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By EDMUND A. PRYCH

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	by	to obtain
centimeter (cm)	0.3937	inch
hectare (ha)	2.471	acre
kilogram (kg)	2.205	pound
kilometer (km)	0.6214	mile
liter (L)	1.057	quart
meter (m)	3.281	foot
atoms per square meter (atoms/m^2)	0.09290	atoms per square foot
milligram per square meter per year (mg/m^2/yr)	2.37×10^{-5}	pound per square foot per year
millimeter (mm)	0.03937	inch
square meter (m^2)	10.76	square foot
degrees Celsius (°C)	1.8 then add 32	degrees Fahrenheit

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

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

By Edmund A. Prych

Abstract

Knowledge of rates at which water from precipitation percolates through soils and sediments at the U.S. Department of Energy Hanford Site is critical for assessing the environmental risks of buried waste and for selecting appropriate strategies for storage and remediation. Two methods, a chloride mass-balance method and a chlorine-36 (^{36}Cl) isotope bomb-pulse method, were tested for estimating long-term average rates of deep percolation at the site. Deep-percolation rates were estimated by the chloride mass-balance method at 13 locations in 6 areas with natural vegetation, and by the bomb-pulse method at 1 location in each of 4 of the areas. Estimated rates are a small fraction of precipitation. Mean annual precipitation on the test areas of the Hanford Site, which is located in semiarid south-central Washington, ranges from about 160 to 210 mm/yr (millimeters per year). Because the bomb-pulse method typically gives an upper limit of the deep-percolation rate and the mass-balance method may underestimate the rate, the estimates by the two methods probably bracket actual rates.

Estimates of deep percolation by the mass-balance method range from 0.008 to 0.11 mm/yr at four locations in two areas covered with more than 4 meters of silt-loam soils and vegetated with sagebrush and other deep-rooted plants and sparse shallow-rooted grasses. Estimated upper limits by the bomb-pulse method at one location in each of these same two areas are 2.1 and 3.4 mm/yr. Rates estimated by the mass-balance method range from 0.012 to 0.30 mm/yr at five locations in three areas where the soils consist of about 0.6 meter of loamy sand or sandy loam overlying tens of meters of sand and gravel and which have vegetal covers similar to the two areas with deep silt-loam soils. The upper limit estimated by the bomb-pulse method for one location in one of these three areas is 2.6 mm/yr. Estimates of deep percolation by both methods for the two areas with deep silt-loam soils are within the range of estimates by previous investigators that used independent methods and data for areas at Hanford with similar soil and vegetal covers. However, the estimates for the three areas with loamy sand or sandy loam soils are less than estimates by previous investigators.

Rates estimated by the mass-balance method at four locations in an area with 0.6 meter of loamy sand overlying about 9 meters of sand and with a vegetal cover consisting of only sparse shallow-rooted grasses range from 0.39 to 2.0 mm/yr. These estimates are higher than estimates by this method for locations in the five areas with deep-rooted plants; however, they still are at the lower end of the range of estimates for this area by other investigators. The ^{36}Cl data collected at one location in this area were not from sufficient depth to define the entire anthropogenic ^{36}Cl profile. These data, when used with the bomb-pulse method, were sufficient only to determine that the upper limit of deep percolation probably is greater than 5.1 mm/yr.

Estimated atmospheric chloride deposition rates, which are obtained from observed ratios of natural chlorine-36 to total-chloride ($^{36}Cl/Cl$) (ratios in deep soil water older than the oldest anthropogenic ^{36}Cl), range from 33 to 39 milligrams per square meter per year. These rates are equal to or greater than twice that due to precipitation alone. Average natural

^{36}Cl/Cl ratios in profiles at different locations ranged from 735×10^{-15} to 876×10^{-15}.

Inventoried amounts of anthropogenic ^{36}Cl suggest that most of the anthropogenic ^{36}Cl that was observed in this study is from 1950's nuclear-weapons tests in the Pacific Ocean, as is assumed when using the bomb-pulse method, and not from operations at Hanford. Inventoried amounts at the three locations where the entire anthropogenic ^{36}Cl profile was defined range from 1.1×10^{12} to 2.5×10^{12} atoms per square meter. These amounts are similar to amounts found by other investigators at sites in the arid southwestern United States that are not near local anthropogenic sources of ^{36}Cl.

Observed depths to the centroids of mass of anthropogenic ^{36}Cl ranged from 1.06 to 1.50 meters at the three locations with deep-rooted vegetation, and the depth was greater than 3.46 meters at the location with only shallow-rooted grass vegetation. At each of the former three locations, depths to the centroid and the peak ^{36}Cl concentration were greater than the depth at which the ^{36}Cl/Cl ratio was a maximum; the age of soil water (estimated using chloride mass-balance calculations) at the depth of the centroid was much older than the period of bomb testing. These inconsistencies may be caused by differences in the rate of vertical movement of water and chloride within different flow paths at a given depth. Because of these differences the mass-balance method probably underestimates percolation rates at some locations.

INTRODUCTION

Radioactive materials for military or civilian applications have been processed, stored, used, or disposed of at the U.S. Department of Energy Hanford Site (fig. 1) in semiarid south-central Washington since 1944. Former names for this facility include Hanford Works, Hanford Reservation, and Hanford Nuclear Reservation. As a result of activities at this facility, the soils and unsaturated sediments at the Hanford Site contain a wide variety of radioactive and other inorganic and organic wastes. A fundamental concern influencing plans for environmental remediation and designs of storage facilities for hazardous materials at the Hanford Site is that water from precipitation percolating through the soils and sediments may transport hazardous materials to the underlying unconfined aquifer, which discharges to the Columbia River. Quantifying the rates at which water from precipitation on the land surface moves vertically downward through the soils and sediments toward the water table is critical for assessing environmental risks posed by existing wastes, and for selecting appropriate isolation or treatment strategies for storage and remediation. Because of the long life of some of the waste materials at Hanford, quantifying percolation rates less than 1 mm/yr may be necessary.

In 1990 the U.S. Geological Survey (USGS) began a 3-year study to test the applicability of two methods, the chloride mass-balance and chlorine-36 isotope bomb-pulse methods, for estimating deep-percolation rates at the Hanford Site. These methods, which use total chloride and the chlorine-36 isotope as soil-water tracers, have been used for estimating deep-percolation rates at other arid and semiarid sites in the western United States (Phillips and others, 1988) where deep percolation is only a fraction of a millimeter per year.

In this report the term "deep percolation" means the movement of water from the surface to sufficient depths, usually below the root zone, so that the water is no longer subject to evapotranspiration. This water eventually will reach the water table and recharge the saturated ground-water system. However, the time for this water to become recharge can vary from a fraction of a year to thousands of years, depending on the percolation rate and the depth to the water table.

Purpose and Scope

This report presents the results of a study of the use of a chloride mass-balance method and a chlorine-36 isotope bomb-pulse method for estimating local long-term average rates of deep percolation of water from precipitation at selected locations on the Hanford Site. Deep percolation was estimated using the mass-balance method at a total of 13 locations in 6 areas. The bomb-pulse method was used for estimates at one location in each of four of the areas.

The report describes the theory and assumptions upon which the two methods are based. The different areas at Hanford where soil samples were collected to obtain data for making estimates are described along with the methods used to collect and analyze the samples. The data needed to make the estimates and supplemental data are presented in graphical form and in

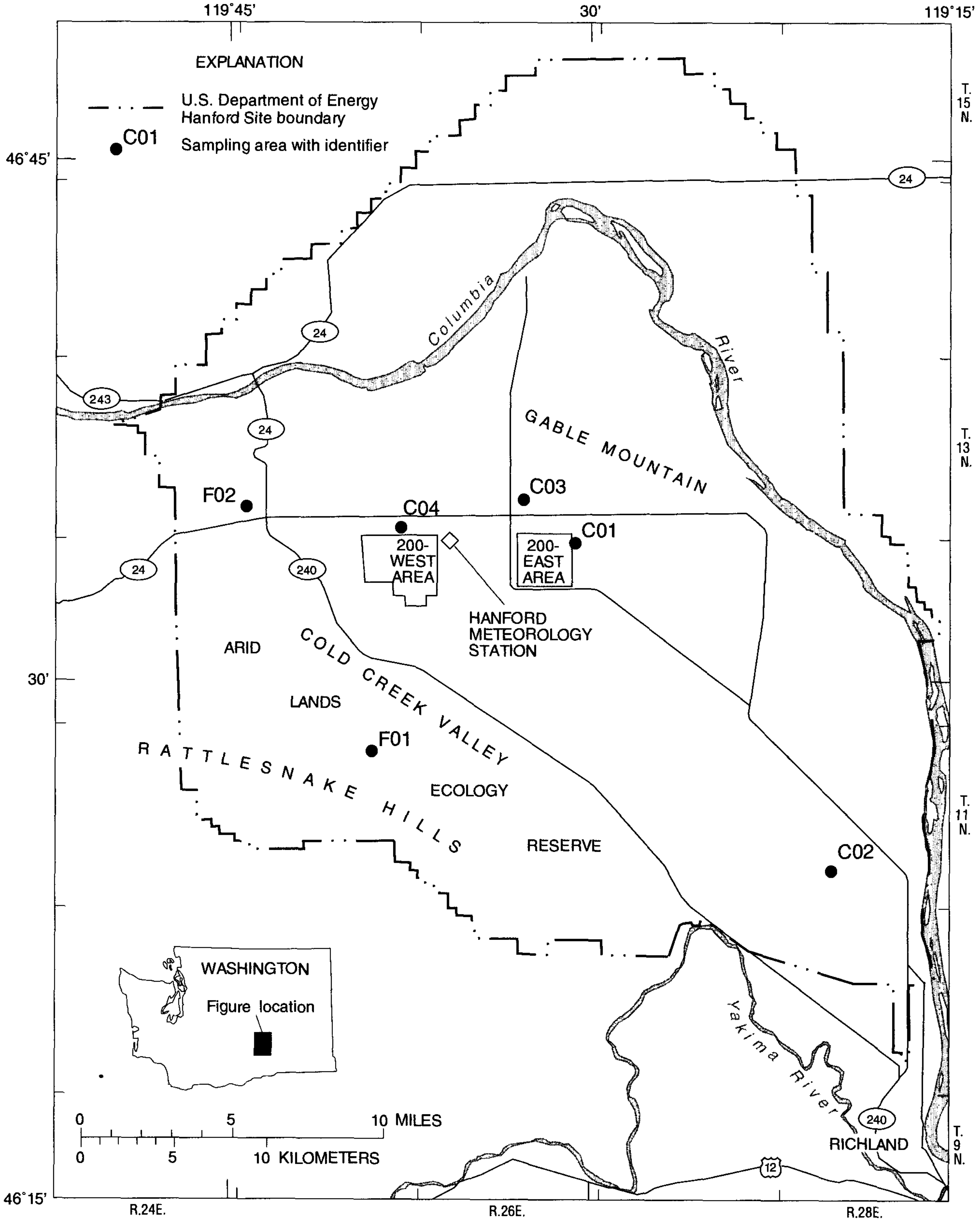

Figure 1. U.S. Department of Energy Hanford Site, showing locations of sampling areas.

tables. These data include vertical profiles of chloride concentration in soil water, ratios of chlorine-36 to total chloride, concentration of chlorine-36 in soil, water content, and matric potential. The report uses the chlorine-36 data to estimate deep percolation by the bomb-pulse method, and to estimate atmospheric-chloride deposition rates, which are necessary for use of the chloride mass-balance method. The chloride-concentration data are used to estimate deep-percolation rates and ages of soil water by the mass-balance method. The report also discusses some anomalies in the data and possible errors in the estimated percolation rates that could be introduced by assumptions upon which the estimation methods are based.

Previous Work

Gee and others (1992), Rockhold and others (1990), and Gee (1987) have summarized information about previous investigations of deep percolation, or recharge, at the Hanford Site. Previous estimates of deep percolation were based on direct measurements with lysimeters, vertical-flux calculations using observed or estimated hydraulic conductivities and water-potential gradients, soil-water accounting methods, or combinations of these methods. The soil-water accounting methods either used field measurements of the water content of soil and observed meteorological data in the calculations, or used only meteorological data and hydraulic properties of the soil. The deep-percolation rates that were estimated by these various methods ranged from zero for areas with a thick surficial layer of fine-grained soil and deep-rooted vegetation, to nearly all of the annual precipitation (about 160 mm/yr) for areas with coarse-grained soils covered with a layer of gravel and without vegetation. The following paragraphs describe some of the previous studies of deep percolation at Hanford. Additional information on estimates for specific areas on the Hanford Site is given in the section "Descriptions of the Hanford Site and Sampling Areas."

Smoot and others (1989) used a numerical model that simulates evaporation at the soil surface and movement of water in liquid and vapor form in unsaturated soil to estimate the quantity of precipitation that would percolate to depths greater than 2 m. Input data for the simulations included estimated hydraulic properties of soil and 10 years of observed daily meteorological data. The calculated 10-year average rates of water movement to a depth of 2 m ranged from 1.8 mm/yr when the soil consisted of a 0.15-m-thick surficial layer of silt loam on top of silty sandy gravel to 155 mm/yr when the surficial layer was clean gravel instead of silt loam.

Bauer and Vaccaro (1990) used 22 years of daily meteorological data and soil-moisture accounting to compute daily changes in water content of soil within the root zone. They equated changes in water content to rain plus snowmelt less evapotranspiration and precipitation intercepted directly by plants. All soil water in excess of the water-holding capacity of the soil in the root zone was assumed to become deep-percolation water. Computed deep percolation was sporadic and did not occur every year. The 22-year averages of computed local values of deep percolation, which depended on topography, vegetal cover, water-holding capacity of the soil, and other factors, ranged from less than 0.01 to 46 mm/yr (H.H. Bauer, U.S. Geological Survey, Tacoma, Washington, oral commun., 1992). The estimated deep percolation was smallest for deep fine-grained soils with vegetation and was largest for coarse-grained soils without vegetation. The computed average value for the Hanford Site was about 10 mm/yr.

Rockhold and others (1990) described work done to estimate recharge in an area on the Hanford Site that they refer to as the 300 Area Grass Site. This area, which will be called the Grass Site in this report, has a sandy soil with only a sparse grass vegetal cover. (See the section "Descriptions of the Hanford Site and Sampling Areas" for a more extensive description of this area.) Vertical profiles of soil moisture in 25 holes were monitored for a number of years at this site using neutron probes. Deep percolation was estimated by a variety of methods. One estimate, obtained from observed changes in soil moisture during a 12-month period beginning in July 1988, was 8.1 mm/yr. Another estimate, which was obtained by multiplying an estimated vertical hydraulic conductivity by an assumed unit gradient in the water potential and was based on the assumption that percolation rates are steady at depths greater than about 1.2 m, was between 0.06 and 28 mm/yr. The large uncertainty in this estimate was a result of the sensitivity of the calculation to the unsaturated hydraulic conductivity, which could not be estimated with a high degree of certainty.

Gee and others (1992) summarized results of investigations at the Hanford Site that have used lysimeters. Observed or calculated deep-percolation rates in these investigations ranged from zero (less than measurable) to more than 100 mm/yr. Deep percolation was greatest in lysimeters with coarse-textured soils without plants and was least in lysimeters with fine-textured soils with and without plants. At least five different groups of lysimeters have been constructed at different locations using various soils and surface covers. Sizes of the lysimeters ranged from 0.3 to 3 m in diameter, and 1.5 to 18 m in depth. In some lysimeters deep percolation was estimated by collecting the drainage at the bottoms of the lysimeters. Other lysimeters were weighed continuously or periodically, and percolation rates were obtained from the history of weight changes and precipitation. In other lysimeters water contents were measured periodically with neutron probes.

An advantage of using lysimeters to estimate deep percolation is that lysimeters can yield direct measurements of percolation. Some disadvantages are that they must be continually operated and maintained for long periods and the cost can be high. Measured deep percolation is also only representative of the period in which the lysimeters are operated; extreme events that result in unusually large amounts of deep percolation may not occur during the period of operation.

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CHLORIDE IN THE ENVIRONMENT

Naturally occurring chloride, the ionic form of chlorine, consists mostly of the two stable isotopes ^{35}Cl and ^{37}Cl. Their natural abundances are 75.53 and 24.47 percent, respectively. The atomic weight of this mixture of isotopes is 35.453 (Weast, 1975, p. B-12). Most chloride salts are highly soluble in water. Major sources of chloride dissolved in shallow ground waters are atmospheric deposition, minerals in soil and rocks, and in some places anthropogenic sources such as road salts and agricultural chemicals. Atmospheric chloride can be the predominant source at locations where sufficient time has passed for water to remove the chloride from the minerals in the rock and soil and where there are no anthropogenic sources. The major source of chloride in the atmosphere is entrainment from the surface of the ocean. This chloride is returned to the Earth's surface in precipitation and dry deposition.

The precipitation-weighted concentration of chloride in precipitation at the Hanford Site, as estimated from data collected at sites in the National Atmospheric Deposition Program (National Atmospheric Deposition Program, 1985-91) is about 0.09 mg/L (fig. 2). Although annual rates of the component of atmospheric deposition by precipitation can be computed by multiplying the observed concentration of chloride in precipitation by the precipitation amount, there is no convenient reliable method for directly determining the dry-deposition component or the total deposition rate. However, Phillips and others (1988) described an indirect method that utilizes

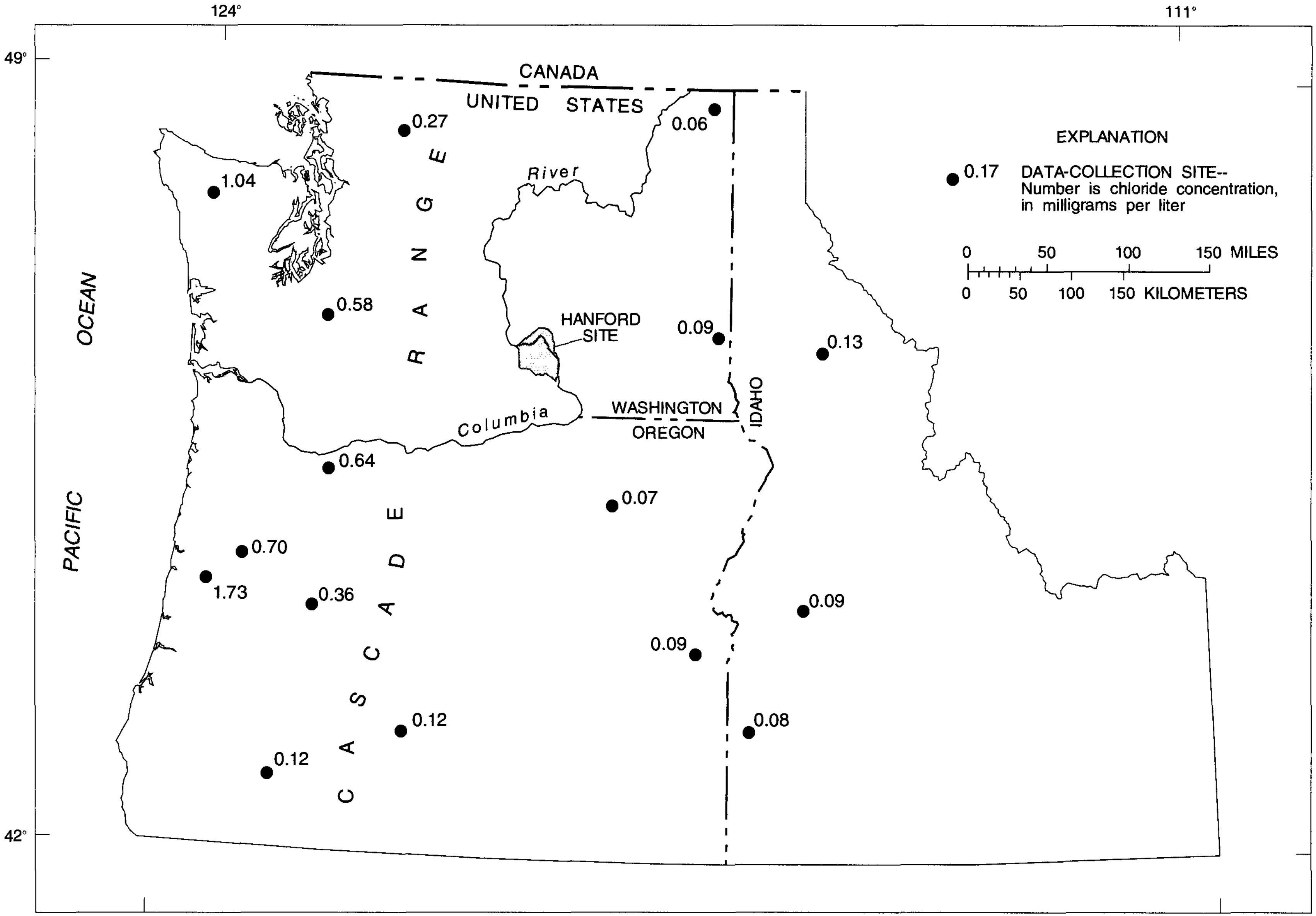

Figure 2. Precipitation-weighted means of observed chloride concentrations in precipitation at sites in the National Atmospheric Deposition Program/National Trends Network in Washington, Oregon, and Idaho for the years 1983 through 1990 (National Atmospheric Deposition Program, 1985-91).

chlorine-36 isotope data for estimating the total deposition rate. This method is described in the section titled "Atmospheric Chloride Deposition."

Chlorine-36 (^{36}Cl) is a rarely occurring radioactive isotope with a half life of about 300,000 years (Bentley and others, 1986). The typical abundance of this isotope in shallow ground water is only about one atom in 10^{12}. It is produced naturally in the atmosphere by the interaction of cosmic rays and argon, and in the lithosphere by radiochemical processes (Bentley and others, 1986). The atmosphere is the dominant source of ^{36}Cl in most shallow ground waters. Andrews and Fontes (1992, fig. 1) modified estimates by Bentley and others (1986) of the rate of atmospheric production and deposition of ^{36}Cl as a function of latitude. The estimated rate for the geomagnetic latitude of the Hanford Site (north 53 degrees) is 15.5 atoms/m^2/s.

Andrews and others (1989) stated that neutron activation of ^{35}Cl is the only in-situ reaction that produces significant ^{36}Cl in a rock matrix. They found good agreement between observed neutron fluxes in Stripa granite and fluxes calculated from concentrations of uranium-238 and thorium-232 in the granite, and between observed concentrations of ^{36}Cl and calculations based on the neutron flux and observed concentrations of ^{35}Cl. An estimated upper limit on the ratio of the concentration of *in-situ*-produced ^{36}Cl to total chloride at the Hanford Site can be calculated using a formula given by Andrews and Fontes (1992, eq. 6) with a neutron flux equal to that in Stripa granite and a maximum age of the soil water at Hanford of 20,000 years (see the section "Descriptions of the Hanford Site and Sampling Areas"). This calculated ratio is 12×10^{-15}. It is an upper limit because concentrations of uranium-238 and thorium-232 in Stripa granite (44 and 33 mg/kg, respectively)—and therefore neutron fluxes—are a factor of 10 greater than in most other rocks (Andrews and others, 1989, table 3). Concentrations in Stripa granite are also considerably larger than concentrations in most soil samples collected at the Hanford Site. (Concentrations in Hanford soils were retrieved from the data base described by Westinghouse Hanford Company, 1991.)

In addition to the naturally produced ^{36}Cl, relatively large amounts of this isotope were created and introduced into the atmosphere by nuclear-bomb tests in the Pacific Ocean during the 1950's. Bentley and others (1986, fig. 10-18) estimated the time history of ^{36}Cl fallout from these tests (fig. 3). The centroid of this temporal distribution of fallout is in the year 1957. During the late 1950's and early 1960's the atmospheric deposition of ^{36}Cl from the bomb tests was about 1,000 times that from natural atmospheric production. Phillips and others (1988, fig. 2) estimated the total ^{36}Cl fallout as a function of latitude. (Although not explicitly stated, it appears that in this case geographic rather than geomagnetic latitude was used.) The estimated fallout for the geographic latitude of the Hanford Site, north 46.5 degrees, is 2.0×10^{12} atoms/m^2. However, Phillips and others (1988) pointed out that an estimate for a particular location is only a rough approximation because "fallout is known to vary greatly as a function of position, weather, and other factors."

Measurable amounts of ^{36}Cl have also been produced and released to the environment from nuclear-materials processing facilities. Beasely and others (1992) collected data on ^{36}Cl in surface water and ground water near the U.S. Department of Energy Savannah River Site, South Carolina. They concluded that the amount of ^{36}Cl deposited on an area within 200 km of the site as a result of past operations at that site was equal to about half that deposited as a result of the 1950's bomb tests. Beasley and others (1993) also found relatively large ^{36}Cl concentrations in ground water on and near the Idaho National Engineering Laboratory and attributed them to activities at the facility. Abnormally large relative ^{36}Cl concentrations have also been observed in recent snow samples downwind from the Idaho facility (L. Dewayne Cecil, U.S. Geological Survey, Idaho Falls, Idaho, oral commun., 1993). Murphy and others (1991a) summarized the small amount of available information on the production and releases of ^{36}Cl at the Hanford Site. They stated that the amount of ^{36}Cl that was released to the environment can be estimated, but that most of it was discharged to the Columbia River or leaked to the ground-water system from detention ponds. The only discharge to the atmosphere would have been from surfaces of the ponds. They suspected that this amount was small, but they gave no quantitative estimates.

DERIVATIONS OF ESTIMATION EQUATIONS

This section derives equations for estimating deep-percolation rates by the mass-balance and bomb-pulse methods, and for estimating the rate of atmospheric deposition of chloride. An equation for estimating the age of soil water or chloride by the mass-balance method is also given.

