 1988 and even larger losses in 1989. By July of 1989, all of the incident precipitation had been removed by evapotranspiration from the vegetated soils (Figure 4). We conclude that absence of vegetation on the sand-filled lysimeter caused increased storage. Increased storage below the root zone eventually leads to recharge.

Fine-textured Soil

None of the lysimeters containing silt loam soil produced any drainage (Table 1). The lack of drainage was irrespective of location, water application (precipitation and irrigation), or the presence or absence of vegetation. On bare lysimeters at the FLTF, water application rates were as much as 320 mm/yr (twice the long-term annual average). Even under these elevated precipitation conditions, bare, silt loam soil did not drain. Evaporation was able to remove the entire water application over the three year test. With plants, the lysimeters (at both ALE and FLTF locations) dried even further and there was no drainage. The lack of drainage suggests that a surface containing silt soil is ideal for limiting water infiltration under Hanford Site conditions. The optimum soil depth needed to effectively control water infiltration is presently under study (Campbell *et al.* 1991). To date we have measured no drainage in barrier (FLTF) lysimeters containing either a 1-m-thick layer or a 1.5-m-thick layer of silt loam soil.

Summary

Recharge is variable at the Hanford Site, ranging from over 100 mm/yr in bare sands and gravels to near zero (non-measurable) amounts in silt-loam soils. The implications for waste management at the Hanford Site are relatively straightforward. Present conditions (bare, coarse, soil surfaces) found at tank farms and other waste sites are conducive to recharge and accelerated contaminant migration. However, waste sites can be managed to greatly reduce recharge and thus significantly increase the time it takes for contaminants to travel to the water table. Vegetation on coarse soils can reduce recharge. Deep-rooted plants, such as sagebrush or tumbleweed are more efficient in utilizing soil water than shallow-rooted plants, such as cheatgrass. Unfortunately, deep-rooted plants can access buried waste and assimilate radioactive and chemical contaminants. For this reason plants are often removed (via herbicides and soil sterilants) from waste site surfaces.

The best cover material for limiting recharge at waste sites appears to be a fine-textured soil, such as the silt loam soil found near the 200 Areas Plateau. Ongoing research is testing how well silt loam soil can perform in reducing recharge under

range of vegetative and climatic conditions. Tests conducted over the past several years are encouraging and suggest that both vegetated and bare silt loam soil (at least 1-m thick) can effectively limit recharge to negligible amounts, even when the precipitation is at least twice the annual average.

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