Atmospheric Chloride Deposition

As stated previously, the rate of deposition of atmospheric chloride by precipitation can be obtained by direct measurement, but the rate of dry deposition cannot be measured directly. Phillips and others (1988) estimated the total atmospheric-deposition rate at a study site in New Mexico indirectly using observed ratios of ^{36}Cl to total-chloride concentrations in deep soil water that fell as precipitation before the 1950's weapons tests and estimated rates of the deposition of ^{36}Cl produced naturally in the atmosphere. They assumed that all chloride isotopes behave identically in soil and water, and that the ratio of vertical fluxes of ^{36}Cl to total chloride by soil water equals the ratio of concentrations. These assumptions yield

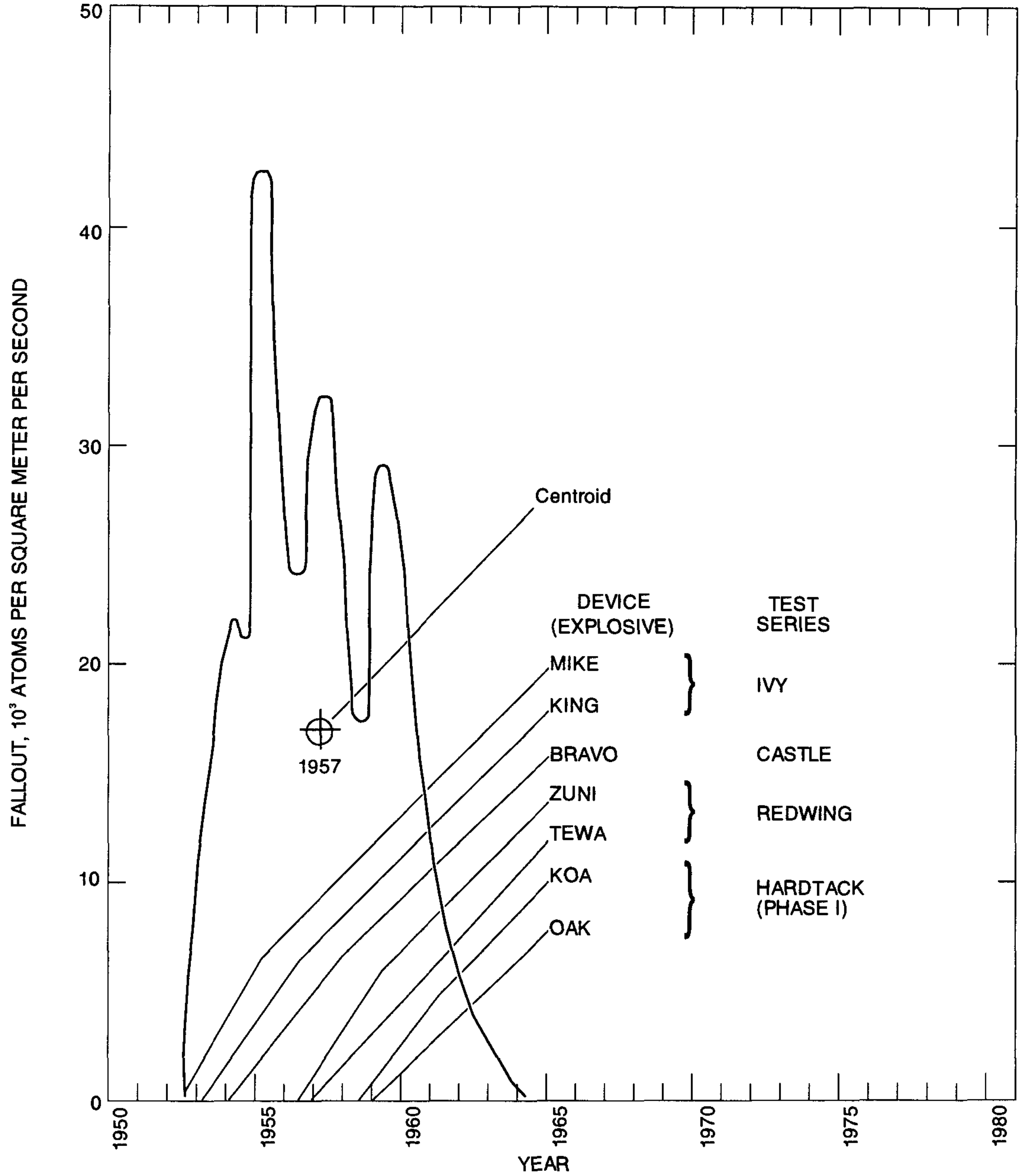

Figure 3. Estimated fallout of chlorine-36 between 30 and 50 degrees north latitude from atmospheric nuclear-weapons testing. (Modified from Bentley and others, 1986, figure 10-18.)

$$q_{^{36}\mathrm{Cl}} / q_{\mathrm{Cl}} = \left[{}^{36}\mathrm{Cl}\right]_{\mathrm{w}} / [\mathrm{Cl}]_{\mathrm{w}} = \left({}^{36}\mathrm{Cl}/\mathrm{Cl}\right)$$

$$q_{\mathrm{Cl}} = q_{^{36}\mathrm{Cl}} / \left({}^{36}\mathrm{Cl}/\mathrm{Cl}\right), \qquad (1)$$

where

q_{Cl} is atmospheric flux of total chloride, in units of mass per unit area per unit time;

$q_{^{36}\mathrm{Cl}}$ is atmospheric flux of ^{36}Cl, in units of mass per unit area per unit time;

$[\mathrm{Cl}]_{\mathrm{w}}$ is concentration of total chloride in soil water, in units of mass per unit volume; and

^{36}Cl/Cl is the ratio $\left[{}^{36}\mathrm{Cl}\right]_{\mathrm{w}} / [\mathrm{Cl}]_{\mathrm{w}}$.

Substituting 15.5 atoms/m^2/s, the value of $q_{^{36}\mathrm{Cl}}$ for the Hanford Site, into equation 1 gives

$$q_{\mathrm{Cl}} = \frac{\left(15.5 \ \mathrm{atoms/m^2/s}\right) \times (35.5 \times 10^3 \ \mathrm{mg/mole}) \times (31.536 \times 10^6 \ \mathrm{s/yr})}{(6.03 \times 10^{23} \ \mathrm{atoms/mole}) \times \left({}^{36}\mathrm{Cl}/\mathrm{Cl}\right)},$$

which reduces to

$$q_{\mathrm{Cl}} = \frac{28.8 \times 10^{-12} \ \mathrm{mg/m^2/yr}}{{}^{36}\mathrm{Cl}/\mathrm{Cl}}. \qquad (2)$$

This equation is used later in this report with observed values of ^{36}Cl/Cl to estimate total atmospheric fluxes of chloride at locations on the Hanford Site, which in turn are used to estimate deep-percolation rates by the chloride mass-balance method. Note that the vertical flux of chloride in the soil may differ from the deposition rate, q_{Cl}, if the deposited chloride is redistributed by overland flow of precipitation before it infiltrates.

Chloride Mass-Balance Method

Eriksson and Khunakasem (1969) demonstrated how an equation for the mass balance of chloride, together with data on chloride concentrations in ground water and long-term average rates of atmospheric deposition of chloride by precipitation, can be used to estimate long-term average rates of recharge to an aquifer. Since then, others (see, for example, Vacher and Ayers, 1980; Claassen and others, 1986; and Dettinger, 1989) have used this method for many different types of areas ranging from small oceanic islands to mountainous drainage basins that range in size from tens to thousands of square kilometers. Others (see, for example, Allison and Hughes, 1978; Mattick and others, 1987; Scanlon, 1991; and Stone, 1987 and 1992) have adapted the method by using chloride concentrations in ground water within the unsaturated zone (soil water) to estimate deep percolation of precipitation on a local scale. Here and elsewhere this report uses the broad engineering definition of soils; it includes all unconsolidated sediments in addition to the chemically and physically modified top 1 or 2 m.

Deep-Percolation Rate

The chloride mass-balance method for estimating the local rate of deep percolation of precipitation is based on the hypothesis that all or a known fraction of chloride in precipitation and dry atmospheric deposition is transported from land surface to the water table by the downward flow of liquid water. As water percolates downward, some evaporates directly or is taken up and transpired by plants. Where this occurs the concentration of chloride in soil water increases with depth because little or no chloride is lost by these processes. At greater depths, where no evapotranspiration occurs, the chloride concentration should be uniform if climate, soil, and other conditions near the surface have been steady for a sufficiently long time. Chloride concentrations and fluxes of chloride and liquid water are related through the equation for chloride flux,

$$q_{\mathrm{Cl}} = [\mathrm{Cl}]_{\mathrm{w}} q_{\mathrm{w}}, \qquad (3)$$

where the local downward flux of chloride per unit area is assumed to equal the total atmospheric chloride flux, q_{Cl}; and q_{w} is the local downward flux of liquid water per unit area. This equation can be rearranged to yield an expression for liquid water flux,

$$q_{\mathrm{w}} = q_{\mathrm{Cl}} / [\mathrm{Cl}]_{\mathrm{w}}, \qquad (4)$$

To estimate the long-term average deep-percolation rate of water, one needs only to substitute into equation 4 the long-term average chloride flux and the concentration of chloride in soil water at a depth greater than that at which evapotranspiration occurs. Chloride concentrations can be obtained by laboratory analyses of soil samples. One may note that if the chloride flux for equation 4 is obtained by using equation 1, then the precipitation quantity is not explicitly used in the computation of the percolation rate.

Implicit in the derivation and uses of equation 4 is the assumption of so-called plug flow. More specifically, it is assumed that (1) the direction of water flow and chloride transport is vertical and downward, (2) areal distributions of the rate of percolation of water and of chloride on the local scale (a few tenths of a meter) are uniform (no preferred pathways), (3) all chloride is dissolved in soil water, and the distribution of the dissolved chloride in the soil water is relatively uniform within a pore (no solid chloride phase, sorption by soil, or anion exclusion), and (4) advection is the dominant mode of chloride transport, and diffusion is relatively unimportant. The last assumption is valid when either the diffusion coefficient or the vertical gradient of the chloride concentration is sufficiently small. Additional assumptions are that (5) minerals in the soil are not a source of chloride, and the only source is precipitation and dry atmospheric deposition, and (6) observed chloride concentrations are at depths great enough so that seasonal variations in concentration are small. The method may still be valid if chloride is taken up by growing vegetation as long as it is also released by decaying vegetation at the same rate.

One should note that water flux, q_w, that is calculated with equation 4 does not include the component of water flux in vapor form because chloride is not volatile and will not move in the vapor phase. Consequently, equation 4 may underestimate or overestimate the net flux of water, depending on the direction of net vapor flux. However, because it is the movement of water in liquid form that transports solutes through the soil profile, often it is this liquid component that is most important for assessing the risks associated with buried wastes.

Age of Soil Water

An average age of chloride or water, a, at any depth z_1 can be estimated by dividing the mass of chloride in soil water above that depth by the atmospheric-chloride deposition rate,

$$a = \frac{1}{q_{Cl}} \int_0^{z_1} (W/100)\ [\mathrm{Cl}]_w\ S_b\ dz, \qquad (5)$$

where

W is water content of the soil, in percent of dry weight;

S_b is bulk density of dry soil divided by the den sity of water; and

z is depth below land surface.

Assumptions implicit in equation 5 are the same as in equation 4.

Chlorine-36 Bomb-Pulse Method

The bomb-pulse method for estimating deep percolation uses as a tracer the relatively large amounts of ^{36}Cl fallout from nuclear-weapons testing in the Pacific Ocean during the 1950's. When ^{36}Cl is dissolved in precipitation that infiltrates the land surface, the anomalously large concentration of ^{36}Cl in soil water provides a time marker on the downward percolating water. The quantity of water in the soil profile shallower than some depth to where concentrations of ^{36}Cl are elevated is the quantity of water that has infiltrated the ground since the time when the fallout occurred and has not yet been lost by evapotranspiration. Therefore, an upper limit on the average rate of deep percolation of precipitation from the period between the time of fallout and the time of sampling can be calculated as

$$q_w \le \frac{\int_0^{z_m} (W/100)\ S_b\ dz}{t_0 - t_m}, \qquad (6)$$

where

z_m is the depth to some characteristic point on the profile of elevated ^{36}Cl concentrations;

t_0 is the time when the vertical profile was observed; and

t_m is some characteristic time on the temporal distribution of ^{36}Cl fallout from the bomb tests.

The calculated value is an upper limit because soil water near the surface may be subject to additional evapotranspiration before moving deeper (see Tyler and Walker, 1994). Although ^{36}Cl is radioactive and its decay properties have been used to date ground waters more than 50,000 years old (see, for example, Bentley and others, 1986), the half life of ^{36}Cl (about 300,000 years) is so much greater than time scales in the present investigation that ^{36}Cl is treated as a conservative substance and the decay properties of the isotope are not used.

Previous investigators who have used bomb-^{36}Cl in studies of deep percolation include Trotman (1983), Norris and others (1987), Phillips and others (1988), and Scanlon and others (1990). Typically, these investigators have used the depth to where

^{36}Cl/Cl is a maximum or the depth to the centroid (center of mass) of bomb-^{36}Cl for z_m as a measure of the distance that water has percolated since the bomb tests. Centroids are used for both z_m and t_m in the current study. However, one should be aware that although the use of peaks, centroids, or medians may have intuitive appeal, the general use of none of these measures of central tendency can be justified theoretically, especially when there is diffusion or when the percolation velocity is a function of depth. A nearly certain (and larger) estimate of the upper limit of deep percolation can be obtained if the maximum observed depth of bomb-^{36}Cl is used for z_m. However, use of this maximum depth probably would produce an excessively high upper limit.

Phillips and others (1988; see also Mattick and others, 1987) used data on the vertical distributions of ^{36}Cl as well as tritium from bomb tests and of total chloride to deduce information on the vertical movement of water through desert soils. They found that most of the ^{36}Cl from bomb tests was in the upper 2 m of the soil profile but that the tritium from bomb tests had moved deeper than ^{36}Cl even though the bomb tests that produced most of the tritium took place about 10 years after the tests that produced the ^{36}Cl. Scanlon (1992) also obtained vertical profiles of ^{36}Cl, tritium, and total chloride in soil water at a site in an arid environment. She found that most ^{36}Cl from bomb tests was in the upper 1 m of soil and that tritium had moved downward nearly twice as far. Several possible reasons for the differences in rates of movement for tritium and ^{36}Cl have been suggested by Scanlon (1992) and by others. One is that there is a net downward flux of water in vapor form, which transports tritium but not chloride.

An important assumption in the bomb-pulse method is that the 1950's bomb tests are the prime source of anthropogenic ^{36}Cl. As was mentioned in a previous section, releases of ^{36}Cl to the atmosphere from operations at Hanford are suspected to have been small; however, elevated concentrations of ^{36}Cl in the environment near two other nuclear-material processing facilities have been attributed to operations at those facilities. Consequently, ^{36}Cl data collected at the Hanford Site must be examined to determine if they are affected by fallout from operations at Hanford. Fortunately, most of the activities at Hanford that might have resulted in releases of ^{36}Cl probably took place during approximately the same period as the bomb tests and therefore probably would not affect deep-percolation estimates made by this method.

DESCRIPTIONS OF THE HANFORD SITE AND SAMPLING AREAS

The Hanford Site occupies 1,450 km^2 of land adjacent to the Columbia River in semiarid south-central Washington (fig. 1). The site is adjacent to and northwest of the city of Richland. The southwestern border of the site is along the ridge of the Rattlesnake Hills. Nearly all activities relating to radioactive materials on the Hanford Site have been limited to the 900-km^2 area south of the river and east of Cold Creek Valley (State Route 240). Lands north and east of the river, but within the site boundaries, are wildlife areas that are managed by Federal and State agencies, and land southwest of State Route 240 is designated as the Arid Lands Ecology Reserve (ALE). The descriptions that follow are mostly of the area south and west of the Columbia River.

The topography of the Hanford Site between Cold Creek Valley and the Columbia River is that of a terraced plain with land-surface altitudes that range from about 100 m above sea level at the river to about 250 m in the northwestern part of the Site. Gable Mountain, a basalt ridge, protrudes about 150 m above the terrace surface. Southwest of Cold Creek Valley, land-surface altitude increases from about 160 m in the valley up to about 1,000 m on the ridges of the Rattlesnake Hills.

Geology

Numerous reports on the geology of the Hanford Site have been written to provide information to the operators and overseers of the site. Among them are the reports by Newcomb and others (1972) and by Delaney and others (1991). Much of the following description is taken from these two reports.

The Hanford Site lies in the Pasco Basin, a broad syncline in the Columbia River Basalts of Miocene age. In some places the upper surface of these rocks is as much as 240 m below land surface, but they are exposed at land surface in the ridge that protrudes above the terraces and in the hills along the southwestern and western boundaries of the site.

The basalts are overlain in most places by the Ringold Formation, a sequence of late Miocene to Pliocene unconsolidated sedimentary strata consisting largely of silt, sand, gravel, and volcanic ash. This formation is exposed on the Hanford Site only on the north side of the Columbia River. The upper surface of this formation is as much as 65 m below the surface of the terraced plain, and locally its maximum thickness is about 180 m.

The informally named Hanford formation of Brown and Isaacson (1977), hereafter referred to simply as the Hanford formation, is the predominant formation exposed at land surface on the site. Units in this formation consist mostly of unconsolidated sediments deposited by the Columbia River during a series of catastrophic floods that occurred when upstream ice dams breached during the middle to late Pleistocene. The last of these floods occurred about 13,000 years ago. The Pasco gravels, an informally named unit within the Hanford formation, consists of upper Pleistocene glaciofluvial and fluvial sands and gravels. In most places they overlie the Ringold Formation and are exposed at land surface on most of the terraced lands between the Columbia River and Cold Creek Valley. The river terraces were formed in the Hanford formation. The material of this formation is usually reworked by wind where it is exposed, and in some places the material is formed into sand dunes. The Pasco gravels are commonly 15 to 30 m thick but may be as much as 60 m thick in some places. Both the Pasco gravels and the Ringold Formation terminate where they butt against the Rattlesnake Hills. In the vicinity of the 200-West Area (fig. 1) other sedimentary units separate the Pasco gravels and Ringold Formation.

The Touchet beds of Flint (1938), another informally named unit within the Hanford formation, consist of silt and fine-sand glaciolacustrine deposits. These sediments mantle the slopes of the Rattlesnake Hills up to altitudes of about 350 m. Alluvial and colluvial deposits of Holocene age are found at land surface along the Columbia River and in Cold Creek Valley.

Surficial Soils

The surficial soils of an area that includes the present Hanford Site were described and mapped by Kocher and Strahorn (1919). Hajek (1966) used this information plus areal photographs and information from more recent soil surveys of adjacent areas to prepare a map of soils on that part of the Hanford Site that is south of the Columbia River. Most of the soils southwest of Cold Creek Valley are silt loams formed on deposits of the Touchet beds of Flint (1938) or fine-grained wind-blown deposits. Most of the surficial soils in the area between Cold Creek Valley and the Columbia River are sandy loams, loamy sands, or sands formed on materials derived from the Pasco gravels.

Climate and Hydrologic Setting

Stone and others (1983) gave an extensive description of the climate at Hanford. Much of the following description is from their report. Long-term annual average precipitation at the Hanford Meteorological Station, which is located on the terraced lands near the 200-West Area (fig. 1), is about 160 mm/yr. Precipitation at Richland, approximately 50 km to the southeast, is about 170 mm/yr (calculated with data in National Oceanic and Atmospheric Administration, 1990). Precipitation on the slopes of the southwest-bordering Rattlesnake Hills increases with land-surface altitude to a maximum of about 280 mm/yr. About 44 percent of the annual precipitation on the terraced plains falls during the three months November through January, while only 12 percent occurs in the months July through September. About 38 percent of the precipitation from December through February is snow. The monthly mean daily temperature for July, the warmest month, is 24.7°C (degrees Celsius), and the monthly mean for January, the coldest month, is -1.5°C. Daily maximum temperatures exceed 32°C on more than half the days in both July and August. The mean annual potential evapotranspiration at the Hanford Site exceeds 1,000 mm/yr (Bauer and Vaccaro, 1990), which is many times precipitation.

Except for the Columbia River, flow in most stream channels on the Hanford Site is ephemeral. Perennial flow occurs in a few locations downstream from springs on the slopes and at the base of the Rattlesnake Hills; however, this water seeps into the channel bottoms, and the channels are normally dry within 2 or 3 km downstream of the springs. Runoff of precipitation into most stream channels occurs only sporadically and does not occur every year. Most periods of runoff are the result of rapidly melting snow or short, intense summer storms on rocky land in the southwestern bordering hills. Even during most periods of runoff the water in the channels seeps into the ground before or a short distance after the channels reach the terraced plain.

Depth to ground water typically is about 30 m over much of the terraced plain, but it is as much as

100 m below land surface at the west end of the plain and reduces to near 0 m along the Columbia River.

Vegetation

The natural vegetal cover over the Hanford Site consists mostly of small shrubs with an understory of grasses. The most common shrubs are sagebrush (*Artemesia tritentata*), bitterbrush (*Purshia tridentata*), and rabbitbrush (*Chrysothamnus nauseouses*), with some hopsage (Grayia spinosa). The common grasses are cheatgrass (*Bromus tectorum*), an annual species that was introduced into eastern Washington during the 1800's, and Sandberg bluegrass (*Poa sandbergii*), a native perennial bunchgrass (U.S. Department of Energy, 1987, p. 4.23). Root depths of grasses tend to be relatively shallow, a few tenths of a meter, whereas the roots of shrubs, such as sagebrush, can extend a few meters below land surface.

Descriptions of Sampling Areas

This section gives brief descriptions of each of the six sampling areas. Their locations are shown on figure 1, and information about each area is summarized in table 1. Additional information about these areas and the methods of collecting samples in them is given in the section "Methods of Sample Collection and Analysis." Each sampling area is given a local name, such as Benson Springs, and a three-character identifier, such as F01. The local name relates the sampling area to previously named features or study areas on the Hanford Site. The three-character identifier is unique to this study and is used on most figures and tables. The letter F or C indicates the predominant texture of the subsurface soil in the area, fine or coarse, respectively, and the number that follows is a sequence number.

All study areas were in a nearly natural state, were only minimally affected by anthropogenic activities, and were populated with natural vegetation. However, the vegetation on one of the areas once had been killed by wildfire.

Area F01, Benson Springs

The Benson Springs sampling area (fig. 1, F01) is on an alluvial fan on the lower slopes of the Rattlesnake Hills at an altitude of about 300 m. Precipitation on this area, estimated from the data in Stone and others (1983), is about 210 mm/yr. This quantity is about one-third greater than on each of the other sampling areas because of the higher altitude of this area. Land surface in the vicinity of the area has a slope of about 5 percent; however, the sampling locations in this study were on local flats. The vegetation consists mostly of sagebrush, with other deep-rooted plants plus sparse grass. The soils are silt loams. Details on the maps of Hajek (1966) and of Kocher and Strahorn (1919) are sufficient only to determine that the soils are one or more of the following series: Lickskillet silt loam, Ritzville silt loam, Scooteny stoney silt loam, or Warden silt loam. The parent materials for these soils are the lacustrine deposits of the Touchet beds of Flint (1938), but the surface has been reworked by wind and water. The thickness of these deposits and the depth to the water table in the area are unknown. However, rocks prevented augering deeper than about 4.5 m at three locations, and water was not encountered in any of the sampling holes, the deepest of which was 4.8 m. A map by Kasza and others (1991) shows the water table in the vicinity of this area to be below the top of the basalts that underlie the sediments.

This area is also the location of a pair of lysimeters (referred to as the ALE lysimeters by Gee and others, 1992) that were operated by Pacific Northwest Laboratories. Both lysimeters were cubes approximately 1.5 m on a side. Each contained undisturbed local soil, but one was vegetated with sagebrush and the other with bunchgrass. No drainage was observed from the bottom of either lysimeter during the 4 years that they were monitored. The deep percolation estimated for this area by Bauer and Vaccaro (1990) was less than 0.1 mm/yr (H.H. Bauer, U.S. Geological Survey, Tacoma, Wash., oral commun., 1993).

Area F02, McGee Ranch

The McGee Ranch sampling area (fig. 1, F02) is near the base of the Rattlesnake Hills on the western border of the terraced lands. Land-surface altitude is about 245 m. Data from Stone and others (1983) indicate that precipitation on this area is about the same as at the Hanford Meteorological Station (160 mm/yr). The soil is Warden silt loam (Hajek, 1966), and the underlying sediments are the Touchet beds of Flint (1938). The land surface at the sampling locations is uneven, with sagebrush plants on 0.3-m-high hummocks. The soil between the hummocks is populated

Table 1. Summary descriptions of sampling areas and test holes

[Test-hole identifier beginning with the letter T denotes dug trench; letter B denotes bored hole. Soil DS indicates silt loam more than 4 meters thick; SG denotes about 0.6 meters of loamy sand or sandy loam overlying tens of meters of sand, gravel, and cobbles; and SS denotes about 0.6 meters of loamy sand overlying about 9 meters of clean sand. Vegetal cover B denotes sagebrush plus other deep-rooted plants and sparse grass; and G denotes only sparse grass]

Sampling area and test-hole identifiers	^{36}Cl data collected	Land-surface altitude (meters)	Maximum sample depth (meters)	Soil	Vegetal cover	Sample-collection dates
F01, Benson Springs				DS	B	
T01	no	302	3.05			05/18/90
T02	yes	300	4.19			05/18/90, 04/23/91
F02, McGee Ranch				DS	B	
T03	yes	247	4.60			05/19/90, 04/23/91
T04	no	247	4.72			05/19/90 to 05/20/90
C01, Liquid Effluent Recovery Facility				SG	B	
B10	no	182	42.7			06/21/90 to 07/11/90
B12	no	182	48.8			07/20/90 to 08/03/90
C02, Grass Site				SS	G	
B14	no	134	9.14			09/25/90 to 09/26/90
B15	no	134	8.81			09/26/90
B16	no	134	8.97			09/27/90
B19	yes	134	9.27			11/19/91 to 11/20/91
C03, 200-BP-1 Operable Unit				SG	B	
B17	no	169	39.4			09/27/90 to 10/19/90
B18	no	169	39.6			10/02/90 to 10/19/90
C04, C-018H Characterization				SG	B	
B20	yes	204	19.8			10/17/91 to 01/16/92

with sparse grass and contains desiccation cracks in many locations. Sampling locations in this study were between the hummocks. Although water was not encountered in any of the sampling holes, which had a maximum depth of 4.7 m, the land 300 m east of the sampling locations is 5 to 10 m lower and is marshy during parts of the year. A water-table elevation map by Kasza and others (1991) indicates that the water table is about 100 m below land surface.

Soil from this sampling area was excavated for use in two groups of lysimeters operated by Pacific Northwest Laboratories. The depth of soil in these lysimeters, which Gee and others (1992) refer to as FLTF and STLF, ranged from 1.5 to 1.7 m. No drainage was observed from these lysimeters when the surface was bare or populated by sagebrush, even when natural precipitation was augmented by irrigation at a rate equal to that of precipitation. However, when a bare silt-loam soil was covered with a thin layer of gravel, drainage quantities from the unirrigated and irrigated lysimeters were about one-half precipitation and precipitation plus irrigation, respectively. The estimate by Bauer and Vaccaro (1990) of deep percolation for this area was less than 0.1 mm/yr (H.H. Bauer, U.S. Geological Survey, Tacoma, Wash., oral commun., 1993).

Area C01, Liquid Effluent Recovery Facility

The liquid-effluent-recovery-facility sampling area (fig. 1, C01) is on terraced lands adjacent to the east side of the Hanford 200-East Area. Precipitation is probably nearly the same as at the Hanford Meteorological Station (160 mm/yr). Local topography has relatively low relief and is similar to other sampling areas on the terraces. Vegetation is primarily sagebrush with sparse grass and is also typical of that found on most of the terrace lands. However, the vegetation and upper few inches of soil were scraped off this area a few months before samples were collected. The surficial soil is either Burbank loamy sand or Ephrata sandy loam about 0.6 m thick. Information given by Connelly and others (1992) indicates that the geologic sequence consists of about 60 m of sand and gravels of the Hanford formation (Pasco gravels) directly overlying basalt. In December 1991 the water table was only a few meters above the top of the basalt (Connelly and others, 1992). However, about 300 m south of the sampling locations an open channel drains waste water from the 200-East Area to a pond about 1 km to the east. Water-surface elevations in the channel and pond are about 2 to 10 m lower than the altitude of land surface in the sampling area

Bauer and Vaccaro (1990) estimated that long-term deep-percolation rates for sagebrush-covered areas on the terraced lands, such as sampling areas C01, C03, and C04, range from about 2.5 to 10 mm/yr (H.H. Bauer, U.S. Geological Survey, Tacoma, Washington, oral commun., 1993). Rates varied with estimated water-holding capacity of the surficial soil.

Area C02, Grass Site

The Grass Site sampling area (fig. 1, C02) is on the terraced lands in the southeastern part of the Hanford Site at an altitude of about 135 m. Precipitation on this area is probably more similar to that at Richland (170 mm/yr) than at the Hanford Meteorological Station. The soil in this area was classified by Hajek (1966) as Rupert sand, but since then this soil has been renamed Quincy sand. The soil profile consists of about 0.6 m of loamy sand underlain by about 9 m of relatively clean sands. Gravel was encountered at a depth of about 9 m in each of four holes that were augered at this site as part of the current study. However, gravel was not encountered at a depth of 3.4 m as reported by Rockhold and others (1990).

The topography in the vicinity of the sampling area is rolling but is relatively flat at the sampling locations. Present vegetation consists of annual and perennial grasses with an absence of shrubs or other deep-rooted plants. Gee (G.W. Gee, Pacific Northwest Laboratories, Richland, Wash., oral commun., 1993) suggested that sagebrush likely vegetated the area at one time but was killed by a wildfire at some unknown date before December 1982, when PNL began to monitor soil moisture at the site, but has not grown back as it has in other places. A wildfire in August 1984 removed all surface vegetation from the area; however, grasses reestablished themselves within a few months, and the area has been grass covered to the present (1993). A water-table elevation map by Kasza and others (1991) indicates that depth to the water table is about 15 m.

Estimates of recharge in this area by personnel of Pacific Northwest Laboratories (Rockhold and others, 1990) were discussed in the "Introduction" section. These estimates ranged from 0.06 to 28 mm/yr. Bauer and Vaccaro (1990) estimated that the long-term average deep-percolation rate for an area on the terraced lands with sandy soil, and vegetated only with grass, is 23 mm/yr.

Area C03, 200-BP-1 Operable Unit

The 200-BP-1 Operable-Unit sampling area (fig. 1, C03) is on terraced lands north of the Hanford 200-East Area. Topography, surficial soil, vegetation, and precipitation are similar to those at sampling area C01. Information given by Connelly and others (1992) indicates that the surficial soil is underlain by 50 m or more of coarse-grained deposits of the Hanford formation (Pasco gravels), and in December 1991 the water table was about 48 m below land surface.

Area C04, C-018H Characterization

The C-018H Characterization sampling area (fig. 1, C04) is on the terraced lands north of the Hanford 200-West Area. Topography and vegetation are similar to those at sampling areas C01 and C03. The surficial soil in this area was classified by Hajek (1966) as either Burbank loamy sand or Ephrata sandy loam. Precipitation is probably the same as at the Meteorological Station (160 mm/yr). Information given by Trent (1992), who describes the area adjacent to and south of this area, suggests that the underlying sedimentary deposits are about 140 m thick and that the water table is about 65 m below land surface.

METHODS OF SAMPLE COLLECTION AND ANALYSIS

Data necessary for using the chloride mass-balance method were obtained by collecting and analyzing samples of soil from several depths in each of 13 test holes. Depths of holes ranged from about 4 to 50 m. One to four test holes were located in each of six different areas. Data for the chlorine-36 bomb-pulse method were obtained from 4 of the 13 holes—1 in each of 4 of the areas. Soil samples were collected by a variety of methods that ranged from manually coring in the sides of trenches that were dug with a backhoe, to power driving a split-spoon sampler in the bottom holes that were constructed by cable-tool machines. Laboratory analyses performed on all the samples included determinations of gravimetric water content, chloride concentration, and matric potential. Particle-size distributions of selected samples were also determined. Ratios of $^{36}Cl/Cl$ were determined for selected samples from those holes used to test the applicability of the bomb-pulse method.

Sampling Methods

Samples from the Benson Springs (F01), McGee Ranch (F02), and Grass Site (C02) areas were collected by USGS personnel from test holes constructed specifically for this study. Samples from holes in the other three areas (C01, C03, and C04) were obtained from holes being constructed for other purposes by subcontractors to the Westinghouse Hanford Company, the operations contractor for the Hanford Site. These samples were collected by personnel of Westinghouse Hanford Company or its subcontractors according to instructions provided by the USGS. Although the land surface in some of the sampling areas is sloped or rolling, each of the sampling holes was constructed on a local flat to minimize surface runoff of precipitation onto or off of the sampling-hole location. Each sampling hole is referred to in this report by an identifier (such as T01 or B10). The letter T or B identifies the hole as a dug trench or bored hole, respectively. The number that follows is a sequence number. These hole identifiers are referenced to other identifiers in Appendix A. Sample-collection dates are listed in table 1.

Areas F01 and F02

Samples were collected from two trenches in each of the areas F01 and F02 (holes T01 through T04, figs. 4 and 5). These trenches, which were excavated with a backhoe, were about 1 m wide, 4 m deep, and 8 m long. A continuous soil core consisting of a series of segments, each 55 mm in diameter and 100 mm long, was collected from each trench by repeatedly hammering a short, thin-walled, stainless-steel tube vertically into the soil along a vertical line about 0.1 m from the edge of the trench. After each core segment was obtained, the soil in a 0.2-m by 0.2-m square area surrounding the location from which the core segment was taken was removed with a square-ended shovel to create an open flat surface for starting the next core segment. In this way a 0.2-m by 0.2-m square notch with a depth equal to that of the trench was excavated in one of the trench walls. In addition to the samples collected from the walls of the trenches, soil samples from the bottom of the trench down to about 0.6 m below the bottom were collected with a hand auger.

Immediately after each core segment was collected, the soil in the thin-walled tube or auger was emptied into a 0.3-L glass jar with a water-tight gasketed metal lid, and an additional seal was made by wrapping the edge of the lid with plastic electrical tape. The sample jars then were placed in an insulated cooler for storage and eventual transportation to the laboratory for the various analyses. All laboratory determinations except for $^{36}Cl/Cl$ ratios were performed on these samples. The latter determination required a larger size sample than was obtained with the thin-walled tube or hand auger.

Because relatively large sample volumes are sometimes required for determining $^{36}Cl/Cl$ ratios, separate samples in 25-cm-long intervals were collected for these determinations. These samples were dug with a shovel out of the side of each trench along a vertical line adjacent to the 20-cm by 20-cm notch where the other samples were collected. Each of these samples, which had a mass of 10 to 20 kg, was placed in a plastic bag, which in turn was placed in a metal container along with other similar samples from the same trench. When these samples were processed it was found that samples of the upper three intervals from holes T02 and T03 did not yield sufficient chloride for determining $^{36}Cl/Cl$ ratios. (These ratios were not determined for samples from holes T01 and T04.) Consequently, the sampling sites were revisited 11 months later to collect an additional 30 kilograms of soil from each of these intervals. The additional material was collected within about 3 m of the original sample-collection location.

Samples were also collected from three augered holes in area F01 and another three in area F02. Samples from these holes, which ranged in depth from about 4 to 6 m, were never analyzed because the samples had dehydrated while being stored in plastic liners, and consequently, original water contents could not be determined.

Areas C01 and C04

Soil samples from the two holes in area C01 (holes B10 and B12, fig. 6), and the one hole in area C04 (hole B20) were obtained when these holes were being constructed by subcontractors to the Westinghouse Hanford Company. Although these holes extended below the water table to depths of about 100 m, samples for this study were collected only

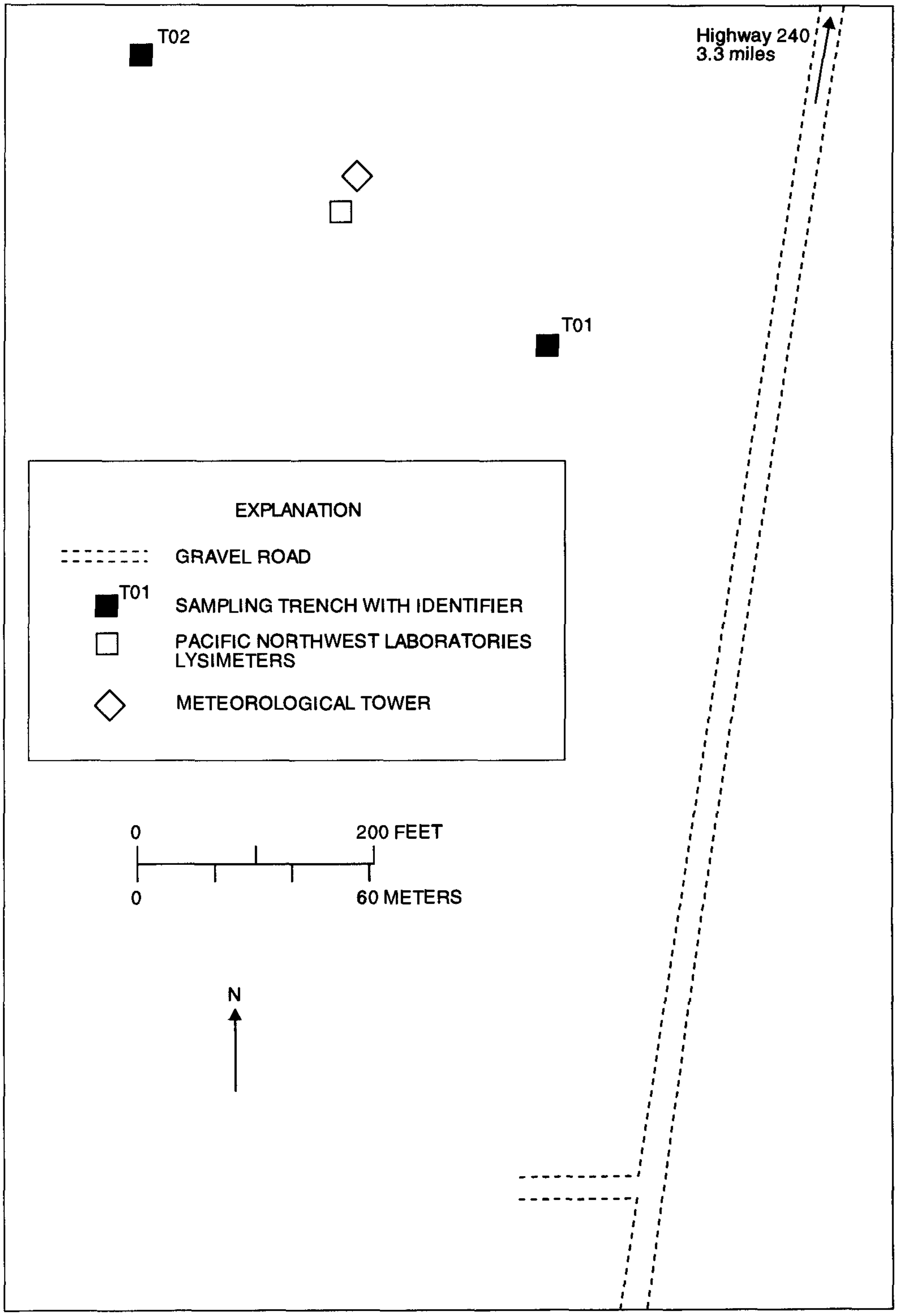

Figure 4. Locations of test holes in sampling area F01, Benson Springs. (See figure 1 for location of sampling area F01.)

down to about 60 m or less and only from above the water table. These holes were constructed by pounding a drive barrel, a short length of carbide-tipped steel pipe about 300 mm in diameter and 500 mm long, ahead of steel casing with a cable-tool apparatus and then advancing the casing. Soil normally would become sufficiently compacted in the drive barrel so that it could be brought to the surface for removal. When the material being drilled was especially hard or there were large rocks, the material was broken up and pulverized with a device termed a "hard tool." When this was done, it was often necessary to add

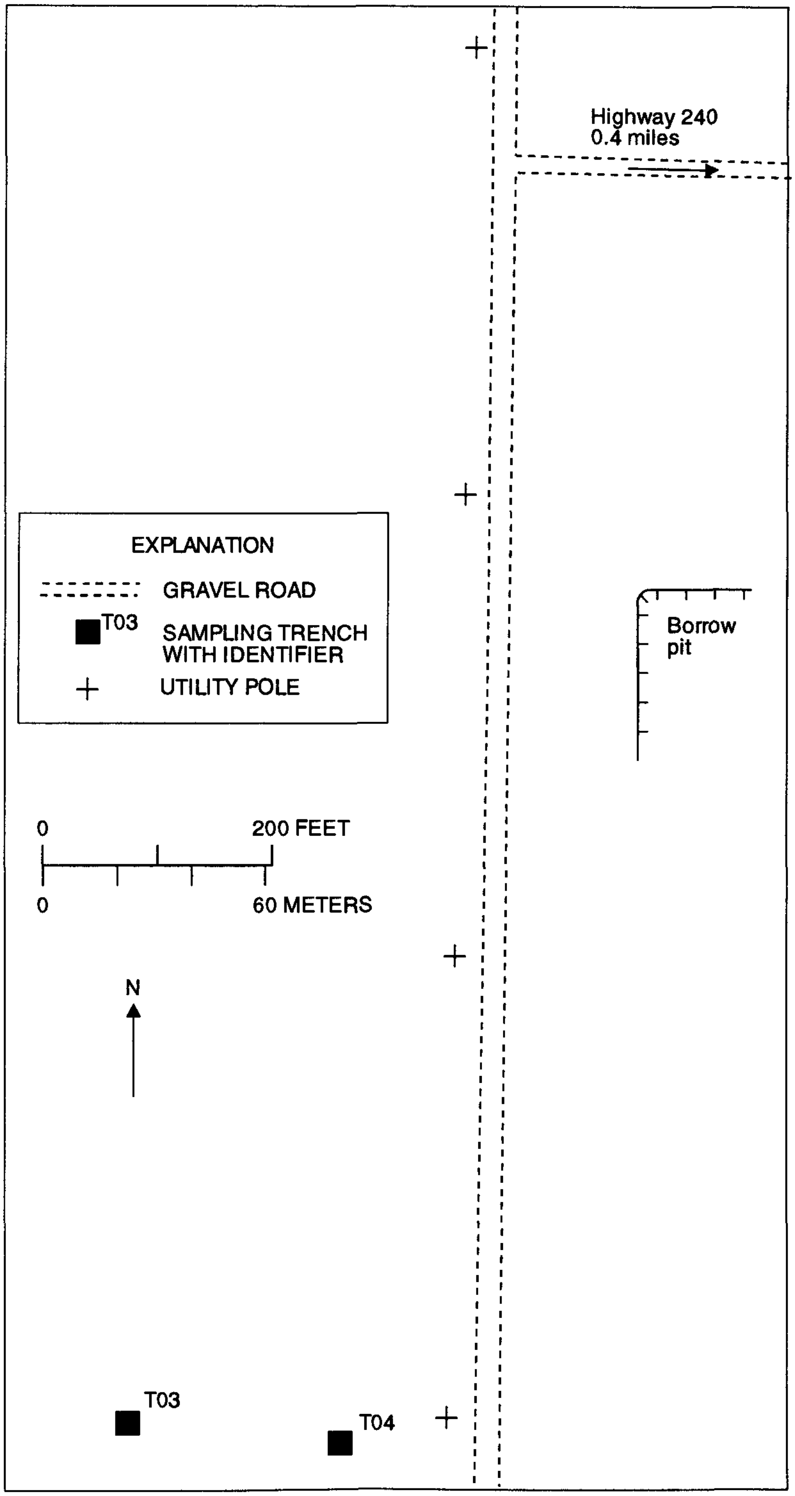

Figure 5. Locations of test holes in sampling area F02, McGee Ranch. (See figure 1 for location of sampling area F02.)

water to the hole to remove the dry pulverized material. This method of constructing holes to obtain geologic information and to install monitoring wells is commonly used at the Hanford Site and is one of the few methods that have been found suitable for the sandy gravels that are typical of the terraced lands at Hanford.

Although four holes were drilled and sampled in area C01, data from only two of the holes (B10 and B12) were used in this report because relatively large quantities of water were added to the other two during drilling. Data from samples deeper than where water was added to a hole are not used in this report except for samples from hole B10, where about 4 L of water was added at depths of 35 ft (10.7 m) and 110 ft (33.5 m).

Each sample from the holes in area C01 was normally collected by emptying one full drive-barrel into a 20-L plastic bucket. A 0.3-L glass jar was filled with soil from the bucket, excluding the larger pieces of gravel, and sealed immediately afterwards. The jar then was placed in the bucket and a lid was placed on the bucket for storage and transport. The contents of the jar were used for determinations of water content and of matric potential. The other laboratory determinations were made on the contents of the bucket.

The method of sampling in area C01 yielded data within 0.5-m-long intervals at selected depths within the soil profiles. This method was modified at hole B20 in area C04 to give samples that contained soil from the entire profile. At this hole the contents of each drive barrel were emptied into a wheelbarrow. Subsamples from the wheelbarrow were added to a 20-L plastic bucket and a glass jar that were used to accumulate and store other subsamples from the same sampling interval.

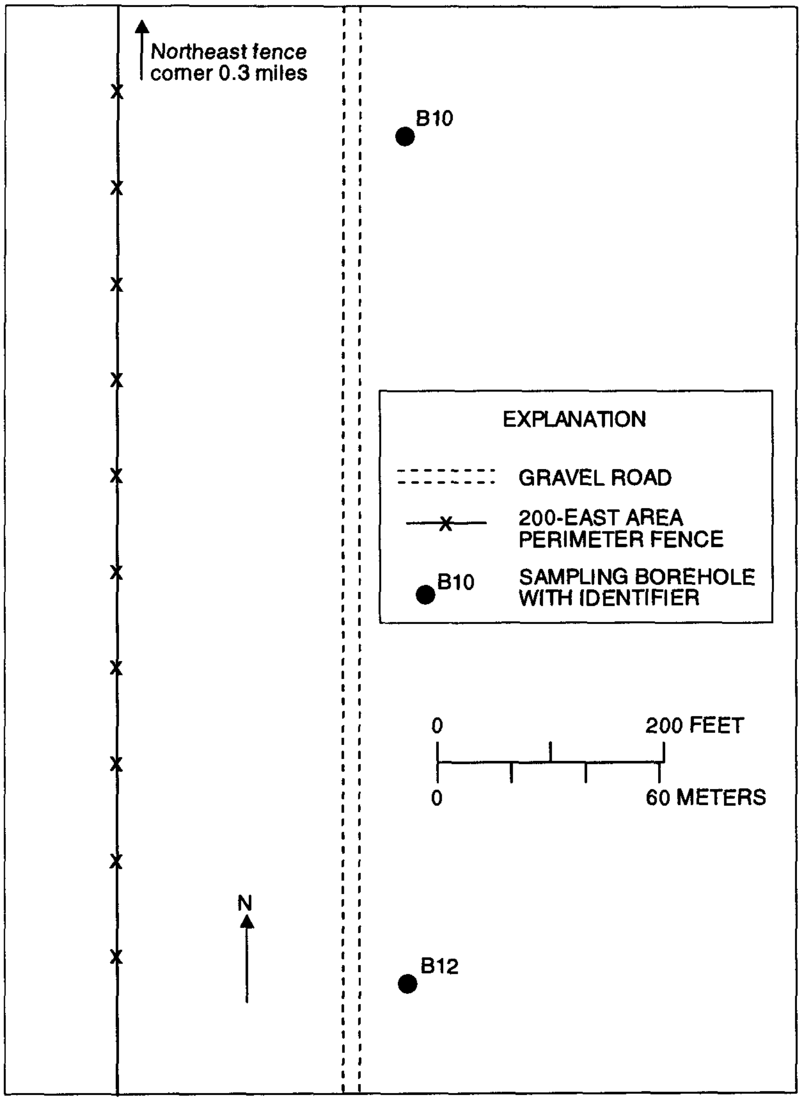

Figure 6. Locations of test holes in sampling area C01, Liquid Effluent Recovery Facility. (See figure 1 for location of sampling area C01.)

A normal pre-construction procedure at the Hanford Site is to scrape away all vegetation and the top few centimeters of soil from the area within about 20 m of the location of a well to be constructed. Consequently, two shallow samples (0.05 to 0.3 m and 0.3 to 0.6 m depth) were collected from area C04 before the construction area for hole B20 was scraped. These samples were collected 5.5 m from where the hole was actually constructed. Pre-construction samples were not collected at any of the other holes.

Area C03

Samples were collected from two holes in area C03 (holes B17 and B18) that were constructed using a cable-tool apparatus and drive barrel similar to those used in areas C01 and C04. However, the samples from the two holes in area C03 were collected with a 100-mm-diameter by 600-mm-long split-spoon sampler.

Area C02

Samples were collected from four holes at the Grass Site (fig. 7), each about 10 m deep. Two of the holes (B15 and B16) were located among the 25 holes installed by PNL for monitoring vertical profiles of water content. To reduce disturbances to the PNL test area, the other two holes (B14 and B19) were located about 15 m from the PNL holes. Samples from holes B15, B16, and B17 from deeper than about 0.6 m were collected with a continuous-corer inside a hollow-stem auger. Samples from the top 0.6 m were collected with a shovel or trowel. The auger was driven by a truck-mounted engine-powered drill and had an outside diameter of 184 mm and an inside diameter of 83 mm. The corer was a 76-mm outside-diameter split metal tube that held a 63-mm outside- diameter by 57-mm inside-diameter by 1.5-m-long plastic core liner that was cut into either 100-mm- or 250-mm-long segments. The lower end of the corer protruded about 6 cm below the cutting head of the auger. Although the corer advanced downward with the auger, the coring device was held in such a way that it did not rotate.

Most samples were collected by advancing the auger and corer about 0.7 m and then withdrawing the corer (but not the auger) from the hole for retrieving the samples. Although the corer was 1.5 m long, the lower end of the corer usually became plugged with compacted soil if the auger was advanced more than 0.7 m at a time. Immediately after the corer was with-

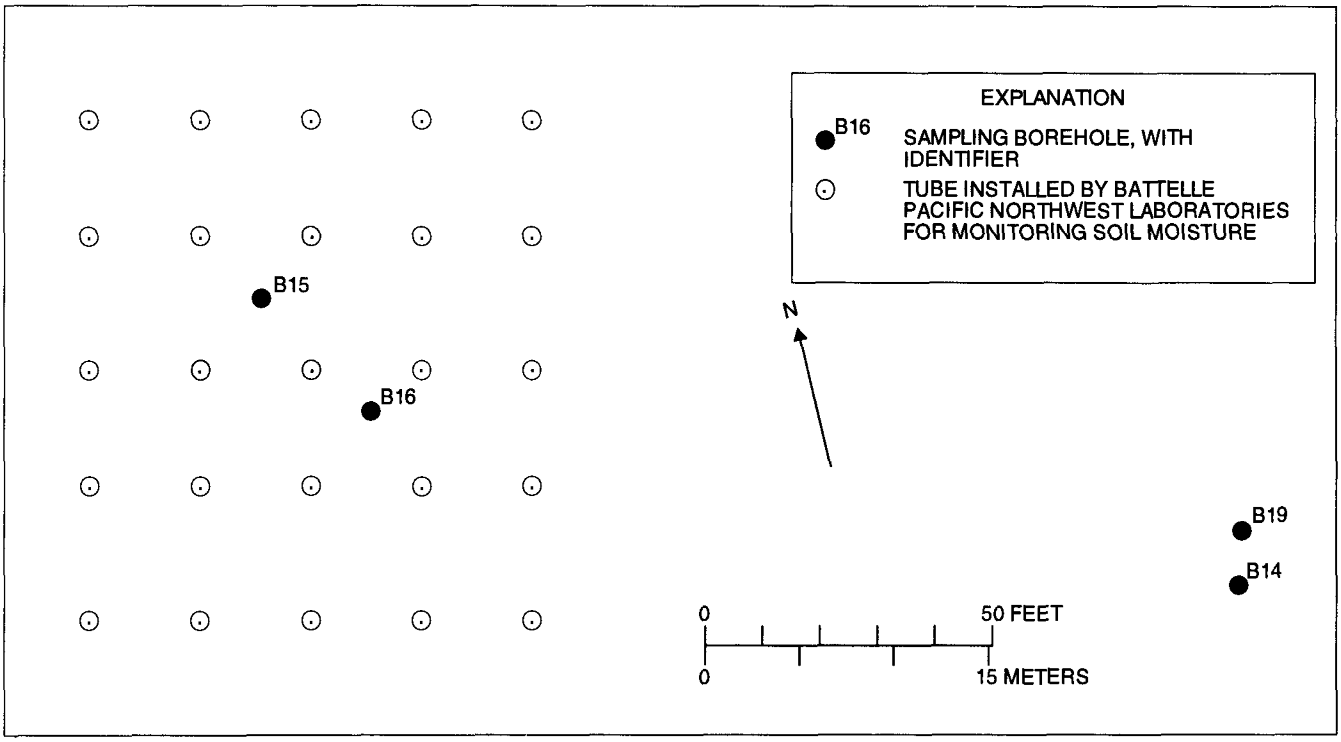

Figure 7. Locations of test holes in sampling area C02, Grass Site. (See figure 1 for location of sampling area C02.)

drawn from the hole, soil samples were removed from the liners and placed in sealed 0.3-L glass jars. If the total length of the core sample was less than the distance that the coring device was advanced, it was assumed that the core came from the top of the interval.

Because analyses of the samples from these holes indicated that the samples did not contain sufficient chloride for determining ^{36}Cl/Cl ratios, larger samples were collected from a fourth hole, B19, 14 months later. Samples from this hole down to a depth of about 2.5 m were obtained by pushing a 250-mm-diameter thin-walled metal pipe into the ground with the hydraulic power system of the truck-mounted drill and excavating from the inside of the tube with shovels and a manual auger-type post-hole digger. Samples from depths between 2.5 and 7.8 m were collected by pushing a 70-mm-diameter thin-walled steel tube ahead of a hollow-stem auger. Typically, the thin-walled tube was pushed a distance of about 0.4 m into the soil below the bottom of the auger and then withdrawn from the hole to retrieve the sample. The auger was then advanced the same distance, and the process was repeated. Measurements of the hole depth inside the auger confirmed that action of the cutting teeth on the bottom of the auger allowed little soil to enter the hollow auger when the auger was advanced. Samples from the depth interval 7.8 m to the bottom of the hole were obtained with the coring device that was used for collecting samples from holes B14, B15, and B16. The samples collected from hole B19 were placed in 20-L plastic buckets, and a representative subsample of each sampling interval was placed in a sealed 0.3-L glass jar.

Analyses of Samples

The samples collected for this study were analyzed to determine matric potential, water content, chloride concentration, particle-size distribution, and the ^{36}Cl/Cl ratio. The first of the three determinations was performed on nearly all soil samples, and the later two were performed on only selected samples.

Matric Potential

Matric potential, the negative value of a quantity that is sometimes called soil suction, is a measure of how strongly the water is held by the soil. The matric potential is one component of the total soil-water potential. The gradient of the total potential, which can have osmotic, gravitational, and other components in addition to the matric component, determines the rate and direction of movement of soil water. In dry soils the matric component often dominates.

In this study a relative measure of the matric potential of each sample was determined using the filter-paper method (McQueen and Miller, 1968, and Hamblen, 1981). This was the first determination made on each sample. Whatman No. 42 paper filters, 55 mm in diameter, were treated to prevent biological activity by soaking in a solution of 3 percent pentachlorophenol in methanol and drying overnight at 105°C. The soil samples in the 0.3-L glass jars were brought to thermal equilibrium by placing them in a thermostatically controlled constant-temperature locker (a refrigerator with heating as well as cooling capabilities) for 7 days or more at 20°C. To reduce possible effects of hysteresis, the treated filters were dried again for 1 hour at 30°C shortly before they were used. A filter then was placed in each jar on top of the soil; the jar was resealed and then placed inverted in the constant-temperature locker for an additional 7 days or more for the water content of the filter to come into equilibrium with the soil. The equilibrium water content of each filter was determined by removing it from the sample jar, shaking or brushing off soil particles, weighing the filter, drying the filter in an oven overnight at 105°C, and weighing again.

A relative matric potential of the soil sample was calculated from the water content of the filter using the formula

$$P = -1.122F^{-3.683}, \qquad (7)$$

where

P is the matric potential, in meters of water; and
F is the equilibrium water content of the filter as a fraction of its dry weight.

Equation 7 is a corrected and modified form of an equation given by Hamblen (1981, p. 357). (The algebraic sign of the first term on the right hand side of Hamblen's equation should be plus not minus.) Matric potentials that were calculated with this formula should be considered to be only relative rather than absolute values because equation 7 was not verified for the particular batch of filters used in this study or for the soils that were being analyzed. Also, because the samples were disturbed the matric potentials of some samples may differ from those of in-place soils. The matric potentials presented graphically in the following section and in tables in the appendix are in units of meters of water. To convert to other commonly used units, the following approximate relations may be used:

0.1 bar ~ 0.1 atmosphere ~ 1 meter of water ~ 10 kilopascals.

These are accurate to within 5 percent.

Water Content

Water contents were determined by analyzing all or parts of the samples stored in the 0.3-L glass jars. Water contents of samples from areas with soil that contained only particles smaller than 2 mm in diameter (areas F01, F02, and C02) were determined by analyzing 100-g subsamples. These were obtained by removing cores of soil from the jars with either a 20-mm- or a 15-mm-diameter metal tube. The subsamples were placed in a pre-weighed glass container, weighed, dried for 2 days in an oven at 105°C, and weighed again. Water content, in percent by weight, was computed as 100 times the weight of water lost by drying divided by the weight of dried soil.

Water contents of samples from areas with soil that contained some particles with diameters larger than 2 mm (areas C01, C03, and C04) were determined by weighing and drying the entire subsamples contained in the 0.3-L jars. However, these water contents needed to be adjusted because the samples in these jars contained less than a representative amount of large-size particles. Wet and dry weights of these samples were obtained as described in the previous paragraph. Each sample then was sieved to determine the weight of the fraction of the sample with particle sizes smaller than 2 mm (sand, silt, and clay). It was assumed that most of the water was associated with the soil particles in this size fraction; therefore, water content of the actual soil was computed by multiplying the laboratory-determined water content of the subsample in the 0.3-L jar by the ratio of percentages of less-than-2-mm material in the 0.3-L jar to that in the entire sample collected in a 20-L bucket. (See the footnote of table A3.) These adjusted water contents are shown on the graphs of the next chapter. In addition, a water content based on only the less-than-2-mm fraction was computed for use in calculating chloride concentrations in soil water. These were calculated by dividing the water content of the sample in the 0.3-L jar by the fraction in the jar of material that was less than 2 mm.

Chloride Concentration

The concentration of chloride in soil water was obtained by determining the amount of chloride per unit weight of dry soil and dividing that concentration by the original water content. The method used to extract chloride from a sample was similar to methods used by other investigators and is described in the following paragraphs.

Concentrations of chloride in soil from areas where the soil consists only of particles smaller than 2 mm were determined by analyzing 100-g subsamples taken from the glass jars. The subsamples were obtained by removing cores of soil from the jars in the same way that subsamples were obtained for water content. Chloride concentrations in soil from areas where the soil contains some particles larger than 2 mm were determined by analyzing 100-g subsamples of only the less-than-2-mm size fraction. This subsample was obtained by sieving the entire contents of the 20-L sample bucket to remove all material larger than 2 mm and repeatedly passing the less-than-2-mm size fraction through a sample splitter to obtain a representative subsample of the desired weight.

To extract the chloride, a subsample was put into a 0.18-L wide-mouth jar and dried in an oven overnight at 105°C. After the subsample had cooled, a quantity of deionized water equal in weight to that of the dried soil was added, and the jar with the soil and water mixture was rotated end over end at one revolution per second for 3 hours. The mixture was then allowed to stand for 1 to 24 hours, after which the water extract was decanted and passed through a 0.45-micron filter. The specific electrical conductivity of the extract was then measured, and the extract was sent to the USGS's National Water-Quality Laboratory in Arvada, Colo., where the chloride concentration was determined by ion chromatography (Fishman and Friedman, 1985).

In addition, chloride concentrations in most of the soil samples were also determined by a commercial laboratory (Northwest Agricultural Consultants, Kennewick, Wash.) using a different method. Instead of using deionized water, this other method used a solution of 1.5 g $CaSO_4.2H_2O$ per liter of water to extract the chloride from the soil. The soil to solution ratio was 1 to 2.5, and the mixture was shaken at 180 cycles per minute in a reciprocating shaker for 30 min. Calcium sulfate in the solution enhanced flocculation of soil particles, and the solution clarified by settling, so filtering was not required. Chloride concentrations in the extracts were determined by a ferric thiocyanate colorimetric method (Fishman and Friedman, 1985).

Although concentrations determined by the two methods nearly always agreed well when the chloride content of the soil was greater than about 25 mg/kg, concentrations sometimes differed by a factor of two or more when the chloride content of the soil sample was less than about 5 mg/kg. Because the reason for the differences in concentrations determined by the two methods could not be determined, only concentrations determined using distilled water and ion chromatography are given and used in this report in order to be consistent with the methods used in other studies of this type.

Particle-Size Distribution

Distributions of particle sizes larger than 0.062 mm were determined by sieving, and distributions of those smaller than 0.062 mm were determined with a device called a SediGraph 5100 (manufactured by the Micrometrics Corporation, Norcross, Ga, see for example Lara and Mathes, 1986). This device uses X-rays to automatically determine concentrations of sediment as functions of time at various depths in a water-filled settling column, and then uses these data to calculate particle-size distributions in a manner similar to that done in the commonly used pipet method (see, for example, Guy, 1977).

Particle-size distributions in fractions less than 2 mm were determined by analyzing 30- to 100-g subsamples. For areas in which nearly all soil particles were less than 2 mm in size (areas F01, F02, and C02), the subsamples were obtained by removing cores of soil from the 0.3-L sample jars. For areas with larger sized particles, subsamples were obtained by repeatedly splitting all the less-than-2-mm material in the 20-L sample buckets. Particle-size distributions in the fractions larger than 2 mm were determined by analyzing the entire contents of the 20-L buckets.

Determinations of distributions of particle sizes with the SediGraph and by sieving the less-than-2-mm fractions were done at the Sediment Analysis Laboratory in the USGS Cascades Volcano Observatory in Vancouver, Wash. Sieving to obtain particle-size distributions in fractions larger than 2 mm was done by project personnel.

Chlorine-36 to Total-Chloride Ratio

The $^{36}Cl/Cl$ ratio in a sample was determined by extracting the chloride from a sample with deionized water, precipitating the chloride as silver chloride (AgCl), purifying the precipitate, and analyzing the AgCl by mass spectrometry using a tandem mass accelerator.

The procedure for extracting chloride from samples for this analysis was nearly the same as for the determination of chloride concentration, the only difference being the sizes of the samples and the apparatus employed. To obtain at least 5 mg of chloride needed to determine the $^{36}Cl/Cl$ ratio, the sizes of the soil samples processed ranged from 1 to about 30 kg. For sample sizes from 1 to 5 kg, 1-kg subsamples of dry soil with equal quantities of water were mixed in 3-L plastic bottles by rotating the bottles end over end at one revolution per second for 3 hours. For larger samples, the entire amount to be processed was mixed with water in a 50-L plastic carboy by rotating for 3 hours at one-half revolution per second. The carboy was rotated by strapping it to a steel frame welded to a portable concrete mixer.

After mixing, the soil and water were allowed to stand for about an hour until some of the solids settled, and then the liquid was decanted and centrifuged at about 3,000 revolutions per minute for 30 minutes to settle additional solids. The liquid was then decanted again, filtered through a 0.45-micron filter, and reduced in volume to about 0.2 L by evaporating at about 90°C.

Chloride was extracted from the concentrated solution by adding silver nitrate ($AgNO_3$) to precipitate silver chloride (AgCl) and filtering through a 0.22-micron filter. Because the ^{36}S isotope interferes with the analysis for ^{36}Cl, sulfur contaminants in the AgCl were removed by repeating a process (Sharon Tullai, University of Rochester, Rochester, N.Y., written commun., May 30, 1989) that included washing and dissolving the precipitate in a sodium hydroxide ($NHOH_4$) solution, adding barium nitrate ($BaNO_3$) to precipitate barium sulphate (BaSO4), filtering the solution to remove the $BaSO_4$, adding nitric acid (HNO_3) to the solution to reprecipitate the AgCl, and recovering the AgCl by filtering again. This process was repeated until the filter for removing the $BaSO_4$

looked clean (about four times). The purified AgCl samples were dried in an oven, placed in glass vials, and kept in the dark until analyzed.

The $^{36}Cl/Cl$ ratios in the AgCl extracts were determined by mass spectrometry in the Nuclear Structure Research Laboratory at the University of Rochester. The methodology is described by Elmore and Phillips (1987).

To check for possible contamination of samples with ^{36}Cl during processing, two blank samples of Weeks Island halite dissolved in water were prepared and processed the same way as were the soil and water mixtures. (Weeks Island halite is an old material in which most of the ^{36}Cl has decayed and consequently has a low $^{36}Cl/Cl$ ratio.) The $^{36}Cl/Cl$ ratios for both blanks were less than 1 percent of the lowest ratio determined for any sample (Appendix B), indicating that contamination during processing was insignificant.

ESTIMATES OF DEEP-PERCOLATION RATES

Long-term average rates of deep percolation were estimated by the chloride mass-balance method using observed profiles of chloride concentration in soil water at 13 locations in 6 areas with natural vegetation. Deep-percolation rates at 4 of these 13 locations, one in each of four of the areas, were estimated by the ^{36}Cl bomb-pulse method using observed profiles of the $^{36}Cl/Cl$ ratio. These ratios were also used to estimate total atmospheric chloride deposition rates, which are necessary for the use of the chloride mass-balance method. Basic data are listed in Appendices B and C.

Atmospheric Chloride Deposition

Long-term average rates of deposition of chloride from the atmosphere to the land surface by precipitation and dry deposition can be computed using estimates of the rate of deposition of ^{36}Cl that is produced naturally in the atmosphere, and determinations of the natural $^{36}Cl/Cl$ ratio [the ratio in deep soil water that fell as precipitation before any anthropogenic production of ^{36}Cl (eq. 2)]. Samples from three of the four locations (holes T02, T03, and B20, figs. 8 and 9) were from depths great enough for estimating $^{36}Cl/Cl$ ratios in soil waters that predate both the 1950's bomb tests and any other production of anthropogenic ^{36}Cl. Average natural values of ratios for individual holes range from 735×10^{-15} to 876×10^{-15} (table 2, and figs. 8 and 9), and ratios in individual samples are given in Appendix B. The deepest sample from hole B19 in area C02 for which $^{36}Cl/Cl$ data are available appears to contain anthropogenic ^{36}Cl. However, $^{36}Cl/Cl$ ratios in the two samples from between 0.6 and 1.4 m depth are less than ratios at greater depths at this location and are about the same as ratios in the deepest samples from locations in areas F01, F02, and C04. Therefore, the average ratio in the 0.6 to 1.4 m depth interval (748×10^{-15}) is assumed not to be affected by anthropogenic ^{36}Cl.

The estimated atmospheric-chloride deposition rates for the four locations range from 33 to 39 mg/m^2/yr (table 2). These rates are two or more times the rates computed for precipitation alone, which implies that the atmospheric flux by dry deposition is at least as large as by precipitation. (An atmospheric chloride flux of 35 mg/m^2/yr is equivalent to a chloride concentration of 0.22 mg/L in precipitation when precipitation is 160 mm/yr.) These estimated deposition rates are used in the following section to estimate deep percolation by the chloride mass-balance method. The ^{36}Cl data for the shallow zone, where $^{36}Cl/Cl$ ratios are elevated, will be used in a later section to estimate deep percolation by the ^{36}Cl bomb-pulse method.

The observed natural $^{36}Cl/Cl$ ratios in deep soil water at T02, T03, and B20 are about five times the value for this location (about 150×10^{-15}) shown on a map of calculated natural ratios in the conterminous United States by Bentley and others (1986, fig. 10-2). This difference is not surprising, considering the steep gradient in the calculated ratio for the area around Hanford and the sparse data available for making the map. The observed ratios at Hanford are also about three times the average ratio (280×10^{-15}) in deep soil water observed by Cecil and others (1992) at one location on the Idaho National Engineering Laboratory. However, observed ratios at Hanford are only about one-third larger than ratios near the Idaho facility in stream and ground-water samples that are believed to be free of anthropogenic ^{36}Cl (Beasley and others, 1993). The Idaho facility is about 500 km southeast of the Hanford Site and also has a semiarid climate. The ratios observed at Hanford are also a little higher than the range (100×10^{-15} to 700×10^{-15}) observed in arid areas of the southwestern United States (Trotman, 1983; Norris and others, 1987; Mattick and others

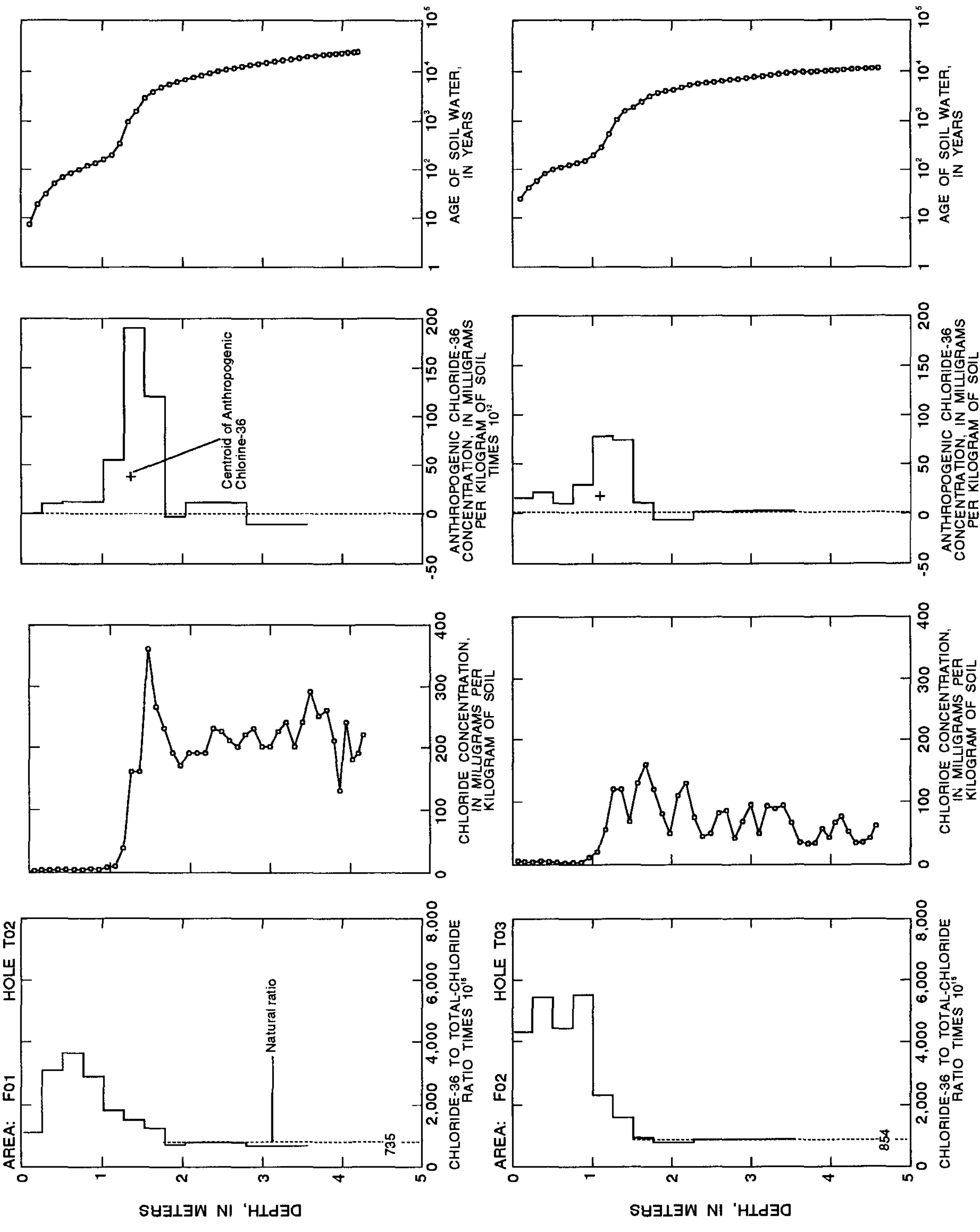

Figure 8. Vertical profiles of observed chlorine-36 to total-chloride ratio, chloride concentration in soil, anthropogenic chlorine-36 concentration in soil, and estimated age of soil water at holes T02 and T03.

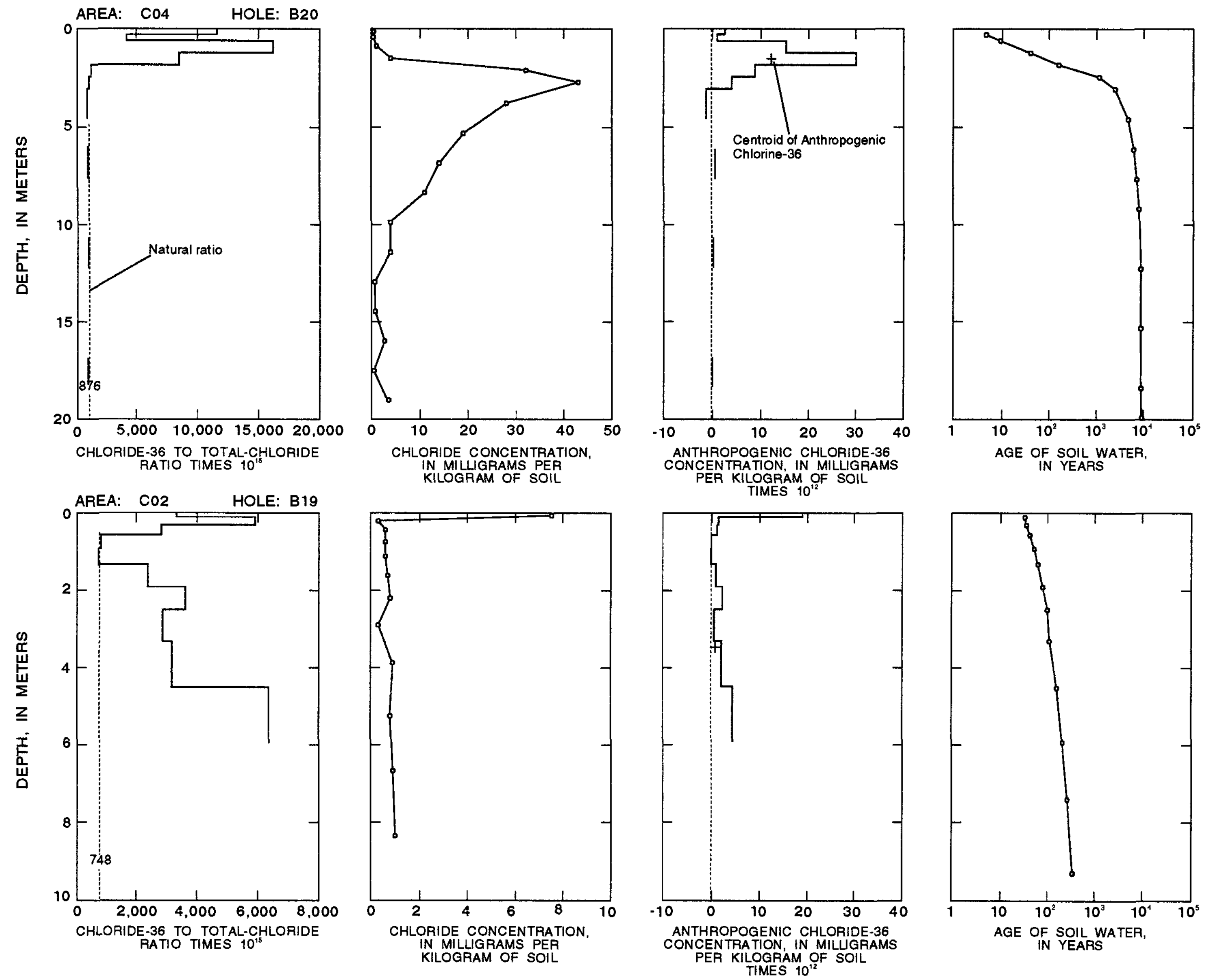

Figure 9. Vertical profiles of observed chlorine-36 to total-chloride ratio, chloride concentration in soil, anthropogenic chlorine-36 concentration in soil, and estimated age of soil water at holes B20 and B19.

Table 2. Observed ratios of chlorine-36 to total chloride (^{36}Cl/Cl) in soil water free of anthropogenic chlorine-36, and estimated rates of atmospheric deposition of chloride

[mm/yr, millimeters per year; mg/m^2/yr, milligrams per square meter per year; atoms/m^2/s, atoms per square meter per second; mg/L, milligrams per Liter]

Sampling location		^{36}Cl/Cl at indicated depth in meters		Precip-itation	Atmospheric deposition of chloride (mg/m^2/yr)	
Area	Hole	Ratio	Depth	(mm/yr)	Total[1]	By precipitation[2]
F01	T02	735×10^{-15}	1.78 to 3.56	210	39	19
F02	T03	854×10^{-15}	1.78 to 3.56	160	34	14
C02	B19	748×10^{-15}	0.56 to 1.32	170	39	15
C04	B20	876×10^{-15}	3.0 to 18.3	160	33	14

[1] Computed using the observed ^{36}Cl/Cl ratio in soil water that is believed to be free of anthropogenic ^{36}Cl and equation 2, which includes an estimated rate for atmospheric deposition of naturally produced ^{36}Cl of 15.5 atoms/m^2/s.

[2] Computed using a chloride concentration in precipitation of 0.09 mg/L. (See figure 2 and section "Chloride in the Environment").

1987; Phillips and others, 1988; and Scanlon and others, 1990).

The observed natural ^{36}Cl/Cl ratios at Hanford are also considerably higher than 12×10^{-15}, the estimated upper limit of the ratio that would result from neutron activation of ^{35}Cl (see the section "Chloride in the Environment"). Consequently, the effect of in-situ production of ^{36}Cl on natural ^{36}Cl/Cl ratios and on calculated total atmospheric-chloride deposition rates probably is less than 2 percent.

Deep Percolation Estimated by the Chloride Mass-Balance Method

Deep-percolation rates were estimated by the chloride mass-balance method (eq. 4) using observed chloride concentrations in soil water below the root zone (typically below about 2 m) and estimated rates of atmospheric deposition of chloride (table 2). Estimates by this method (table 3) range from 0.008 to 2.0 mm/yr, which are only about 0.004 to 1 percent of precipitation. However, comparisons of profiles of total chloride and chlorine-36 in a later part of this section indicate that the mass-balance method may underestimate deep-percolation rates.

Areas F01 and F02

Estimated deep-percolation rates in the two areas with fine-grained soils (F01 and F02) range from 0.008 to 0.11 mm/yr (table 3). At three of the four holes in these two areas (holes T01 and T02 in area F01, and hole T03 in area F02), chloride concentrations in soil water within the upper 1 m of the soil column were relatively low (less than 150 mg/L) but increased abruptly to relatively large values (in the thousands of milligrams per liter) at greater depths (figs. 10 and 11). Estimated deep-percolation rates at T01, T02, and T03, which range from 0.008 to 0.024 mm/yr (table 3), were calculated from the smallest concentrations observed below the root zones and therefore are the largest possible estimates of deep percolation at these locations.

At hole T04, which was only about 60 m from T03 and at a location where the vegetation and surficial soil appeared to be the same as at T03, concentrations did not exceed 400 mg/L, even at a depth of nearly 5 m (fig. 11). Although concentrations did increase abruptly at a depth of about 1.6 m, as at T01, T02, and T03, concentrations did not reach values as high as at these other locations. Concentrations decreased again before following a general trend of increasing with depth. The calculated percolation rate

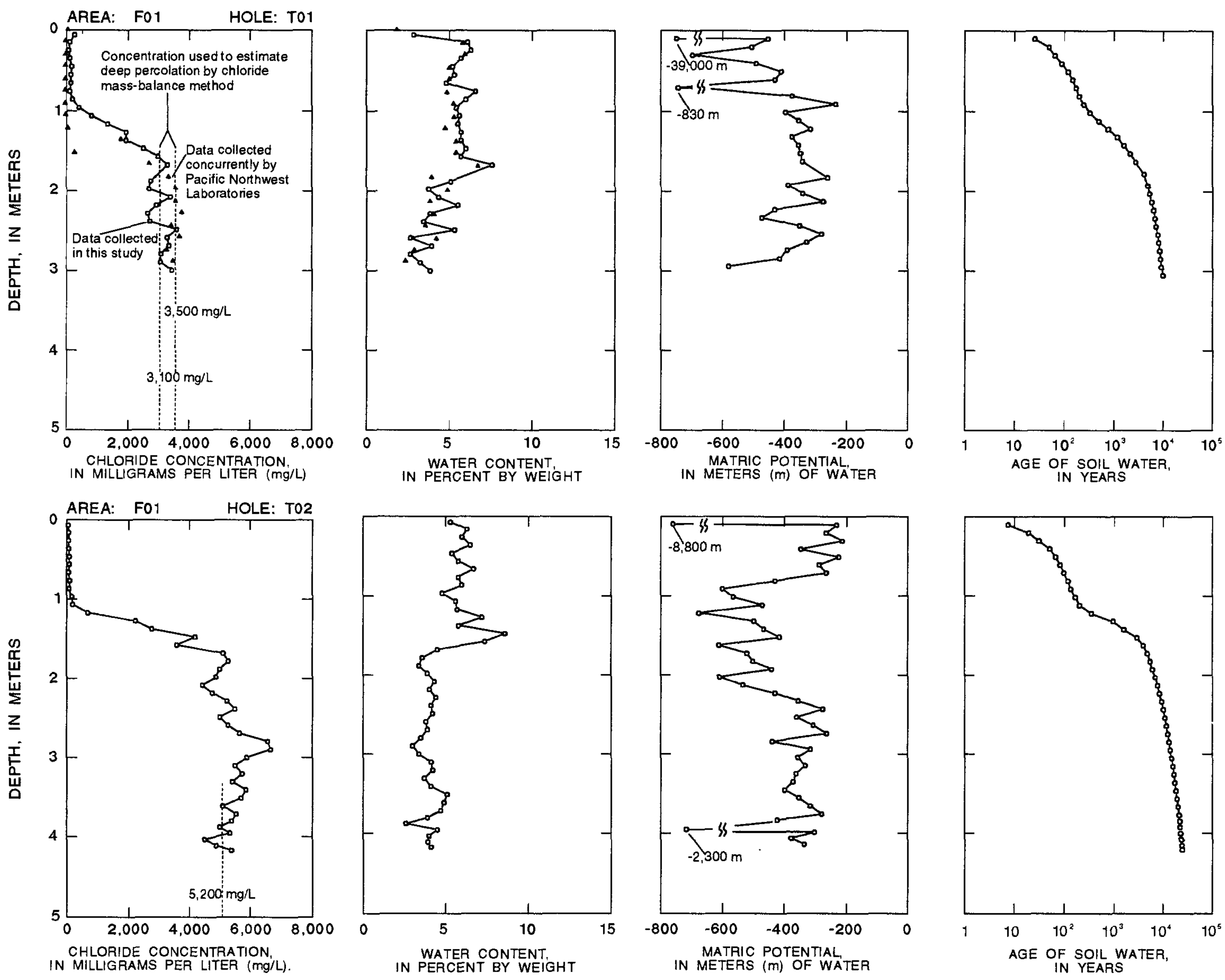

Figure 10. Vertical profiles of observed chloride concentration in soil water, water content and matric potential of soil, and estimated age of soil water at holes T01 and T02 in area F01.

Table 3. Long-term average rates of deep percolation of precipitation estimated by the chloride mass-balance method and the chlorine-36 bomb-pulse method

[Numbers in parentheses denote alternate interpretations of data that give larger, but less likely, estimates of deep percolation; $mg/m^2/yr$, milligrams per square meter per year; mg/L, milligrams per liter; mm/yr, millimeters per year; --, indicates no data; <, indicates less than]

Sampling location		Atmospheric chloride deposition[1] ($mg/m^2/yr$)	Chloride concentration (mg/L)	Deep percolation estimated by indicated method (mm/yr)	
Area	Hole			Mass-balance	Bomb-pulse[2]
Benson Springs					
F01	T01	39	3,100	0.013	--
F01	T02	39	5,000	0.008	<3.4
McGee Ranch					
F02	T03	34	1,400	0.024	<2.1
F02	T04	34	320	0.11	--
			(80)	(0.42)	
Liquid Effluent Recovery Facility					
C01	B10	33	760	0.042	--
			(12)	(2.8)	
C01	B12	33	1,600	0.021	--
			(6)	(5.5)	
200-BP-1 Operable Unit					
C03	B17	33	520	0.062	--
			(18)	(1.8)	
C03	B18	33	110	0.30	--
			(28)	(1.2)	
C-018H Characterization					
C04	B20	33	2,700	0.012	<2.6
			(50)	(0.66)	
Grass Site					
C02	B14	39	100	0.39	--
C02	B15	39	20	2.0	--
C02	B16	39	35	1.1	--
C02	B19	39	27	1.4	5.1[a]

[1] From table 2: area F01, value from hole T01; area F02, value from hole T03; areas C01, C03, and C04, value from hole B20; area C02, value from hole B19.

[2] From table 4.

[a] Actual rate at hole B19 may be larger than this value.

at T04 is 0.11 mm/yr when the concentration near the bottom of the sampled interval (320 mg/L) is used. However, the estimated percolation rate at greater depths would be less if the concentration continued to increase with depth below the sampled interval. Conversely, the estimated percolation rate would be greater (0.42 mm/yr) if the smaller concentration (80 mg/L) observed between 2.5 and 3.0 m were used. The reason for the larger apparent deep percolation at T04 is not known, but it may be the result of a

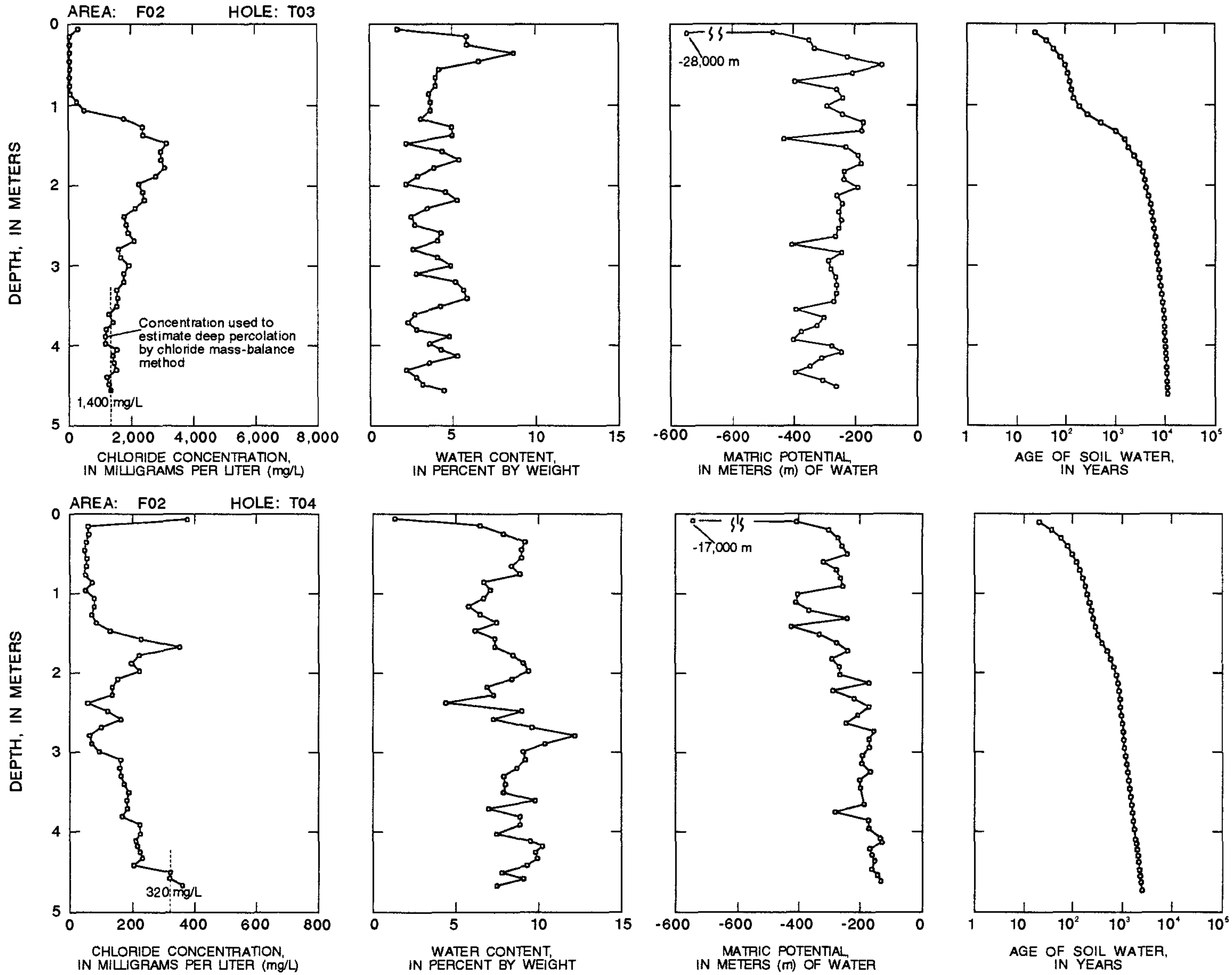

Figure 11. Vertical profiles of observed chloride concentration in soil water, water content and matric potential of soil, and estimated age of soil water at holes T03 and T04 in area F02.

redistribution of water by the hummocky topography in area F02 (see, for example, Link and others, 1994).

The estimates of deep percolation at all four locations in the two areas of fine-grained soil are in the range of estimates by previous investigators using other methods. These include estimates of 0.0 mm/yr using lysimeters (Gee and others, 1992), 1.8 mm/yr using a numerical model (Smoot and others, 1989), and less than 0.1 mm/yr using soil-moisture accounting (Bauer and Vaccaro, 1990). Although absolute differences between current and previous estimates are of the order of a few millimeters or less, relative differences are of the order of factors of 10 or more.

Visual inspections of the walls of trenches T01, T02, and T03 at the times the samples were collected revealed layered evaporite deposits at about 1 m depth and deeper. Thicknesses of these layers ranged from a few tens to a few hundreds of millimeters. At T01 the thickness of the shallowest layer varied over this range within 1 m horizontally. Plant roots were abundant in the soil above the topmost evaporite layer but were sparse below this layer. There was a dense mat of roots on top of the upper evaporite deposit in some places. The concentration profiles and visual observations of roots and evaporite deposits in these three trenches suggest that most of the precipitation that infiltrates the land surface at these locations remains in the upper 1 or 2 m of soil until it evaporates or is used by plants; little percolates to greater depths. The observed evaporite deposits at T04 were much less developed than at the other trenches, which may be related to the larger estimated percolation rate at this location.

When the samples for this study were being collected from trench T01, staff of the Pacific Northwest Laboratories (PNL) collected and analyzed an independent set of samples from the wall of this trench along a vertical line about 1 m east of where the samples for the current study were being collected. These data were provided to the author by Ellyn M. Murphy (E.M. Murphy, Battelle, Pacific Northwest Laboratories, Richland, Wash., written commun., July 12, 1990), and graphs of the data were published by Murphy and others (1991a). The average chloride concentration in soil water from deeper than 1.8 m in the PNL set of samples was 13 percent greater than the average concentration in corresponding samples collected for the present study (see fig. 10). This larger concentration would result in an estimated percolation rate that is 13 percent lower than the 0.013 mm/yr obtained in the present study. The average concentration in the PNL samples from shallower than 0.8 m was about four times as great as the average in corresponding samples for the present study (130 mg/L). Although the difference between concentrations at the shallow depths was large, these concentrations were in the root zone and were not used in making estimates by the mass-balance method; however, they were used in calculations of the age of soil water. The differences in concentrations in both the deep and shallow samples either could reflect actual differences in concentrations in the samples collected from the two closely spaced locations or could be a result of small differences in laboratory procedures for determining concentrations, even though both laboratories used basically the same methods.

Vertical profiles of water content of the soil were similar at T01, T02, and T03 (figs. 10 and 11). Water contents at depths below about 2 m were mostly between 3 and 5 percent by weight at T01 and T02 but were slightly smaller (2 to 5 percent) at T03. (To obtain water content in percent by volume, multiply water content in percent by weight by the ratio of the dry bulk density of the soil to the density of water, which for these silty soils is about 1.4.) Water contents at depths shallower than about 1.2 m were mostly between 5 and 7 percent by weight at T01 and T02 but were smaller and larger at T03. Water contents, as well as chloride concentrations, in this shallow zone probably vary seasonally in response to infiltrating precipitation and evapotranspiration. The observed small water contents at a depth of about 0.1 m at T01, T03, and T04 probably were a result of a dry period that preceded the sampling. Water contents at T04 at nearly all depths were larger (mostly in the range 6 to 10 percent) than at T01, T02, or T03, which is consistent with the smaller chloride concentrations and larger estimated percolation rate at T04.

Observed values of matric potential were of the order of minus hundreds of meters of water. The relatively large negative values (large soil suction) indicate that the flow of water was probably controlled more by gradients in matric potential than by gravity. At each of the four sampling locations in areas F01 and F02, the direction of the potential gradient within about 0.1 m of land surface indicates that at the time of sampling the soil was losing water to the atmosphere (water flows in the direction of decreasing potential). A loss of water to the atmosphere is consistent with the fact that a dry season preceded the time of sampling. Gradients in matric potential at depths greater than a few tenths of a meter were not consistent among holes or with depth at some of the holes. In some cases the direction of the general gradient is obscured by scatter of the data. At T01 the general trend of the matric potential suggests the flow of water was upward in the zone shallower than about 1 m and was downward below this depth. At T02 the gradients suggest that between about 0.2 and 1 m depth water was flowing down, and between about 1 and 3 m depth water was flowing up. At T03 there was a steep gradient indicating upward flow of soil water at depths shallower than about 0.5 m, but the apparent trend in matric potential below this depth suggests downward flow. At T04 the trend in matric potential suggests an upward flow of soil water throughout the depth of the soil profile.

The observed matric potentials and inferred directions of flow could represent only the time that the samples were collected and not be representative of mean annual flow directions. Measurements of potential with in-place thermocouple psychrometers at an arid site near Beatty, Nev., varied seasonally down to depths of about 7 m (Fischer, 1992). However, variations in water content at depths greater than about 2 m were too small to be detected.

The estimated ages of soil water at the bottom of the sampled profiles are about 2,500 years at T04, 10,000 years at T01 and T03 and 23,000 years at T02 (figs. 10 and 11). Ages were estimated using equation 5 with observed chloride concentrations, estimated chloride fluxes from table 2, and a dry bulk specific gravity of 1.4 g/cm^3. The oldest ages at T01, T03, and T04 are consistent in that they are less than 13,000 years, the approximate youngest age of the Touchet beds, which is the parent material in areas F01 and F02. The oldest estimated age at T02 exceeds the estimated age of the soil. The reason for the abnormally high estimated age is unknown, but one possible reason is that this location may have received runoff, and hence chloride, from adjacent locations. If this were true, then the chloride flux used in the denominator of equation 5 for this location is low and the estimated age is high. This would also mean that the chloride-flux term in the numerator of equation 4 for estimating deep percolation are also low, causing the deep percolation at this location to be underestimated.

A deep-percolation rate computed from a chloride concentration at a given depth is an estimate of the deep-percolation rate that is a result of the climate, soil, and vegetation that existed at and during some period following the time the soil water at that depth fell as precipitation. The estimated ages of soil water near the tops of the zones of large chloride concentration at T01, T02, and T03 range from about 1,000 to 3,000 years. Consequently, the present soil, vegetation, and climate conditions will result in deep-percolation rates that equal the estimated rates only if these conditions have not changed in the previous 1,000 to 3,000 years. (The rates for T03 were estimated from chloride concentrations at the bottom of the profile where the estimated age is about 10,000 years but where the chloride concentrations are smaller and yield estimates that are greater than would be obtained if the larger concentrations at lesser depths were used.)

Areas C01, C03, and C04

The soil in each of the areas C01, C03, and C04 consists of about 0.6 m of silty sand overlying tens of meters of material that is predominantly sandy gravel or gravelly sand. The upper parts of the distributions of chloride concentration in these areas (figs. 12, 13, and 14) were similar to the distributions in areas F01 and F02 (figs. 10 and 11) in that concentrations were relatively small near the surface but increased rather abruptly by a factor of 10 or more at depth. However, the depths at which the increases occurred are 2 to 8 m as compared with 1 to 2 m in areas F01 and F02. Maximum concentrations at holes B12 and B20 were in the thousands of milligrams per liter, as they were at three of the four holes in areas F01 and F02. At B10 and B17 concentrations exceeded 500 mg/L, but at B18 maximum concentrations were only about 200 mg/L and concentrations varied erratically. Also, concentrations at all holes in areas C01, C03, and C04 decreased to less than about 50 mg/L at depths greater than about 10 m. Similar decreases in concentration with depth were not observed in the data from areas F01 and F02, perhaps because samples from areas F01 and F02 were not collected from as great a depth (maximum of 5 m) as were samples from areas C01, C03, and C04 (more than 20 m). It is proposed that the elevated concentrations at the intermediate depths are the result of climatic, soil, and vegetal conditions that existed over the past few thousand years and that the smaller concentrations at greater depths are relics of different earlier conditions. Events that changed conditions are discussed later in this section.

Deep-percolation rates at locations in areas C01, C03, and C04 were estimated from the chloride concentrations in the depth intervals with the greatest concentrations (table 3, and figs. 12, 13, and 14). The

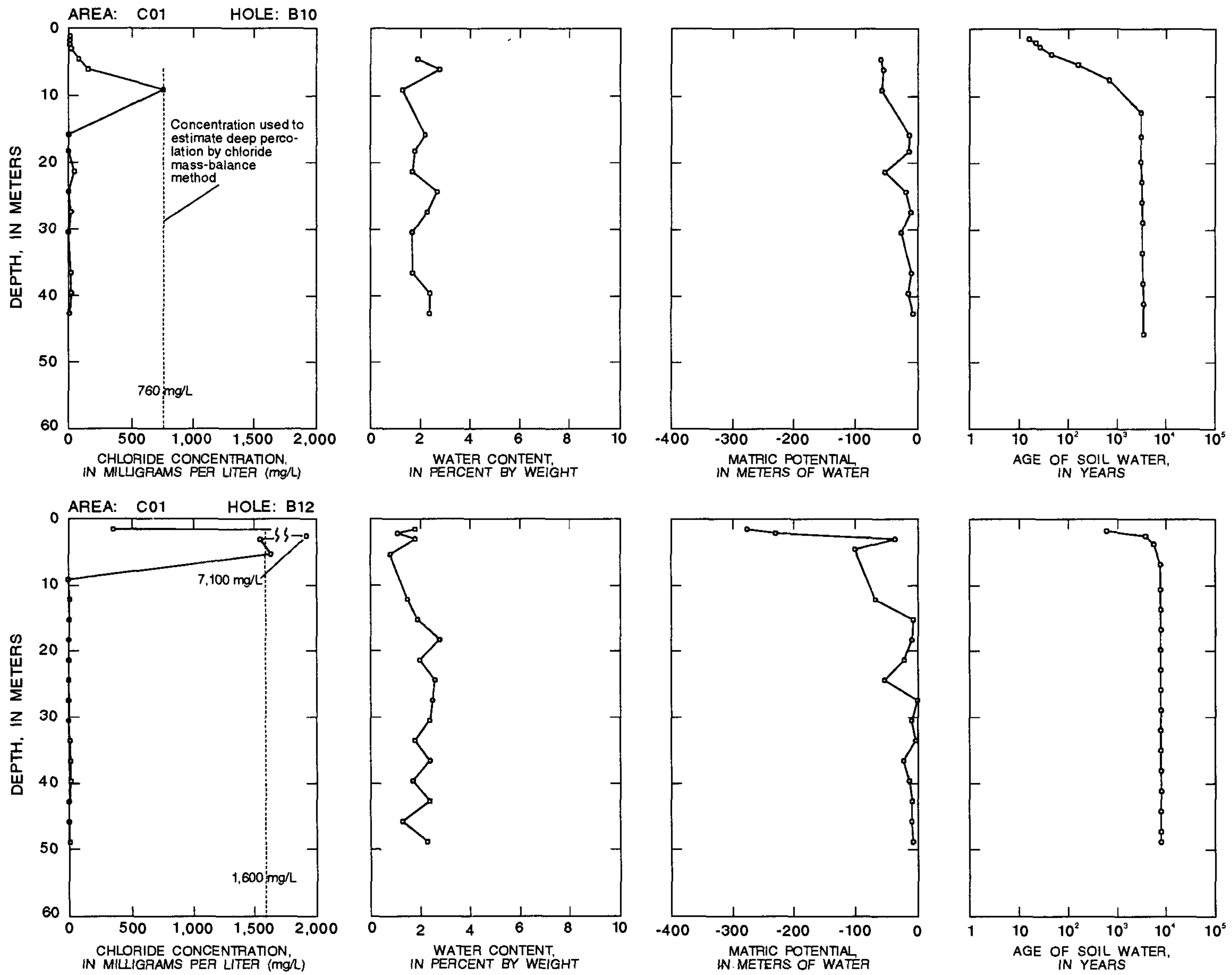

Figure 12. Vertical profiles of observed chloride concentration in soil water, water content and matric potential of soil, and estimated age of soil water at holes B10 and B12 in area C01.

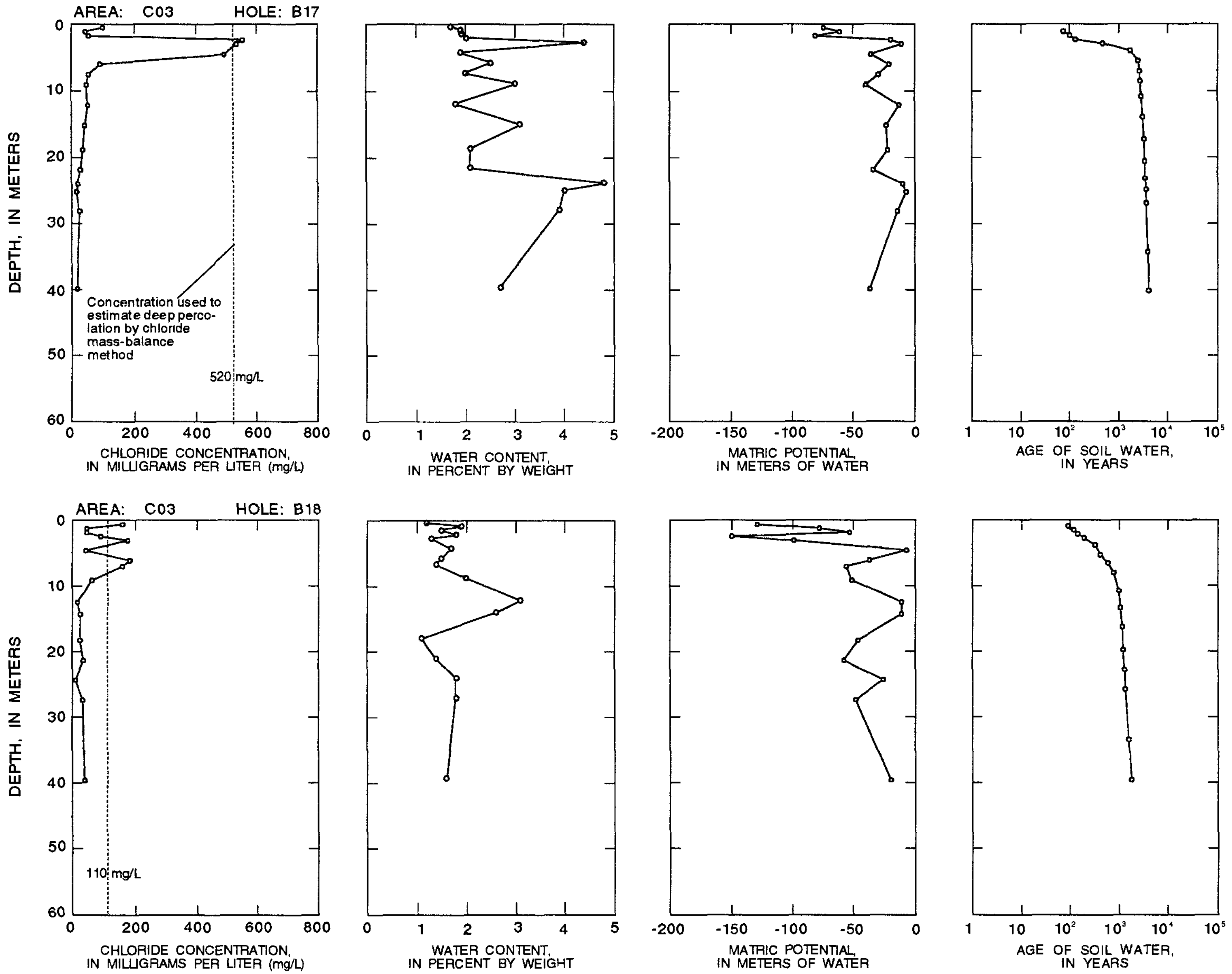

Figure 13. Vertical profiles of observed chloride concentration in soil water, water content and matric potential of soil, and estimated age of soil water at holes B17 and B18 in area C03.

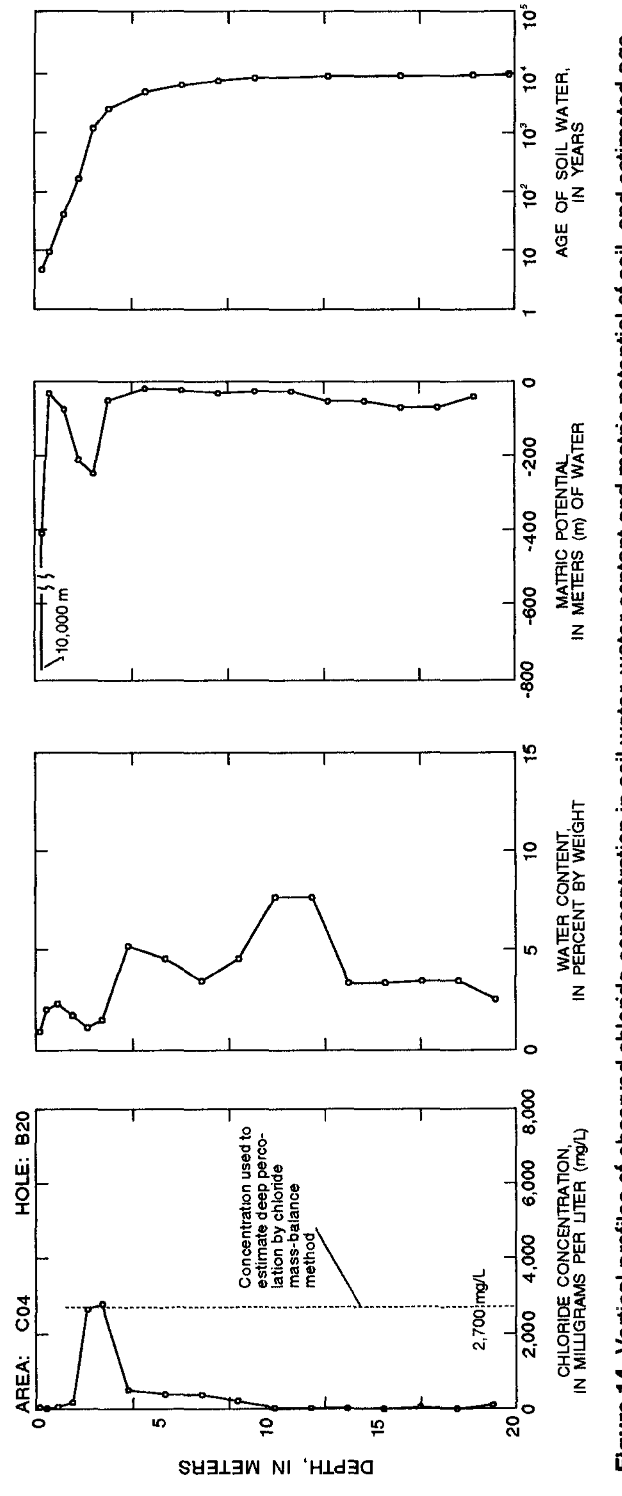

Figure 14. Vertical profiles of observed chloride concentration in soil water, water content and matric potential of soil, and estimated age of soil water at hole B20 in area C04.

estimated rates range from 0.012 to 0.30 mm/yr. These estimates are a factor of 10 or more less than the range of 2.5 to 10 mm/yr estimated for these types of areas by Bauer and Vaccaro (1990).

In areas C01, C03, and C04 typical water contents were smaller and matric potentials were higher (smaller soil suction) than in areas F01 and F02. These differences are to be expected because the soils in areas C01, C03, and C04 are coarser and have lower water-retention capacities than the silty soils in areas F01 and F02. Water contents were about 2 percent by weight at holes B10, B12, and B18 but were slightly larger at B17 and B20. (To obtain water contents in percent by volume of soils in areas C01 through C04, multiply water contents in percent by weight by the ratio of the dry bulk density of the soil to the density of water, which for these coarse-grained soils is about 1.7.) Matric potentials near the surface at B12, B17, B18, and B20 indicate that soil water was moving upward during the sampling period, as it was in areas F01 and F02. Matric potentials at depths greater than about 20 m were on the order of -50 m of water. Although there is considerable scatter in the data, overall gradients in matric potential at depths greater than 20 m appear to have been in the range of about 0 to 1 (decreasing upward). Because the gradient in gravitational potential is unity (decreasing downward), resulting gradients in the total (matric plus gravitational) potential (0 to 1 decreasing downward) suggest no flow or a slight downward flow.

Vertical profiles of chloride concentration similar to those in areas C01, C03, and C04 in which concentrations are elevated at an intermediate depth as compared to concentrations at greater and lesser depths also have been observed by Murphy and others (1991b) at one location on the Hanford Site and by other investigators at other arid or semiarid areas (see, for example, Stone, 1987 and 1992; and Scanlon, 1991). One reason that has been suggested for this type of profile is a change in climate—the relatively small concentrations at the greater depths being the result of a wet paleoclimate and the larger concentrations at intermediate depths being the result of a current dry climate.

The profile observed by Murphy and others (1991b) was at a location on the terrace lands of the Hanford Site approximately midway between areas F02 and C04 (fig. 1). The soil at this location consists of about 1.5 m of eolian silt loam, similar to that at sampling area F02 of the present study, underlain by about 50 m of the Pasco gravels unit of the Hanford formation. Chloride concentrations at this location were also in the thousands of milligrams per liter in an interval about 2 to 5 m below land surface, but concentrations were less than 100 mg/L at greater depths. The age of soil water at the bottom of the interval with large chloride concentrations was estimated to be about 13,000 years. One of the proposed reasons for the relatively small concentrations at depth was that the deeper water is partly residual water from the catastrophic floods on the Columbia River, the last of which occurred about 13,000 years ago. This location was inundated by the floods, and the flood waters, which probably had relatively small chloride concentrations, most likely saturated the soil and flushed or diluted the chloride that was in the soil at that time. (Typical chloride concentrations in modern Columbia River water are less than 5 mg/L.) Water with larger chloride concentrations at intermediate depths was assumed to be percolating water from precipitation during the past 13,000 years that has become more concentrated in chloride as a result of evapotranspiration.

Jolly and others (1989) found relatively large differences in thickness of the near-surface layer with small chloride concentrations among locations with similar soil and climate in Australia. They attributed the differences to changes in land use in some areas during the past 100 years. They concluded that removing native vegetation had resulted in increased deep percolation with a corresponding decrease in chloride concentration.

A possible reason for the decrease in chloride concentration at depth that was observed in areas C01, C03, and C04 of the present study can be constructed by combining and modifying the explanations that Murphy and others (1991b) and Jolly and others (1989) proposed for their data. Because the estimated ages of soil water at the bottoms of the intervals with elevated concentrations in areas C01, C03, and C04 range from about 1,000 to 8,000 years, all the deep water with small chloride concentration cannot be residual river water from the flood that occurred 13,000 years ago. Instead, it is proposed here that the small concentrations at depth are a result of deep percolation having been much greater for a period of about 5,000 or more years (depending on location) following the last catastrophic flood than it has been in more recent times. The change in percolation rate is attributed to changes in hydraulic conductivity and water-holding capacity of the top 1 or 2 m of soil and in vegetation. Change in climate is a less likely cause of the change in percolation because similar effects are not evident in the data from areas F01 and F02.

The floods that saturated and flushed the soil most likely also disturbed or deposited the sands and gravels that presently are beneath the present surficial soil. It is proposed here that for thousands of years following the last flood the surficial soil on the Pasco gravels, and perhaps the vegetation, was poorly developed. During this period the vertical hydraulic conductivity of the upper few meters was relatively high, water-holding capacity was relatively low, and deep-rooted plants were not prevalent. Consequently, deep-percolation rates during this period were relatively high, and the percolating water had relatively small chloride concentrations. Percolation rates during this period, which can be estimated from the chloride concentrations in the deep soil water (table 3, values in parentheses), ranged from 0.66 to 5.5 mm/yr and are of the order 10 to 100 times the percolation rates estimated using the larger chloride concentrations at the intermediate depths. Eventually the surficial soil was modified by weathering and deposition of fine-grained wind-blown deposits, and a community of deep-rooted plants became established. Consequently, vertical hydraulic conductivity decreased, and water-holding capacity and evapotranspiration increased, resulting in decreases in deep-percolation rates and increases in the chloride concentrations of the percolating water. The elevated chloride concentrations at the intermediate depths in figures 12 to 14 are a result of percolation during this period, and the estimated deep-percolation rates for this period (representing more recent conditions) are those in table 3 without parentheses.

An alternative reason for the small chloride concentrations at depth is that the deep water is water that percolated rapidly from the land surface to these depths along preferred pathways and was not subject to much evapo- transpiration. This explanation is unlikely, however, because anthropogenic ^{36}Cl is absent at the depths where the chloride concentrations are small (fig. 9, hole B20).

Area C02

In area C02, the Grass Site sampling area, the soil profile consists of about 0.6 m of loamy sand underlain by about 9 m of relatively clean sand. Chloride concentrations at all four sampling locations in this area were relatively small and did not increase with depth as did the concentrations in the other sampling areas (figs. 15 and 16). Concentrations used to estimate deep percolation by the chloride mass-balance method ranged from 20 to 100 mg/L, and the estimated percolation rates range from 0.39 to 2.0 mm/yr (table 3). The estimates of deep percolation rates for this area are larger than the estimated rates for any of the other areas. One reason for this is probably that the vegetal cover at C02 consists only of sparse, shallow-rooted grasses, whereas the other areas have deep-rooted plants, which can withdraw water from deeper in the soil column, in addition to grasses. Another reason may be that the hydraulic conductivity of the shallow soil at C02 is greater than at C01, C03, or C04.

Although the estimated percolation rates at the four locations in area C02 are larger than those estimated at the other three areas with coarse-grained soils, the rates estimated in the present study for the locations in C02 are at the low end of the range of Rockhold and others' (1990) estimates (0.06 to 28 mm/yr) and are much less than Bauer and Vaccaro's (1990) estimate (23 mm/yr). It may be possible that the estimated deep-percolation rates in this area are smaller than actual current rates. If area C02 was vegetated with deep-rooted plants before the wildfire, as suggested by Gee (see the description of area C02 in the section "Descriptions of Hanford Site and Sampling Areas"), and if deep-percolation rates were less before the fire than they are now, the chloride mass-balance method would underestimate deep-percolation rates for present conditions if present chloride concentrations have not yet come into equilibrium with present percolation rates. It also may be possible that the chloride concentrations determined for the samples from area CO2, which were small, are in error. (See section on chloride concentrations in the section "Methods of Sample Collection and Analysis".)

Water contents at all four holes in area C02 tended to increase with depth from about 2 percent by weight at 1 m below land surface to about 5 percent by weight at 9 m depth at the bottom of the sampling interval (figs. 15 and 16). Water content in the top 0.5 m at B19 increased toward the surface to about 9 percent, but water content at each of the other three holes in this area either decreased slightly toward the surface or had the same trend as was observed deeper in the profile. The probable reason for the larger water content near land surface at B19 is that the weather was cooler and wetter prior to the collection of samples from this location (November 19 and 20, 1991) than prior to the collection of samples from the other three locations (September 25-27, 1990). The differences between the near-surface water content at B19 and the other 3 holes are similar to the seasonal differences observed by Rockhold and others (1990), who monitored water content using neutron probes in 25 holes in the area for a number of years.

Values of matric potential at depths greater than about 3 m at locations B14, B15, and B16 were on the order of only -1 m of water (figs. 15 and 16), suggesting that water flow at these depths was controlled mainly by gravity rather than by matric potential. The potentials at these depths at B19 were greater than -5 m except for one value of about -20 m. Gradients of matric potential near the surface were relatively steep and changed with water content. The potential decreased towards the surface at B14, B15, and B16, indicating an upward flow of water at the time the samples were collected. At B19 the gradient of the potential in the surficial 0.2 m indicates that water from the relatively moist surface was draining downward. A comparison of matric potential and water content at depths between 0.6 and 3 m at B14, B15, and B16 indicates that the potential is a sensitive function of water content for water contents less than about 2.5 percent by weight.

Estimated ages of soil water at the bottoms of the sampling intervals range from about 300 to 700 years except at B14, where the age is about 1,900 years (figs. 15 and 16).

Deep Percolation Estimated by the Chlorine-36 Bomb-Pulse Method

In this section concentrations of anthropogenic ^{36}Cl are used to estimate upper limits of deep-percolation rates by the bomb-pulse method. In three of the four holes where ^{36}Cl data were collected, ^{36}Cl/Cl ratios were elevated in about the top 1.5 or 3 m but were at natural levels at greater depths (holes T02 and T03 on fig. 8, and hole B20 on fig. 9). At the fourth hole (B19, fig. 9) ^{36}Cl/Cl ratios were elevated even in the deepest sample.

Deep-percolation is estimated (eq. 6) by dividing the quantity of water in the soil profile shallower than some characteristic point on the ^{36}Cl profile by the elapsed time between the centroid of ^{36}Cl fallout

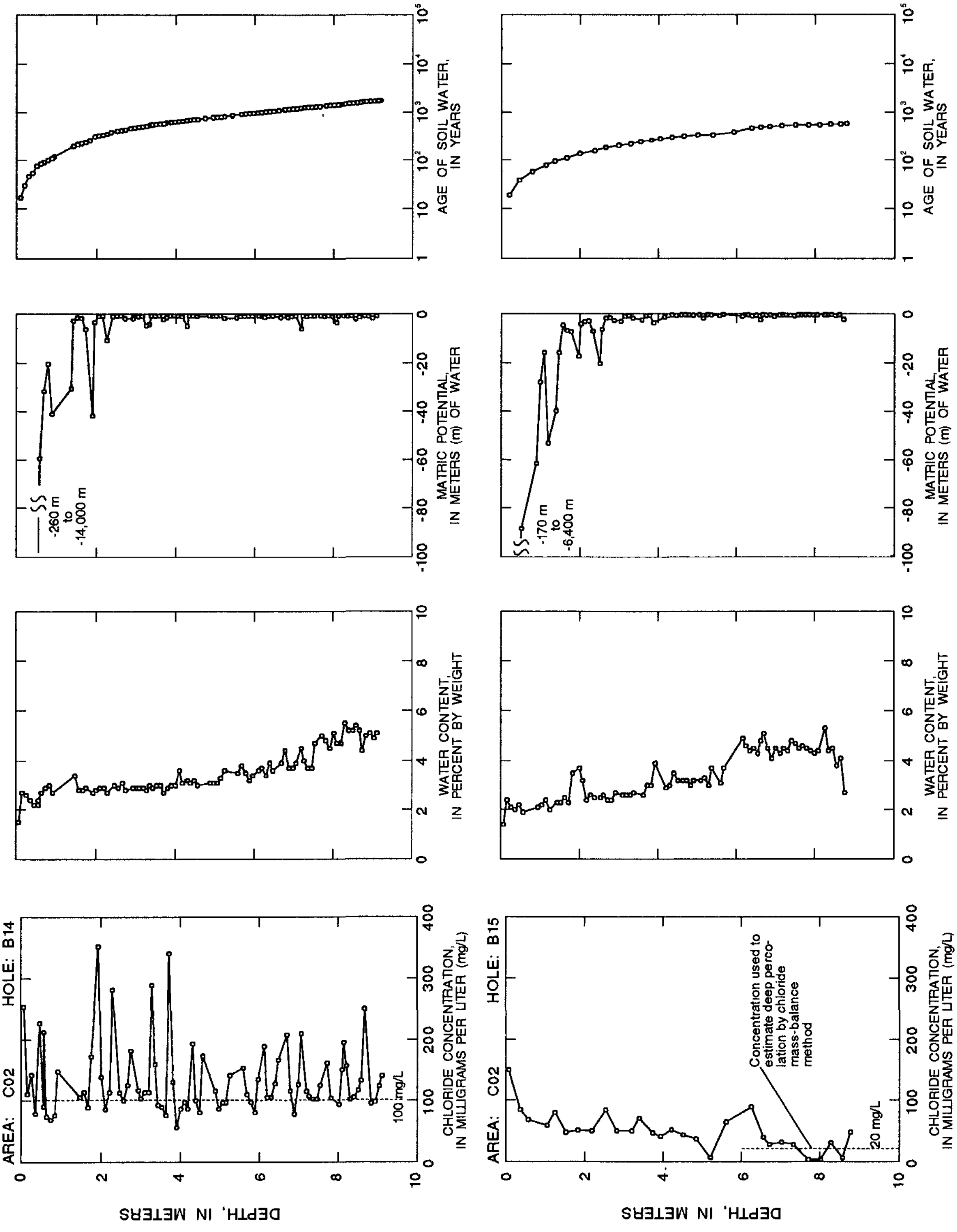

Figure 15. Vertical profiles of observed chloride concentration in soil water, water content and matric potential of soil, and estimated age of soil water at holes B14 and B15 in area C02.

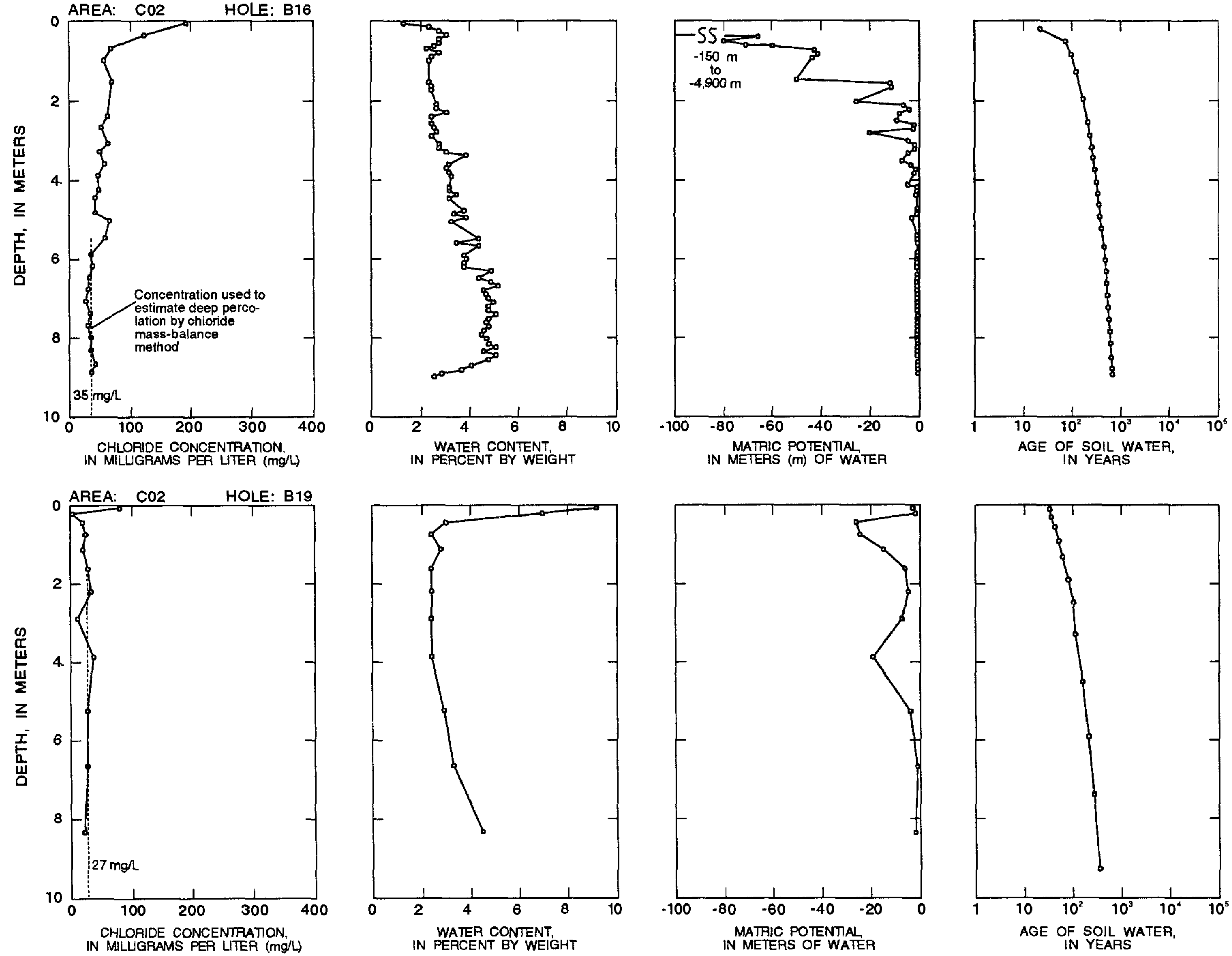

Figure 16. Vertical profiles of observed chloride concentration in soil water, water content and matric potential of soil, and estimated age of soil water at holes B16 and B19 in area C02.

from the bomb tests (1957) and sample collection (1990 to 1992). This calculation gives an upper limit rather than an unbiased estimate of the quantity of post-bomb precipitation that will become deep percolation because a fraction of the water present in the root zone will be lost by evapotranspiration before the water moves deeper. The characteristic point on the ^{36}Cl profile that is used here is the centroid (center of mass) of anthropogenic ^{36}Cl. The vertical distribution of anthropogenic ^{36}Cl (figs. 8 and 9) is obtained by subtracting the natural ^{36}Cl/Cl ratio from the observed ratio and multiplying by the concentration of total chloride and the ratio of the atomic weights of the two forms of chloride (36.0/35.4). Note that these concentrations are in units of mass of chloride per mass of dry soil rather than per volume of soil water. If the dry bulk density of the soil is approximately uniform, the centroids of the distributions of ^{36}Cl concentration shown in figures 8 and 9 approximate the centers of mass of anthropogenic ^{36}Cl.

Estimated Rates

Upper limits of deep-percolation rates estimated by the bomb-pulse method at the three locations with deep-rooted vegetation (T02, T03, and B20) are 3.4, 2.1, and 2.6 mm/yr, respectively (table 4). All three of these estimates are about 100 times the rates estimated by the mass-balance method. Average concentrations of total chloride in soil water shallower than the centroids at these three locations were about one-tenth the concentrations below the root zone, which suggests that about nine-tenths of the soil water that was shallower than the centroids at the time of sampling may eventually be lost by evapotranspiration, and therefore the calculated upper limits may be as much as 10 times the actual deep-percolation rates. Dividing the upper limits by 10 would yield percolation rates that are less than 1 mm/yr; however, they still would be about 10 times the estimates obtained by the mass-balance method.

Because ratios of ^{36}Cl/Cl were elevated even in the deepest samples from hole B19 in area C02 (fig. 9), the data do not define the entire profile of anthropogenic ^{36}Cl at this location. Therefore, the calculated depth to the centroid (3.46\x11m) and the deep-percolation rate (5.1 mm/yr) are less than would be calculated if data from greater depths were available. Also, because there is little difference between chloride concentrations in shallow and deep soil water, the quantity of shallow water that eventually will be lost by evapotranspiration is probably small. Consequently, the estimate of 5.1 mm/yr probably is not an upper limit on the deep-percolation rate at this location, and the actual deep-percolation rate is probably greater than this quantity. Although 5.1 mm/yr is still larger than the rates estimated by the mass-balance method at the four test locations in area C02 (0.39 to 2.0 mm/yr), the estimates by the mass-balance method may be too small if there is residual chloride in the soil water from the period before the wildfire when deep-percolation rates in this area may have been less.

Depths below land surface to the centroid of anthropogenic ^{36}Cl at T02, T03, and B20 ranged from 1.06 to 1.50 m (figs. 8 and 9, and table 4). Depths to the peak ^{36}Cl/Cl ratio were only about half as much, and depths to the maximum observed depth of anthropogenic ^{36}Cl are one and one-half to two times the depths to the centroids (table 4). The upper limits of deep percolation that would be computed if either of these depths were used in place of the depth to the centroid would also be about half or one and one-half to two times the values obtained using the centroids. Depths to the medians of the distributions (not shown) are within 10 percent of depths to centroids. The computed depth to the centroid at B19 (3.46 m) is more than twice that at the other three locations even though as much as two-thirds of the anthropogenic ^{36}Cl may be below the deepest analyzed sample (see following subsection).

Inventoried Amounts of Anthropogenic Chlorine-36

Inventoried amounts of anthropogenic ^{36}Cl in the soil at T02, T03, and B20 range from 1.1×10^{12} to 2.5×10^{12} atoms/m^2. These amounts were computed by integrating the anthropogenic-^{36}Cl concentration over depth and multiplying by soil density and the appropriate units conversion factor (see table 4). The reason for the differences among locations is unknown, but similar differences have been observed at other study sites (see, for example, Phillips and others, 1988). The inventoried amount at B19 (0.39×10^{12} atoms/m^2) is about one-third the minimum at the other three locations, which suggests that two-thirds or more of the anthropogenic ^{36}Cl at this location may have moved deeper than the deepest sample collected there. All calculated amounts are less than or only slightly more than 2.0×10^{12} atoms/m^2, the total bomb fallout estimated for the latitude of Hanford (Phillips and others, 1988). The inventoried amounts are also less than or

Table 4. Deep-percolation rates estimated by the chlorine-36 bomb-pulse method, and observed amounts and depths of vertical movement of anthropogenic chlorine-36

[atoms/m^2, atoms per square meter; mm/yr, millimeters per year; g/cm^3, grams per cubic centimeter; cm^2, square centimeter, m^2, square meter; g/mole, grams per mole; mg/g, milligrams per gram; --, indicates not determined; <, indicates less than; >, indicates greater than]

Sampling location		Natural ^{36}Cl/Cl ratio[a]	Amount of anthropogenic ^{36}Cl,[b] in atoms/m^2	Depth to indicated point on vertical ^{36}Cl profile, in meters, and estimated age of soil water at that depth, in years: Peak of ^{36}Cl/Cl ratio		Center of mass of anthropogenic ^{36}Cl		Maximum depth of anthropogenic ^{36}Cl		Estimated deep percolation,[c] in mm/yr
Area	Hole			Depth	Age	Depth	Age	Depth	Age	
F01	T02	$735\text{x}10^{-15}$	$2.5\text{x}10^{12}$	0.64	85	1.37	1,200	1.78	5,000	<3.4
F02	T03	$854\text{x}10^{-15}$	$1.5\text{x}10^{12}$	0.38-0.89	75-140	1.06	230	1.78	3,300	<2.1
C02	B19	$748\text{x}10^{-15}$	$0.39\text{x}10^{12}$	--	--	>3.46	>120	>5.91	>210	5.1[d]
C04	B20	$876\text{x}10^{-15}$	$1.1\text{x}10^{12}$	0.91	25	1.50	95	3.05	2,500	<2.6

[a] From table 2.

[b] Obtained by integrating the concentration of anthropogenic ^{36}Cl in soil (figs. 8 and 9) from land surface to the maximum depth of observed anthropogenic ^{36}Cl, multiplying by the estimated dry bulk density of the soil (1.4 g/cm^3 in areas F01 and F02, and 1.7 g/cm^3 in areas C02 and C04), and multiplying by the units conversion factor:
$[(6.02\text{x}10^{23}$ atoms/mole) x $(10^4$cm^2/m^2)] / [(36 g/mole) x $(10^3$ mg/g)].

[c] Estimated by dividing the amount of water in soil profile above center of mass of anthropogenic ^{36}Cl by the time elapsed between the centroid of bomb-^{36}Cl fallout (1957) and the time of sampling [1990 at T02 and T03 (elapse time 33 years); 1991 at B19 (elapse time 34 years); and 1992 at B20 (elapse time 35 years)].

[d] Data from hole B19 was not deep enough to define entire profile of anthropogenic ^{36}Cl; therefore, total anthropogenic ^{36}Cl is greater than observed, and deep-percolation rate may be greater than estimated value.

similar to amounts inventoried by Norris and others (1987) at one of two sites in Nevada ($6\text{x}10^{12}$ atoms/m^2), by Trotman (1983) and Phillips and others (1988) at three sites in New Mexico ($0.74\text{x}10^{12}$, $0.89\text{x}10^{12}$, and $2.5\text{x}10^{12}$ atoms/m^2), and by Scanlon (1992) at one location in Texas ($2.5\text{x}10^{12}$ atoms/m^2). Cecil and others (1992) inventoried $44\text{x}10^{12}$ atoms/m^2 at one location on the Idaho Engineering Laboratory and attributed the large amount to stack emissions at this facility.

The fact that the inventoried amounts of anthropogenic ^{36}Cl at Hanford are less than or only slightly more than estimated total bomb-^{36}Cl fallout and are similar to amounts inventoried by others at other semiarid locations in North America that are not near sources of anthropogenic ^{36}Cl supports the assumption that most of the anthropogenic ^{36}Cl observed at the Hanford test locations is, as assumed, from the 1950's bomb tests. Any fallout from Hanford operations that occurred before the dates of the bomb tests would increase the estimated upper limits on percolation. Fallout from Hanford operations that might have occurred at about the same time as the bomb tests would not affect estimated percolation rates regardless of the amount of fallout. Fallout from Hanford operations that occurred later than the bomb tests would decrease estimates and also could cause secondary peaks in ^{36}Cl/Cl ratios and ^{36}Cl concentrations at depths less than the primary peaks caused by the bomb tests. Although ^{36}Cl/Cl ratios at T03, B19, and B20 (figs. 8 and 9) do have secondary peaks at depths less than 0.5 m, the masses of ^{36}Cl associated with these peaks (as seen in the profiles of ^{36}Cl concentration) are relatively small and have little effect on the computed depths of the centroids and estimated percolation rates.

Differences Between Depths to Centroid of Anthropogenic Chlorine-36 and Peak of ^{36}Cl/Cl Ratio

The time between the centroid of the temporal distribution of bomb-^{36}Cl fallout and sampling varies from 33 to 35 years (footnote 3, table 4). However, the estimated ages of soil water at the depths of the anthropogenic-^{36}Cl centroid are considerably greater (95 to 850 years), and the estimated ages of soil water at the maximum observed depths of anthropogenic ^{36}Cl are greater still (>210 to 5,000 years). Estimated ages at the depths of the peak ^{36}Cl/Cl ratio (20 to 130 years) more closely approximate the elapsed time between the bomb tests and sampling; however, this should not be interpreted to mean that the depth to the peak ratio should be used in preference to the depth to the centroid when estimating deep percolation by the bomb-pulse method. The reason that depths to the centroids of the ^{36}Cl distributions are greater than depths to where the ^{36}Cl/Cl ratios are maximum is suspected to be a result of differences in the rate of vertical movement of water and chloride along different flow paths as discussed in the following paragraphs.

The depth to the center of mass of anthropogenic ^{36}Cl was greater than the depth to the maximum ^{36}Cl/Cl ratio at holes T02, T03, and, to a lesser extent, at B20 (figs. 8 and 9). Given the temporal distribution of fallout from the 1950's bomb tests (fig. 3), these differences in depths would not be expected if all chloride at a given depth moved vertically at the same rate (so-called piston flow). The reason that depths to the centroid are greater is believed to be a result of variations within a given depth in the mobility or rate of vertical movement of chloride. Vertical distributions of concentrations of total chloride and of ^{36}Cl indicate that a substantial fraction of anthropogenic ^{36}Cl had moved into the zone of elevated total-chloride concentrations where estimated ages of soil water (or chloride) are much older than the age of the anthropogenic ^{36}Cl (figs. 8 and 9). This should not be interpreted to mean that the ^{36}Cl isotope is inherently more mobile than other chloride isotopes. Instead, the data can be interpreted to imply that there are significant differences in the rates of vertical movement of water and chloride along different flow paths. These variations must occur over horizontal distances smaller than the horizontal dimensions of the samples from which the data were obtained (about 0.3 m or less).

It is proposed that the observed combination of relatively large concentrations of ^{36}Cl and relatively low ^{36}Cl/Cl ratios in the zone of large total-chloride concentrations is a result of the combination of some water and chloride from the time of the 1950's bomb tests in pathways of relatively rapid movement and a larger amount of older water in adjacent pathways or zones of relatively slow movement. Slowly moving water would be more subject to evapotranspiration than rapidly moving water and would tend to have larger chloride concentrations. Water would move more slowly in zones with fine soil texture and poorly connected pore spaces than in zones with coarse soil texture, cracks in soil, or old root channels. Although some chloride also could be immobilized by being sorbed to soil particles, it is commonly accepted that there is little adsorption of anions (chloride) by soil when the pH is basic or neutral, as is typical of Hanford and other arid-land soils (see, for example, Bohn and others, 1985, p. 188). Also, any chloride in the soil that was in a crystalline state rather than dissolved in soil water would be immobile but still would be extracted by the laboratory process used to determine chloride concentration. It is not known if there are any chloride salts in the evaporites.

An alternative explanation for the differences between depths to peak ratios and to centroids is that the peak ratios result from relatively recent fallout of small amounts of ^{36}Cl from operations at Hanford, whereas the locations of centroids are controlled by the relatively large amounts of bomb fallout at the earlier time. However, this explanation does not account for the abnormally large estimated ages of soil water at the depths of the centroids.

Effects of Variations in Rates of Chloride Movementon Estimated Rates of Deep Percolation

An assumption implicit in equation 4 for estimating the rate of deep percolation by the chloride mass-balance method is that the rate of movement of water and chloride at any given depth is uniform. However, as proposed in the preceding section, the rate of movement of chloride in some cases may be variable at a given depth. Consequently, it is prudent to consider how this variability may affect deep-percolation rates that are estimated by both the mass-balance and the bomb-pulse methods.

Chloride Mass-Balance Method

An expression for the downward flux of chloride, $d(Q_{Cl})$, through some small horizontal area dA can be written as the sum of an advective flux plus a diffusive and dispersive flux:

$$d(Q_{Cl}) = (\Theta wc)dA - \Theta D(dc/dz)dA, \qquad (8)$$

where

Θ is the dimensionless volumetric water content;
w is the average downward water velocity in dA, with units of length per unit time;
c is the average chloride concentration in soil water in dA, with units of mass per unit volume;
D is a dispersion coefficient with units of length squared per unit time; and
z is the vertical coordinate, which is positive downward, with units of length.

The first term on the right-hand side of this equation is the advective flux, and the second term is the diffusive and dispersive flux. The size of dA is chosen so that its horizontal dimensions are at least as large as an individual pore space but are less than the horizontal dimensions of a soil sample and less than the distance over which the proposed variations in velocity and concentration under consideration occur. The coefficient D must be defined so that this flux term includes both molecular diffusion and the flux caused by variations of velocity and concentration within dA (so-called hydrodynamic dispersion) but not by variations occurring over distances larger than the dimensions of dA. Integrating equation 8 over an area As that is about the size of a soil sample yields

$$\int_{A_s} dQ_{\mathrm{Cl}} = \int_{A_s} \Theta(wc)dA - \int_{A_s} \Theta D(dc/dz)dA. \qquad (9)$$

If one now writes w and c as sums of their averages over A_s ($\overline{w}$ and $\overline{c}$)plus deviations from the averages w' and c',

$$w = \overline{w} + w'$$

$$c = \overline{c} + c',$$

and introduces these expressions into equation (9), one obtains

$$\int_{A_s} dQ_{\mathrm{Cl}} = \int_{A_s} \Theta(\overline{w}\overline{c})dA + \int_{A_s} \Theta(w'c')dA + \int_{A_s} \Theta(\overline{w}c')dA$$
$$+ \int_{A_s} \Theta(w'\overline{c})dA - \int_{A_s} \Theta D(d\overline{c}/dz)dA - \int_{A_s} \Theta D(dc'/dz)dA. \qquad (10)$$

Because integrals over A_s of the deviations w' and c' are zero, because $\overline{w}$ and $\overline{c}$ are constants within A_s, and if Q and D are assumed to be constants, the third, fourth, and last terms on the right hand side of equation 10 are zero, and the first and last terms on the right hand side are easily integrated so that the equation becomes

$$\int_{A_s} dQ_{\mathrm{Cl}} = \left[\Theta(\overline{w}\overline{c}) + \Theta\left(\overline{w'c'}\right) - \Theta D(d\overline{c}/dz)\right]A_s, \qquad (11)$$

where $\overline{w'c'}$ is the average value of $w'c'$ over A_s. The term $\Theta(\overline{w'c'})$ is a chloride flux caused by variations in velocity and concentration within A_s over scales larger than the length scale characteristic of dA. Under some conditions this can also be included as part of the dispersive flux term by modifying the definition of D. However, this will not be done here. Solving equation 11 for $\Theta\overline{w}$ yields

$$\Theta\overline{w} = \frac{\frac{1}{A_s}\int_{A_s} dQ_{Cl} - \Theta\left(\overline{w'c'}\right) + \Theta D(d\overline{c}/dz)}{\overline{c}}. \qquad (12)$$

If one recognizes that the product $\Theta\overline{w}$ is the same as q_w, the percolation rate per unit area in equation 4, that the first term in the numerator of equation 12 is the same as q_{Cl}, the chloride flux per unit area, and that c is the same as $[\mathrm{Cl}]_w$, then one can rewrite equation 11 as

$$q_w = \frac{q_{\mathrm{Cl}} - \Theta\left(\overline{w'c'}\right) + \Theta D(d\overline{c}/dz)}{[\mathrm{Cl}]_w}, \qquad (13)$$

which is a more nearly correct form of equation 4 for estimating deep percolation by the chloride mass-balance method. One can see that if large chloride concentrations ($c'>0$) are correlated with low percolation velocities ($w'<0$) and small concentrations ($c'<0$) are correlated with high velocities ($w'>0$) as was hypothesized, then the term $-\Theta(\overline{w'c'})$ is positive. If this term is not included when estimating deep percolation by the chloride mass-balance method, the percolation rate will be underestimated. On the other hand, the percolation rate will be overestimated if $-\Theta(\overline{w'c'})$ is negative. By similar reasoning, errors can be introduced when the dispersive term is not included.

Data are not available for calculating the magnitude of the term $-\Theta(\overline{w'c'})$ and the effects of not including this term when estimating deep-percolation rates. However, if one assumes that the ^{36}Cl/Cl ratio at the depth of the centroid of anthropogenic ^{36}Cl should be at least as high as the maximum ratio in the profile and that the reason it is not as high is the presence of old less mobile chloride (with low ^{36}Cl/Cl ratios) in the zone of large total- chloride concentrations, then one can hypothesize that the fraction of more mobile chloride is on the order of the ^{36}Cl/Cl ratio at the depth of the centroid of anthropogenic ^{36}Cl divided by the maximum observed ratio in the profile. At holes T02, T03, and B20 this quotient is on the order of one-third (figs. 8 and 9). Because it is the concentration of mobile chloride that should be used in equation 4, deep-percolation rates in table 3 at locations T02, T03, and B20, and perhaps other locations, that were estimated by using equation 4 may be low by a factor of about three. However, even if the percolation rates in table 3 that were obtained with equation 4 were multiplied by this factor, the percolation rates estimated for most locations except those in area C02 would still be less than 1 mm/yr.

Chlorine-36 Bomb-Pulse Method

If all water and chloride at a given depth do not move at the same rate, then it would not be valid to assume that all water in the soil profile shallower than the centroid of anthropogenic ^{36}Cl infiltrated the ground since the time of the bomb tests. If some of the water shallower than the centroid is older than the bomb tests, the upper limit of deep percolation estimated with the bomb-pulse method would still be a valid upper limit; however, the estimate would exceed the actual value by more than it would if all the water were younger than the bomb tests.

Areal Variability Of Estimates

Deep-percolation rates that were estimated by the chloride mass-balance method (table 3) vary considerably among locations with similar soil and vegetal cover. Differences between estimates in the same area range from about 50 percent in area F01 to a factor of about five in areas F02, C02, and C03. Also, rates estimated for areas with similar soil and vegetal cover differ by a factor of two or more. Examples are areas F01 and F02 and areas C01, C03, and C04. Reasons for the differences between estimated rates within individual areas and between supposedly similar areas are unknown, but these variations are typical of what other investigators have found. Cook and others (1989) investigated the variability of deep-percolation rates over an area of about 14 hectares using the chloride mass-balance method and a geophysical technique to estimate chloride concentrations. They found that the distribution of percolation rates was approximately log-normally distributed and that the standard deviation was 0.91 natural log units. From this, one can compute that the ratio of percolation rates one standard deviation larger and smaller than the mean ($e^{0.91}/e^{-0.91}$) is about six. Variations in estimated deep-percolation rates in the current study are consistent with this ratio. Because of the variability, it is apparent that if one desires an accurate estimate of the average deep percolation for an area, estimates must be obtained at a large number of locations.

SUMMARY AND CONCLUSIONS

Quantifying rates at which water from precipitation moves down through unsaturated soils and sediments and potentially recharges the aquifer beneath the U.S. Department of Energy Hanford Site is critical for assessing the environmental risk posed by stored or buried radioactive and other wastes at the site and for selecting appropriate isolation or treatment strategies for storage and remediation. In the present study, long-term average rates of deep percolation of water from precipitation on the Hanford Site in semiarid south-central Washington were estimated at a total of 13 locations in 6 undisturbed areas using a chloride mass-balance method and at 1 location in each of 4 of the areas using a chlorine-36 (^{36}Cl) bomb-pulse method.

To estimate deep-percolation rates by the chloride mass-balance method, the long-term atmospheric-chloride deposition rate was divided by chloride concentration in soil water deeper than that at which evapotranspiration occurs. The deposition rate was estimated by dividing the natural rate of production of ^{36}Cl in the atmosphere by the observed ^{36}Cl/Cl ratio in deep soil water that is older than the oldest anthropogenic ^{36}Cl. This method was based on the assumptions that atmospheric deposition was the only source of chloride; that all chloride was dissolved in soil water; that all water and chloride at a given depth moved downward at a uniform rate; and that chloride concentrations in the percolating water changed (increased) with depth only because some of the water, but none of the chloride, was lost by evapotranspiration.

The bomb-pulse method used as a tracer ^{36}Cl from atmospheric fallout from nuclear-weapons tests in the Pacific Ocean during the 1950's. Anomalously large relative concentrations of ^{36}Cl in soil water served as a marker on water that fell as precipitation during the period of fallout. The quantity of soil water shallower than the centroid of mass of bomb-^{36}Cl was approximately the quantity of water that infiltrated the land surface since the fallout occurred and had not yet been lost by evapotranspiration. This quantity of water divided by the time elapsed since the bomb tests is an upper limit on the deep-percolation rate because some of the shallow soil water may be lost by evapotranspiration before it moves deeper.

Implicit in both methods was the assumption that all chloride and water at a given depth move at the same rate (plug flow). Because this assumption probably was never fully satisfied, the mass-balance method probably underestimated the deep-percolation rate. Consequently, the estimates by the two methods probably bracketed actual deep-percolation rates.

Of the six areas where deep-percolation rates were estimated, two of them (F01 and F02) were covered with more than 4 m of silt loam, and three of them (C01, C03, and C04) had a 0.6-m-thick surficial layer of loamy sand or sandy loam overlying tens of meters of sand and gravel. All five of these areas were vegetated with sagebrush and other deep-rooted plants plus sparse shallow- rooted grasses. The sixth area (C02) also had a 0.6-m-thick surficial layer of loamy sand overlying about 9 m of sand; however, this area was vegetated with only sparse shallow-rooted grasses. Estimates by the bomb-pulse method were made at one location in each of areas F01, F02, C04, and C02.

Observed average natural ^{36}Cl/Cl ratios in deep soil water ranged from 735×10^{-15} to 876×10^{-15}, and the corresponding estimated atmospheric chloride fluxes ranged from 33 to 39 mg/m^2/yr. These fluxes are two or more times the flux from precipitation alone, which implies that dry deposition was a major component of the atmospheric flux.

Deep-percolation rates estimated by the chloride mass-balance method at four locations in the two areas with deep silt loam (F01 and F02) ranged from 0.008 to 0.11 mm/yr. These estimates are consistent with estimates by previous investigators that used soil-moisture accounting and lysimetery. Estimates at five locations in three areas with sandy soils overlying thick deposits of sand and gravel (areas C01, C03, and C04) ranged from 0.012 to 0.30 mm/yr. These estimates are a factor of 10 or less than estimates by previous investigators that used soil-moisture accounting. Vertical profiles of chloride concentration in soil water at these five areas that were vegetated with sagebrush and other deep-rooted plants indicate that most of the annual precipitation (160 to 210 mm/yr) is held within the top few meters of soil where it evaporates or is taken up by plants and transpires.

Estimates by the mass-balance method at four locations in area C02, where the vegetal cover consisted only of sparse shallow-rooted grasses, ranged from 0.39 to 2.0 mm/yr and were higher than estimates for the other areas which had deep-rooted plants. However, these estimates may be less than actual present deep-percolation rates because the observed chloride concentrations may not be in equilibrium with present vegetation. Some of the chloride in soil water in this area may be residual from when the area was populated with deep-rooted plants, which were killed by wildfire sometime before December 1992, and deep-percolation rates were lower than at present. The estimates for this area are at the low end of the range of estimates by previous investigators.

Upper limits of the deep-percolation rate estimated by the bomb-pulse method at the three areas with deep-rooted plants (F01, F02, and C04) ranged from 2.1 to 3.4 mm/yr. Chloride concentrations in the water shallower than the centroids of anthropogenic ^{36}Cl indicate that the calculated upper limits of deep-percolation rates at these three areas may be about 10 times the actual rates. The estimate at C02, which was vegetated only with grass, was 5.1 mm/yr; however, this estimate is suspected of being less than the actual rate rather than being an upper limit because data were not collected from deep enough at this location to define the entire anthropogenic ^{36}Cl profile. Observed depths to the centroid of anthropogenic ^{36}Cl at the three locations in F01, F02, and C04 ranged from 1.06 to 1.50 m, and the depth to the centroid that was calculated with the available data at the location in area C02 was 3.46 m. Inventoried amounts of anthropogenic ^{36}Cl at the locations in F01, F02, and C04 ranged from 1.1×10^{12} to 2.5×10^{12} atoms/m^2. These amounts are similar to amounts inventoried by others at locations in North America that are not near local sources of ^{36}Cl, which implies that the source of most of the anthropogenic ^{36}Cl at the test locations at Hanford was the 1950's weapons tests and not operations at the Hanford Site. The inventoried amount at C02, where the entire profile of anthropogenic ^{36}Cl was not defined, was 0.39×10^{12} atoms/m^2.

Estimates of deep percolation in this study by the mass-balance and bomb-pulse methods are consistent with results from previous investigations in that they support the hypotheses that (1) in undisturbed areas of the Hanford Site with fine-grained surficial soils and deep-rooted plants most of the water from direct precipitation is held in the upper 1 or 2 m of the soil column until it returns to the atmosphere by evapotranspiration, and only a small percentage percolates deeper; and (2) deep-percolation rates in areas with coarse-grained surficial soils and only shallow-rooted plants are greater than in areas with fine-grained soils and deep-rooted plants. However, although deep-percolation rates estimated in this and previous studies for many areas on the Hanford Site are small, rates estimated by different methods for the same or similar areas can differ by more than a factor of 10.

This study also demonstrated that both the chloride mass-balance and ^{36}Cl bomb-pulse methods for estimating deep-percolation rates are suitable for use on most of the Hanford Site. Limitations on the use of the methods at Hanford appear to be no different than at other arid or semiarid sites. If the mass-balance method is used to estimate the deep-percolation rate at a location where rates are expected to be a few percent of precipitation or greater, such as in areas without deep-rooted vegetation, special care would be required in determining the small chloride concentrations that would be expected at these locations. The deep-percolation rates that were estimated in this study agree reasonably well with estimates that have been made by other investigators using different methods and probably are representative of large undisturbed areas of the Hanford Site with similar surficial soils and vegetation. However, as found in this and other studies, deep percolation can be strongly dependent on the type of surficial soil and vegetation; therefore, the estimates in this study should not be assumed to be typical of sites with surficial soil or vegetation that differ from that at the test locations of this study, or of sites disturbed by construction. Additional information that could be useful to understanding the hydrology of the Hanford Site could be estimates of deep-percolation rates by the chloride mass-balance and chlorine-36 bomb-pulse methods at one or more locations that have been stripped and kept clear of vegetation since at least the mid 1950's.

A better understanding of the reliability and accuracy of the mass-balance or the bomb-pulse methods for estimating deep percolation could be obtained (1) by ascertaining if chloride concentrations that are determined by the laboratory methods used in this study are representative of chloride concentrations in percolating soil water and if they are not, by testing other existing methods or developing new methods for determining concentrations of mobile chloride, and (2) by determining reasons for the large differences in chloride concentrations seen when concentrations are small.

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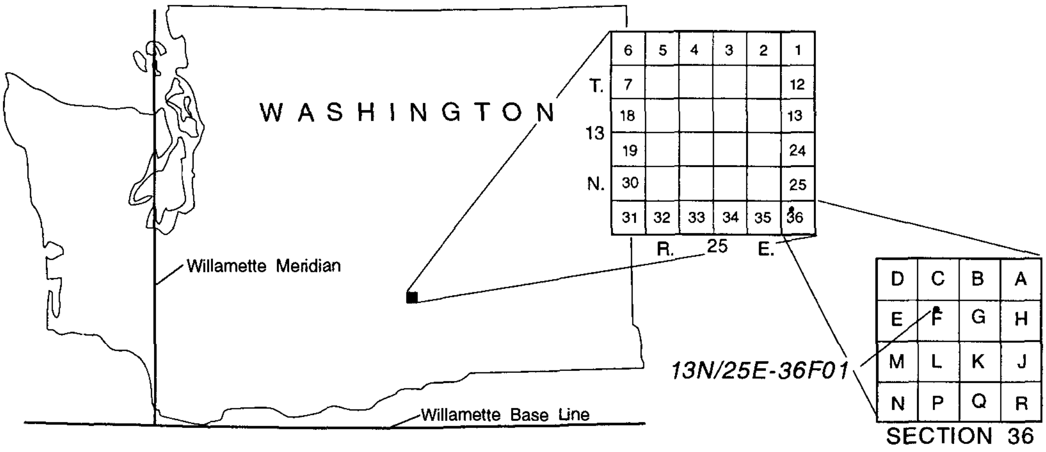
Appendix A. Cross-reference list of test-hole indentifiers

[-- indicates no identifier]

Sampling area and test-hole identifier used in this report	U.S. Geological Survey		Hanford Site	
	Local well name[1]	Site number	Informal name	Well number
F01, Benson Springs				
T01	11N/25E-02M01	462750119391001	--	--
T02	11N/25E-02M02	462750119391002	--	--
F02, McGee Ranch				
T03	13N/25E-30L01	463453119442301	--	--
T04	13N/25E-30L02	463453119442001	--	--
C01, Liquid Effluent Recovery Facility				
B10	13N/26E-36N01	463352119304601	LF-1	299-E35-2
B12	12N/26E-01D01	463346119304601	LF-3	299-E26-10
C02, Grass Site				
B14	11N/28E-29P01	462420119200001	--	--
B15	11N/28E-29P02	462420119200002	--	--
B16	11N/28E-29P03	462420119200003	--	--
B19	11N/28E-29P04	462420119200004	--	--
C03, 200-BP-1 Operable Unit				
B17	13N/26E-27P01	463451119330001	--	699-52-57
B18	13N/26E-27B01	463625119323301	--	699-55-55
C04, C-018H Characterization				
B20	13N/25E-36F01	463419119375301	C-018H No.1	699-48-77B

[1] Local well name consists of Township/Range-Section number, a letter identifying a 40-acre plot within the section as shown in the sketch below, and a two-digit sequence number.



Appendix B. Ratios of chlorine-36 to total chloride

[nd, no data; nc, not computed]

Sampling interval (inches[1] below land surface)		Chlorine-36 to total-chloride ratio x 10^{15}	
Top	Bottom	Value[2]	Standard deviation[2,3]
Area F01 Hole T02			
1	10	1,126	49
10	20	3,103	189
20	30	3,653	224
30	40	2,923	223
40	50	1,838	164
50	60	1,531	90
60	70	[a]1,237	61
60	70	[a]1,286	103
60	70	[b]1,262	nc
70	80	723	37
80	110	793	48
110	140	690	95
70	140	[b]735	nc
[c]blank		4.9	3.6
Area F02 Hole T03			
1	10	4,338	168
10	20	5,447	561
20	30	4,450	222
30	40	5,528	201
40	50	[a]2,283	157
40	50	[a]2,226	147
40	50	[a]2,407	74
40	50	[b]2,305	nc
50	60	1,602	222
60	70	933	69
70	90	788	38
90	110	884	43
110	140	889	88
70	140	[b]854	nc
Area C02 Hole B19			
1	4	3,288	147
4	12	5,503	396
4	12	[d]6,110	280
4	12	[b]5,806	nc
12	22	2,796	77
22	36	787	81
36	52	708	31
22	52	[b]748	nc
52	73	[a]3,072	301
52	73	[a]1,644	64
52	73	[b]2,358	nc

Appendix B. Continued

Sampling interval (inches[1] below land surface)		Chlorine-36 to total-chloride ratio x 10^{15}	
top	bottom	value[2]	standard deviation[2,3]
Area C02 Hole B19--Continued			
75	98	3,576	216
98	130	2,844	159
130	175	3,131	223
180	233	6,259	654
233	291	nd	nd
291	365	nd	nd
[c]blank		0	7.1
Area C04 Hole B20			
2	12	11,578	402
12	24	4,157	672
24	48	16,200	1,492
48	72	8,560	479
72	96	[a]1,119	54
72	96	[a]1,180	63
72	96	[d]1,130	30
72	96	[b]1,143	nc
96	120	968	46
120	180	830	52
240	300	914	44
420	480	903	156
660	720	858	57
120	720	[b]876	nc

[1] To convert inches to meters, multiply by 0.0254.

[2] Laboratory determination performed under direction of Dr. Pankaj Sharma at Nuclear Structure Research Laboratory, University of Rochester, Rochester, New York.

[3] Standard deviation of laboratory determination.

[a] Replicate extraction and analysis.

[b] Average of replicates or of samples in indicated depth intervals.

[c] Blank sample prepared by dissolving Weeks Island halite in deionized water that was used for processing soil samples, mixing, and extracting and purifying AgCl using same procedures used with soil samples.

[d] Analyses of duplicate sample performed at PRIME Lab, Purdue University.

Appendix C. Results of various laboratory analyses of samples

[To convert depth interval from inches to meters, multiply by 0.0254; --, no data; <, less than; >, greater than; (a), includes silt plus clay; (b), two values are for subsamples from upper and lower halves of sampling interval; (e), estimate]

Depth interval (inches below land surface)		Water content of filter paper (percent dry weight)	Water content of soil sample excluding large particles (percent dry weight)	Chloride content of soil with particle sizes less than 2 millimeters (milligrams per kilogram dry soil)	Specific conductance of water extract for chloride determination (micromohs per centimeter)	Amount of sample with particle sizes less than 2 millimeters (percent dry weight)		Amount of sample (percent dry weight) in indicated size class (millimeter)					
Top (A)	Bottom (B)	(C)	(D)	(E)	(F)	Water-content sample (G)	Total sample (H)	Cobbles and boulders (>64) (I)	Gravel (2 to 64) (J)	Sand (0.062 to 2) (K)	Silt plus clay (<0.062) (L)	Silt (0.002 to 0.062) (M)	Clay (<0.002) (N)
						Area F01 Hole T01							
1	4	5.86	2.8	7.1	487	100	100	0	0	74	26	--	--
4	8	19.61	6.1	6.7	539	100	100	0	0	73	27	--	--
8	12	19.03	6.3	4.1	466	100	100	0	0	55	45	--	--
12	16	17.45	5.7	6.4	402	100	100	0	0	51	49	--	--
16	20	19.19	5.2	8.6	394	100	100	0	0	45	55	--	--
20	24	20.15	5.3	7.5	313	100	100	0	0	--	--	--	--
24	28	19.89	4.8	7.0	444	100	100	0	0	38	62	62	0.4
28	32	16.61	6.6	7.4	649	100	100	0	0	50	50	--	--
32	36	20.63	6.0	12	760	100	100	0	0	46	54	--	--
36	40	23.40	5.4	21	1,020	100	100	0	0	48	52	--	--
40	44	20.32	5.6	45	1,820	100	100	0	0	48	52	--	--
44	48	20.95	5.5	73	4,180	100	100	0	0	42	58	--	--
48	52	21.60	5.7	110	3,750	100	100	0	0	--	--	--	--
52	56	20.61	5.7	110	3,600	100	100	0	0	29	71	--	--
56	60	20.94	6.0	150	5,220	100	100	0	0	52	48	--	--
60	64	21.05	5.7	170	3,570	100	100	0	0	46	54	--	--
64	68	21.15	7.6	250	3,980	100	100	0	0	50	50	--	--
72	76	22.76	5.1	140	1,440	100	100	0	0	39	61	--	--
76	80	20.45	3.7	99	2,300	100	100	0	0	45	55	--	--
80	84	21.15	4.3	145	2,860	100	100	0	0	44	56	--	--
84	88	22.41	5.5	160	3,480	100	100	0	0	34	66	--	--
88	92	19.87	3.8	100	2,200	100	100	0	0	57	43	--	--
92	96	19.38	3.4	92	1,030	100	100	0	0	35	65	--	--
96	100	21.00	5.3	190	2,160	100	100	0	0	33	67	--	--
100	104	22.29	2.6	85	998	100	100	0	0	48	52	--	--
104	108	21.38	3.9	130	2,260	100	100	0	0	36	64	--	--
108	112	20.41	2.6	80	1,100	100	100	0	0	43	57	--	--
112	116	20.09	3.2	98	1,120	100	100	0	0	40	60	--	--
116	120	18.35	3.8	130	1,430	100	100	0	0	38	62	58	4.2

Appendix C. Continued.

Depth interval (inches below land surface)		Water content of filter paper (percent dry weight)	Water content of soil sample excluding large particles (percent dry weight)	Chloride content of soil with particle sizes less than 2 millimeters (milligrams per kilogram dry soil)	Specific conductance of water extract for chloride determination (micromohs per centimeter)	Amount of sample with particle sizes less than 2 millimeters (percent dry weight)		Amount of sample (percent dry weight) in indicated size class (millimeter)					
Top (A)	Bottom (B)	(C)	(D)	(E)	(F)	Water-content sample (G)	Total sample (H)	Cobbles and boulders (>64) (I)	Gravel (2 to 64) (J)	Sand (0.062 to 2) (K)	Silt plus clay (<0.062) (L)	Silt (0.002 to 0.062) (M)	Clay (<0.002) (N)
						Area F01 Hole T02							
1	4	8.77	5.3	2.0	158	100	100	0	0	57	43	--	--
4	8	23.42	6.3	3.2	364	100	100	0	0	34	66	64	1.5
8	12	22.61	6.0	3.2	246	100	100	0	0	44	56	--	--
12	16	23.97	6.5	5.5	408	100	100	0	0	49	51	--	--
16	20	21.06	5.4	4.3	331	100	100	0	0	72	58	--	--
20	24	23.64	5.8	4.4	374	100	100	0	0	70	30	--	--
24	28	22.13	6.7	3.8	331	100	100	0	0	62	38	--	--
28	32	22.62	5.8	5.4	325	100	100	0	0	28	72	--	--
32	36	19.88	6.0	4.5	376	100	100	0	0	48	52	50	1.6
36	40	18.17	4.8	7.4	456	100	100	0	0	40	60	--	--
40	44	18.46	5.6	9.5	560	100	100	0	0	39	61	--	--
44	48	19.39	5.7	38	718	100	100	0	0	44	56	--	--
48	52	17.59	7.2	160	1,140	100	100	0	0	46	54	--	--
52	56	19.09	5.8	160	1,200	100	100	0	0	49	51	--	--
56	60	19.45	8.6	360	4,400	100	100	0	0	50	50	--	--
60	64	20.07	7.4	265	8,550	100	100	0	0	44	56	--	--
64	68	18.08	4.5	230	3,320	100	100	0	0	40	60	--	--
68	72	18.88	3.6	190	1,520	100	100	0	0	51	49	--	--
72	76	19.07	3.4	170	1,290	100	100	0	0	49	51	--	--
76	80	19.75	3.9	190	2,460	100	100	0	0	45	55	--	--
80	84	18.09	4.3	190	1,880	100	100	0	0	25	75	73	1.7
84	88	18.74	4.0	190	1,480	100	100	0	0	41	59	--	--
88	92	19.86	4.4	230	3,490	100	100	0	0	43	57	--	--
92	96	20.92	4.1	225	3,450	100	100	0	0	49	51	--	--
96	100	22.37	4.2	210	1,330	100	100	0	0	44	56	--	--
100	104	20.84	3.8	200	1,320	100	100	0	0	43	57	--	--
104	108	21.75	3.9	220	1,230	100	100	0	0	--	--	--	--
108	112	22.65	3.5	230	1,320	100	100	0	0	40	60	--	--
112	116	19.77	3.0	200	1,160	100	100	0	0	44	56	--	--
116	120	21.59	3.4	200	1,410	100	100	0	0	44	56	--	--
120	124	20.91	4.1	225	1,400	100	100	0	0	49	51	46	4.9
124	128	21.27	4.2	240	1,480	100	100	0	0	33	67	--	--
128	132	20.81	3.7	200	1,170	100	100	0	0	36	64	--	--

Appendix C. Continued.

Depth interval (inches below land surface)		Water content of filter paper (percent dry weight)	Water content of soil sample excluding large particles (percent dry weight)	Chloride content of soil with particle sizes less than 2 millimeters (milligrams per kilogram dry soil)	Specific conductance of water extract for chloride determination (micromohs per centimeter)	Amount of sample with particle sizes less than 2 millimeters (percent dry weight)		Amount of sample (percent dry weight) in indicated size class (millimeter)					
Top (A)	Bottom (B)	(C)	(D)	(E)	(F)	Water-content sample (G)	Total sample (H)	Cobbles and boulders (>64) (I)	Gravel (2 to 64) (J)	Sand (0.062 to 2) (K)	Silt plus clay (<0.062) (L)	Silt (0.002 to 0.062) (M)	Clay (<0.002) (N)
					Area F01 Hole T02--Continued								
132	136	20.66	4.1	240	1,400	100	100	0	0	23	77	--	--
136	140	20.29	5.1	290	1,660	100	100	0	0	36	64	--	--
140	144	20.96	4.9	250	1,550	100	100	0	0	25	75	--	--
144	148	21.57	4.7	260	1,390	100	100	0	0	31	69	--	--
148	151	22.31	3.9	210	1,200	100	100	0	0	37	63	--	--
151	154	19.97	2.6	130	741	100	100	0	0	48	52	--	--
154	157	12.57	4.5	240	1,280	100	100	0	0	33	67	--	--
157	160	21.84	4.0	180	1,060	100	100	0	0	29	71	--	--
160	163	20.59	3.9	190	1,060	100	100	0	0	31	19	--	--
163	165	21.22	4.1	220	1,160	100	100	0	0	35	65	61	3.6
					Area F02 Hole T03								
1	4	6.38	1.7	5.8	348	100	100	0	0	24	76	--	--
4	8	19.45	5.9	4.0	275	100	100	0	0	48	52	49	3.4
8	12	21.06	5.9	3.6	276	100	100	0	0	49	51	--	--
12	16	21.33	8.7	5.4	298	100	100	0	0	64	36	--	--
16	20	23.69	6.6	4.2	281	100	100	0	0	42	58	--	--
20	24	28.57	4.2	3.0	245	100	100	0	0	41	59	--	--
24	28	24.20	4.0	2.5	268	100	100	0	0	54	46	--	--
28	32	20.34	4.0	2.9	297	100	100	0	0	39	61	--	--
32	36	22.79	3.6	3.2	296	100	100	0	0	45	55	53	1.6
36	40	23.30	3.7	11	790	100	100	0	0	51	49	--	--
40	44	22.12	3.7	20	1,610	100	100	0	0	51	59	--	--
44	48	23.28	3.1	56	915	100	100	0	0	29	71	--	--
48	52	25.48	5.0	120	3,520	100	100	0	0	34	66	--	--
52	56	25.24	5.0	120	4,180	100	100	0	0	30	70	--	--
56	60	19.85	2.2	69	754	100	100	0	0	38	62	--	--
60	64	23.57	4.4	130	1,850	100	100	0	0	42	58	--	--
64	68	24.81	5.4	160	4,420	100	100	0	0	35	65	--	--
68	72	25.18	3.9	120	1,210	100	100	0	0	33	67	--	--
72	76	23.41	2.9	81	1,000	100	100	0	0	40	60	--	--
76	80	23.39	2.2	50	756	100	100	0	0	67	33	--	--
80	84	24.78	4.6	110	1,150	100	100	0	0	48	52	47	4.7

Appendix C. Continued.

Depth interval (inches below land surface)		Water content of filter paper (percent dry weight)	Water content of soil sample excluding large particles (percent dry weight)	Chloride content of soil with particle sizes less than 2 millimeters (milligrams per kilogram dry soil)	Specific conductance of water extract for chloride determination (micromohs per centimeter)	Amount of sample with particle sizes less than 2 millimeters (percent dry weight)		Amount of sample (percent dry weight) in indicated size class (millimeter)					
Top (A)	Bottom (B)	(C)	(D)	(E)	(F)	Water-content sample (G)	Total sample (H)	Cobbles and boulders (>64) (I)	Gravel (2 to 64) (J)	Sand (0.062 to 2) (K)	Silt plus clay (<0.062) (L)	Silt (0.002 to 0.062) (M)	Clay (<0.002) (N)
						Area F02 Hole T03--Continued							
84	88	22.81	5.3	130	1,400	100	100	0	0	32	63	--	--
88	92	23.25	3.5	75	694	100	100	0	0	33	67	--	--
92	96	22.97	2.5	45	476	100	100	0	0	51	49	--	--
96	100	23.16	2.7	50	486	100	100	0	0	47	53	--	--
100	104	22.93	4.3	82	694	100	100	0	0	38	62	--	--
104	108	22.67	4.1	86	684	100	100	0	0	35	65	--	--
108	112	20.18	2.6	42	437	100	100	0	0	27	73	--	--
112	116	23.18	4.1	69	594	100	100	0	0	40	60	--	--
116	120	22.19	4.9	95	695	100	100	0	0	16	84	--	--
120	124	22.36	2.8	50	443	100	100	0	0	32	68	67	1.6
124	128	22.70	5.2	93	673	100	100	0	0	31	69	--	--
128	132	22.77	5.7	89	659	100	100	0	0	26	74	--	--
132	136	22.76	5.9	94	695	100	100	0	0	27	73	--	--
136	140	22.57	4.3	67	550	100	100	0	0	52	48	--	--
140	144	20.37	2.7	35	380	100	100	0	0	49	51	--	--
144	148	21.88	2.3	33	316	100	100	0	0	60	40	--	--
148	151	21.46	2.8	34	370	100	100	0	0	65	35	--	--
151	155	20.62	4.8	57	500	100	100	0	0	23	77	--	--
155	158	20.24	3.6	43	408	100	100	0	0	42	58	--	--
158	161	22.40	4.3	64	470	100	100	0	0	33	67	--	--
161	164	23.13	5.3	76	535	100	100	0	0	35	65	58	6.6
164	168	21.74	3.6	53	412	100	100	0	0	32	68	--	--
168	171	21.08	2.2	34	309	100	100	0	0	45	55	--	--
171	175	20.33	2.8	35	312	100	100	0	0	64	36	--	--
175	178	21.81	3.2	42	365	100	100	0	0	43	57	--	--
178	181	22.74	4.5	62	395	100	100	0	0	38	62	--	--
						Area F02 Hole T04							
1	4	7.34	1.3	4.9	765	100	100	0	0	51	49	--	--
4	8	20.21	6.5	3.9	625	100	100	0	0	34	16	--	--
8	12	21.94	7.9	4.9	519	100	100	0	0	36	64	--	--
12	16	22.54	9.2	5.0	486	100	100	0	0	27	73	--	--
16	20	22.86	9.0	4.4	366	100	100	0	0	26	74	--	--

Appendix C. Continued.

Depth interval (inches below land surface) Top (A)	Depth interval (inches below land surface) Bottom (B)	Water content of filter paper (percent dry weight) (C)	Water content of soil sample excluding large particles (percent dry weight) (D)	Chloride content of soil with particle sizes less than 2 millimeters (milligrams per kilogram dry soil) (E)	Specific conductance of water extract for chloride determination (micromohs per centimeter) (F)	Amount of sample with particle sizes less than 2 millimeters (percent dry weight) Water-content sample (G)	Amount of sample with particle sizes less than 2 millimeters (percent dry weight) Total sample (H)	Amount of sample (percent dry weight) in indicated size class (millimeter) Cobbles and boulders (>64) (I)	Amount of sample (percent dry weight) in indicated size class (millimeter) Gravel (2 to 64) (J)	Amount of sample (percent dry weight) in indicated size class (millimeter) Sand (0.062 to 2) (K)	Amount of sample (percent dry weight) in indicated size class (millimeter) Silt plus clay (<0.062) (L)	Amount of sample (percent dry weight) in indicated size class (millimeter) Silt (0.002 to 0.062) (M)	Amount of sample (percent dry weight) in indicated size class (millimeter) Clay (<0.002) (N)
					Area F02 Hole T04--Continued								
20	24	23.30	9.0	5.1	521	100	100	0	0	32	68	--	--
24	28	21.61	8.4	4.6	366	100	100	0	0	27	73	--	--
28	32	22.46	8.9	4.1	424	100	100	0	0	40	60	--	--
32	36	22.72	6.7	4.8	540	100	100	0	0	56	44	42	1.7
36	40	22.89	7.1	3.6	496	100	100	0	0	54	46	--	--
40	44	20.25	6.7	5.3	625	100	100	0	0	48	52	--	--
44	48	20.17	5.8	4.6	437	100	100	0	0	44	56	--	--
48	52	20.80	6.5	4.6	320	100	100	0	0	29	71	--	--
52	56	23.27	7.5	6.5	385	100	100	0	0	35	65	--	--
56	60	19.98	6.2	8.1	340	100	100	0	0	45	55	--	--
60	64	21.37	7.4	17	443	100	100	0	0	38	62	--	--
64	68	22.46	7.4	26	3,220	100	100	0	0	36	64	--	--
68	72	23.33	8.5	19	5,660	100	100	0	0	42	58	--	--
72	76	22.16	9.1	18	4,580	100	100	0	0	36	64	--	--
76	80	22.63	9.4	21	4,480	100	100	0	0	34	66	--	--
80	84	22.68	8.4	13	4,580	100	100	0	0	45	55	--	--
84	88	25.55	6.9	9.5	4,540	100	100	0	0	54	46	--	--
88	92	22.18	7.3	10	3,160	100	100	0	0	57	43	--	--
92	96	23.88	4.4	2.6	392	100	100	0	0	55	45	--	--
96	100	25.55	9.0	11	2,880	100	100	0	0	35	65	--	--
100	104	24.28	7.3	10	3,160	100	100	0	0	22	78	--	--
104	108	23.18	9.6	9.9	1,920	100	100	0	0	31	69	--	--
108	112	26.28	12.2	7.9	4,780	100	100	0	0	35	65	--	--
112	116	25.61	10.4	7.4	5,310	100	100	0	0	48	52	--	--
116	120	25.64	9.1	9.8	3,910	100	100	0	0	50	50	--	--
120	124	24.74	9.2	9.9	1,920	100	100	0	0	34	66	64	1.9
124	128	24.68	12.2	7.9	4,780	100	100	0	0	40	60	--	--
128	132	25.71	7.9	13	785	100	100	0	0	45	55	--	--
132	136	24.46	8.0	14	812	100	100	0	0	39	61	--	--
136	140	24.52	7.9	15	767	100	100	0	0	63	37	--	--
140	144	--	9.8	18	915	100	100	0	0	53	47	--	--
144	148	24.97	7.0	13	623	100	100	0	0	72	28	--	--
148	152	22.35	8.9	15	763	100	100	0	0	38	62	--	--

Appendix C. Continued.

Depth interval (inches below land surface)		Water content of filter paper (percent dry weight)	Water content of soil sample excluding large particles (percent dry weight)	Chloride content of soil with particle sizes less than 2 millimeters (milligrams per kilogram dry soil)	Specific conductance of water extract for chloride determination (micromohs per centimeter)	Amount of sample with particle sizes less than 2 millimeters (percent dry weight)		Amount of sample (percent dry weight) in indicated size class (millimeter)					
Top (A)	Bottom (B)	(C)	(D)	(E)	(F)	Water-content sample (G)	Total sample (H)	Cobbles and boulders (>64) (I)	Gravel (2 to 64) (J)	Sand (0.062 to 2) (K)	Silt plus clay (<0.062) (L)	Silt (0.002 to 0.062) (M)	Clay (<0.002) (N)
Area F02 Hole T04--Continued													
152	156	25.49	8.9	20	828	100	100	0	0	42	58	--	--
156	161	25.58	7.5	17	985	100	100	0	0	48	52	--	--
161	163	27.36	9.5	20	1,740	100	100	0	0	37	63	--	--
163	166	27.57	10.2	22	1,680	100	100	0	0	32	68	--	--
166	169	25.64	9.8	22	883	100	100	0	0	33	67	--	--
169	172	25.96	9.9	23	1,180	100	100	0	0	35	65	--	--
172	176	26.35	9.3	19	2,040	100	100	0	0	23	77	--	--
176	179	25.92	7.8	25	758	100	100	0	0	35	65	--	--
179	182	26.82	9.1	29	1,220	100	100	0	0	32	68	--	--
182	186	27.40	7.5	27	1,710	100	100	0	0	41	59	--	--
Area C01 Hole B10													
36	48	--	3 (e)	0.8	455	--	25 (e)	--	--	--	--	--	--
60	72	--	3 (e)	0.7	323	--	25 (e)	--	--	--	--	--	--
84	96	--	3 (e)	0.6	281	--	25 (e)	--	--	--	--	--	--
108	120	--	3 (e)	1.4	246	--	25 (e)	--	--	--	--	--	--
168	180	33.98	3.2	5.9	420	44	25 (e)	--	--	--	--	--	--
228	240	34.84	2.8	18	360	25	25 (e)	--	--	--	--	--	--
348	360	34.35	3.0	44	315	51	22	20	58	22 (a)	--	--	--
612	624	50.75	3.0	<0.1	127	40	28	5.4	66	28 (a)	--	--	--
708	720	50.94	3.0	0.2	145	28	17	7.8	75	17 (a)	--	--	--
828	840	35.28	2.1	4.0	220	26	22	3.0	75	22 (a)	--	--	--
948	960	46.45	2.7	0.3	143	25	25	9.6	66	25 (a)	--	--	--
1,068	1,080	53.90	3.1	2.2	173	28	21	2.2	77	21 (a)	--	--	--
1,188	1,200	42.50	2.5	<0.1	138	49	34	0	66	34 (a)	--	--	--
1,428	1,440	55.18	3.0	2.8	170	22	13	3.2	84	13 (a)	--	--	--
1,548	1,560	49.19	2.9	2.4	176	27	22	18	60	22 (a)	--	--	--
1,668	1,680	61.15	3.0	1.4	155	21	17	0	83	17 (a)	--	--	--
Area C01 Hole B12													
48	60	22.42	2.5	11	640	80	58	5.0	38	44	13	13	0.6
72	84	23.57	1.7	440	4,800	27	18	15	67	18 (a)	--	--	--
108	120	38.85	2.4	110	1,850	34	25	7.9	67	22	3.1	2.9	0.2

Appendix C. Continued.

Depth interval (inches below land surface)		Water content of filter paper (percent dry weight) (C)	Water content of soil sample excluding large particles (percent dry weight) (D)	Chloride content of soil with particle sizes less than 2 millimeters (milligrams per kilogram dry soil) (E)	Specific conductance of water extract for chloride determination (micromohs per centimeter) (F)	Amount of sample with particle sizes less than 2 millimeters (percent dry weight)		Amount of sample (percent dry weight) in indicated size class (millimeter)					
Top (A)	Bottom (B)					Water-content sample (G)	Total sample (H)	Cobbles and boulders (>64) (I)	Gravel (2 to 64) (J)	Sand (0.062 to 2) (K)	Silt plus clay (<0.062) (L)	Silt (0.002 to 0.062) (M)	Clay (<0.002) (N)
Area C01 Hole B12--Continued													
168	180	29.47	2.5	90	1,260	45	15	20	65	15 (a)	--	--	--
348	360	--	2.3 (e)	<0.1	174	--	--	0	9.7	85	7.7	5.5	0.2
468	480	32.81	2.1	0.6	228	34	24	0	76	24 (a)	--	--	--
588	600	60.00	2.6	0.4	153	35	26	2.2	71	27 (a)	--	--	--
708	720	56.81	2.8	0.4	148	35	35	0	65	35 (a)	--	--	--
828	840	44.95	2.1	0.4	160	21	19	0	81	19 (a)	--	--	--
948	960	35.08	2.6	0.3	141	30	30	0	70	28	2.0	1.9	0.1
1,068	1,080	105.31	3.0	<0.1	168	23	20	0	80	20 (a)	--	--	--
1,188	1,200	56.08	2.4	0.4	185	19	19	0	81	19 (a)	--	--	--
1,308	1,320	76.11	3.0	1.4	268	28	16	1.6	82	16 (a)	--	--	--
1,428	1,440	44.26	2.7	1.2	230	36	32	0	67	33 (a)	--	--	--
1,548	1,560	50.93	2.7	1.6	202	30	19	0	81	19 (a)	--	--	--
1,668	1,680	57.83	2.6	0.6	261	25	23	1.9	75	23 (a)	--	--	--
1,788	1,800	56.40	2.8	0.4	249	36	17	0	83	17 (a)	--	--	--
1,908	1,920	60.36	4.3	1.3	392	35	18	0	82	18 (a)	--	--	--
Area C02 Hole B14													
1	4	7.73	1.5	3.8	460	100	100	0	0	65	35	--	--
4	8	19.43	2.7	3.0	290	100	100	0	0	--	--	--	--
8	12	18.34	2.6	3.7	186	100	100	0	0	--	--	--	--
12	16	16.09	2.4	1.9	225	100	100	0	0	86	14	--	--
16	20	18.74	2.2	5.0	277	100	100	0	0	--	--	--	--
20	24	28.60	2.2	2.0	186	100	100	0	0	--	--	--	--
24	27	34.10	2.7	2.0	138	100	100	0	0	99.3	0.7	--	--
27	31	40.41	2.9	2.0	117	100	100	0	0	--	--	--	--
31	35	45.57	3.0	2.3	113	100	100	0	0	--	--	--	--
35	37	37.71	2.7	4.0	117	100	100	0	0	98.0	2.0	--	--
54	56	40.83	--	--	--	100	100	0	0	--	--	--	--
56	60	78.80	3.4	3.6	177	100	100	0	0	99.3	0.7	--	--
60	64	92.56	2.8	3.2	136	100	100	0	0	--	--	--	--
64	68	90.68	2.8	2.5	108	100	100	0	0	99.7	0.3	--	--
68	70	63.01	2.9	5.0	138	100	100	0	0	--	--	--	--
75	77	37.49	2.7	9.5	166	100	100	0	0	--	--	--	--

Appendix C. Continued.

Depth interval (inches below land surface)		Water content of filter paper (percent dry weight)	Water content of soil sample excluding large particles (percent dry weight)	Chloride content of soil with particle sizes less than 2 millimeters (milligrams per kilogram dry soil)	Specific conductance of water extract for chloride determination (micromohs per centimeter)	Amount of sample with particle sizes less than 2 millimeters (percent dry weight)		Amount of sample (percent dry weight) in indicated size class (millimeter)					
Top (A)	Bottom (B)	(C)	(D)	(E)	(F)	Water-content sample (G)	Total sample (H)	Cobbles and boulders (>64) (I)	Gravel (2 to 64) (J)	Sand (0.062 to 2) (K)	Silt plus clay (<0.062) (L)	Silt (0.002 to 0.062) (M)	Clay (<0.002) (N)
					Area C02 Hole B14--Continued								
77	81	74.88	2.8	3.9	124	100	100	0	0	99.0	1.0	--	--
81	85	106.46	2.9	2.5	118	100	100	0	0	--	--	--	--
85	89	115.91	2.9	3.3	133	100	100	0	0	--	--	--	--
89	91	54.28	2.7	7.6	133	100	100	0	0	99.7	0.3	--	--
95	99	110.54	3.0	3.4	131	100	100	0	0	--	--	--	--
99	103	118.88	2.9	2.9	128	100	100	0	0	--	--	--	--
103	107	121.25	3.1	3.9	136	100	100	0	0	99.8	0.2	--	--
107	109	89.61	2.8	5.1	136	100	100	0	0	--	--	--	--
115	116	88.28	2.9	3.4	118	100	100	0	0	--	--	--	--
116	120	103.56	2.9	3.0	123	100	100	0	0	99.7	0.3	--	--
120	124	106.39	2.9	3.3	166	100	100	0	0	--	--	--	--
124	128	112.07	2.9	3.3	155	100	100	0	0	--	--	--	--
128	130	68.51	2.8	8.1	175	100	100	0	0	--	--	--	--
131	133	70.96	3.0	4.8	136	100	100	0	0	99.6	0.3	--	--
133	137	118.98	2.9	2.7	115	100	100	0	0	--	--	--	--
137	141	116.45	3.0	2.7	118	100	100	0	0	--	--	--	--
141	145	123.18	3.0	2.3	105	100	100	0	0	99.8	0.2	--	--
145	147	84.73	2.7	9.2	132	100	100	0	0	--	--	--	--
148	152	96.39	2.9	3.8	141	100	100	0	0	--	--	--	--
152	156	121.69	3.0	1.7	115	100	100	0	0	99.4	0.6	--	--
156	160	128.86	3.0	2.6	120	100	100	0	0	--	--	--	--
160	164	117.73	3.6	3.5	135	100	100	0	0	--	--	--	--
164	166	102.42	3.1	2.7	124	100	100	0	0	99.3	0.7	--	--
169	171	67.47	3.2	6.2	167	100	100	0	0	--	--	--	--
171	175	113.20	3.1	3.1	134	100	100	0	0	99.8	0.2	--	--
175	179	119.06	3.2	2.6	127	100	100	0	0	--	--	--	--
179	181	108.71	3.0	5.2	133	100	100	0	0	--	--	--	--
191	194	123.77	3.1	3.6	146	100	100	0	0	--	--	--	--
194	198	113.73	3.1	2.7	155	100	100	0	0	99.6	0.4	--	--
198	202	119.06	3.1	3.0	142	100	100	0	0	--	--	--	--
202	204	120.55	3.3	3.2	149	100	100	0	0	--	--	--	--
206	208	90.70	3.6	5.1	172	100	100	0	0	97.9	2.1	--	--
218	222	93.56	3.5	5.4	164	100	100	0	0	97.9	2.1	--	--

Appendix C. Continued.

Depth interval (inches below land surface)		Water content of filter paper (percent dry weight)	Water content of soil sample excluding large particles (percent dry weight)	Chloride content of soil with particle sizes less than 2 millimeters (milligrams per kilogram dry soil)	Specific conductance of water extract for chloride determination (micromohs per centimeter)	Amount of sample with particle sizes less than 2 millimeters (percent dry weight)		Amount of sample (percent dry weight) in indicated size class (millimeter)					
Top (A)	Bottom (B)	(C)	(D)	(E)	(F)	Water-content sample (G)	Total sample (H)	Cobbles and boulders (>64) (I)	Gravel (2 to 64) (J)	Sand (0.062 to 2) (K)	Silt plus clay (<0.062) (L)	Silt (0.002 to 0.062) (M)	Clay (<0.002) (N)
					Area C02 Hole B14--Continued								
222	226	106.66	3.8	4.2	147	100	100	0	0	--	--	--	--
226	230	111.76	3.5	3.4	145	100	100	0	0	--	--	--	--
230	234	115.93	3.2	2.6	146	100	100	0	0	99.6	0.4	--	--
234	236	113.70	3.4	4.6	135	100	100	0	0	--	--	--	--
240	242	118.79	3.6	6.8	158	100	100	0	0	--	--	--	--
242	246	109.64	3.7	3.9	141	100	100	0	0	99.7	0.3	--	--
246	250	98.55	3.4	3.6	133	100	100	0	0	--	--	--	--
250	254	117.70	3.9	5.0	170	100	100	0	0	--	--	--	--
254	256	118.61	3.6	6.0	157	100	100	0	0	99.2	0.8	--	--
262	265	96.64	3.9	8.1	195	100	100	0	0	--	--	--	--
265	269	125.00	4.4	5.1	168	100	100	0	0	99.6	0.4	--	--
269	273	96.51	3.7	2.9	148	100	100	0	0	--	--	--	--
273	277	109.34	3.7	4.7	147	100	100	0	0	99.8	0.2	--	--
277	279	119.38	3.9	8.2	201	100	100	0	0	--	--	--	--
283	284	63.56	4.5	5.2	194	100	100	0	0	--	--	--	--
284	288	122.96	4.0	4.3	175	100	100	0	0	99.3	0.7	--	--
288	292	107.66	3.7	3.8	160	100	100	0	0	--	--	--	--
292	296	123.23	3.7	3.8	165	100	100	0	0	--	--	--	--
296	298	113.73	4.7	5.9	195	100	100	0	0	99.1	0.9	--	--
302	306	124.60	5.0	8.1	203	100	100	0	0	--	--	--	--
306	310	110.50	4.8	5.0	182	100	100	0	0	--	--	--	---
310	314	121.24	4.5	--	--	100	100	0	0	--	--	--	--
314	318	106.45	5.1	4.8	200	100	100	0	0	98.2	0.8	--	--
318	320	74.55	4.7	7.1	200	100	100	0	0	--	--	--	--
320	321	116.86	4.7	9.2	205	100	100	0	0	--	--	--	--
321	325	127.59	4.7	7.4	184	100	100	0	0	99.6	0.4	--	--
325	329	122.85	5.5	5.6	206	100	100	0	0	--	--	--	--
329	333	110.02	5.2	5.5	192	100	100	0	0	--	--	--	--
333	337	117.65	5.2	6.1	202	100	100	0	0	99.3	0.7	--	--
337	339	86.94	5.4	7.2	208	100	100	0	0	--	--	--	--
341	342	100.00	5.2	13	224	100	100	0	0	--	--	--	--
342	346	125.71	4.4	--	--	100	100	0	0	--	--	--	--
346	350	117.56	5.0	4.8	177	100	100	0	0	99.6	0.4	--	--

Appendix C. Continued.

Depth interval (inches below land surface)		Water content of filter paper (percent dry weight)	Water content of soil sample excluding large particles (percent dry weight)	Chloride content of soil with particle sizes less than 2 millimeters (milligrams per kilogram dry soil)	Specific conductance of water extract for chloride determination (micromohs per centimeter)	Amount of sample with particle sizes less than 2 millimeters (percent dry weight)		Amount of sample (percent dry weight) in indicated size class (millimeter)					
Top (A)	Bottom (B)	(C)	(D)	(E)	(F)	Water-content sample (G)	Total sample (H)	Cobbles and boulders (>64) (I)	Gravel (2 to 64) (J)	Sand (0.062 to 2) (K)	Silt plus clay (<0.062) (L)	Silt (0.002 to 0.062) (M)	Clay (<0.002) (N)
					Area C02 Hole B14--Continued								
350	354	109.32	5.1	5.0	192	100	100	0	0	--	--	--	--
354	358	90.25	4.9	6.1	197	100	100	0	0	--	--	--	--
358	360	118.88	5.1	7.2	195	100	100	0	0	99.2	0.8	--	--
						Area C02 Hole B15							
1	4	9.57	1.4	2.1	154	100	100	0	0	73	27	--	--
4	8	26.65	2.4	--	--	100	100	0	0	--	--	--	--
8	12	23.32	2.1	--	--	100	100	0	0	--	--	--	--
12	16	19.63	2.0	1.7	116	100	100	0	0	--	--	--	--
16	20	25.68	2.2	--	--	100	100	0	0	--	--	--	--
20	24	30.52	1.9	1.3	63	100	100	0	0	--	--	--	--
35	39	33.65	2.1	--	--	100	100	0	0	--	--	--	--
39	43	41.58	2.2	1.3	83	100	100	0	0	--	--	--	--
43	47	48.48	2.4	--	--	100	100	0	0	--	--	--	--
47	51	34.99	2.0	1.6	85	100	100	0	0	--	--	--	--
55	58	37.82	2.3	--	--	100	100	0	0	--	--	--	--
58	62	48.46	2.3	1.1	86	100	100	0	0	99.7	0.3	--	--
62	66	66.94	2.5	--	--	100	100	0	0	--	--	--	--
66	70	60.34	2.3	--	--	100	100	0	0	--	--	--	--
70	74	59.47	3.5	1.8	145	100	100	0	0	--	--	--	--
78	80	47.24	3.7	--	--	100	100	0	0	--	--	--	--
80	84	68.92	3.2	--	--	100	100	0	0	--	--	--	--
84	88	73.70	2.4	1.2	87	100	100	0	0	--	--	--	--
88	92	75.66	2.6	--	--	100	100	0	0	--	--	--	--
92	96	59.76	2.5	--	--	100	100	0	0	--	--	--	--
99	101	45.25	2.5	2.1	100	100	100	0	0	--	--	--	--
101	105	61.75	2.6	--	--	100	100	0	0	--	--	--	--
105	109	84.59	2.4	--	--	100	100	0	0	--	--	--	--
109	113	87.27	2.4	1.2	86	100	100	0	0	99.8	0.2	--	--
113	117	76.54	2.7	--	--	100	100	0	0	--	--	--	--
120	124	74.44	2.6	--	--	100	100	0	0	--	--	--	--
124	128	94.52	2.6	1.3	102	100	100	0	0	--	--	--	--
128	132	101.93	2.6	--	--	100	100	0	0	--	--	--	--

Appendix C. Continued.

Depth interval (inches below land surface)		Water content of filter paper (percent dry weight)	Water content of soil sample excluding large particles (percent dry weight)	Chloride content of soil with particle sizes less than 2 millimeters (milligrams per kilogram dry soil)	Specific conductance of water extract for chloride determination (micromohs per centimeter)	Amount of sample with particle sizes less than 2 millimeters (percent dry weight)		Amount of sample (percent dry weight) in indicated size class (millimeter)					
Top (A)	Bottom (B)	(C)	(D)	(E)	(F)	Water-content sample (G)	Total sample (H)	Cobbles and boulders (>64) (I)	Gravel (2 to 64) (J)	Sand (0.062 to 2) (K)	Silt plus clay (<0.062) (L)	Silt (0.002 to 0.062) (M)	Clay (<0.002) (N)
						Area C02 Hole B15--Continued							
132	135	85.11	2.7	1.9	94	100	100	0	0	--	--	--	--
141	145	78.19	2.6	--	--	100	100	0	0	--	--	--	--
145	149	102.02	3.0	1.4	111	100	100	0	0	--	--	--	--
149	153	104.51	3.0	--	--	100	100	0	0	--	--	--	--
153	157	71.07	3.9	1.6	98	100	100	0	0	--	--	--	--
164	168	91.48	2.9	1.5	99	100	100	0	0	99.3	0.7	0.67	0.03
168	172	106.36	3.0	--	--	100	100	0	0	--	--	--	--
172	176	115.27	3.5	--	--	100	100	0	0	--	--	--	--
176	180	105.10	3.2	1.4	96	100	100	0	0	--	--	--	--
181	185	115.38	3.2	--	--	100	100	0	0	--	--	--	--
185	189	117.20	3.2	--	--	100	100	0	0	--	--	--	--
189	193	116.94	3.0	1.1	88	100	100	0	0	--	--	--	--
193	195	109.11	3.2	--	--	100	100	0	0	--	--	--	--
199	203	118.64	3.2	--	--	100	100	0	0	--	--	--	--
203	207	85.12	3.3	0.2	95	100	100	0	0	--	--	--	--
207	211	120.30	3.0	--	--	100	100	0	0	--	--	--	--
211	213	114.62	3.7	--	--	100	100	0	0	--	--	--	--
219	223	104.76	3.1	2.0	97	100	100	0	0	99.2	0.8	--	--
223	225	131.98	3.7	--	--	100	100	0	0	--	--	--	--
242	244	97.13	4.9	--	--	100	100	0	0	--	--	--	--
244	248	116.67	4.6	4.1	112	100	100	0	0	--	--	--	--
248	252	119.78	4.4	--	--	100	100	0	0	--	--	--	--
252	256	100.92	4.5	--	--	100	100	0	0	--	--	--	--
256	260	110.34	4.3	1.7	106	100	100	0	0	--	--	--	--
260	262	78.71	4.8	--	--	100	100	0	0	--	--	--	--
262	266	119.38	5.1	1.4	112	100	100	0	0	--	--	--	--
266	270	110.24	4.5	--	--	100	100	0	0	--	--	--	--
270	274	115.79	4.1	--	--	100	100	0	0	--	--	--	--
274	278	96.14	4.5	1.4	111	100	100	0	0	--	--	--	--
279	282	113.42	4.3	--	--	100	100	0	0	--	--	--	--
282	286	119.13	4.5	--	--	100	100	0	0	--	--	--	--
286	290	116.41	4.4	1.2	110	100	100	0	0	--	--	--	--
290	294	111.48	4.8	--	--	100	100	0	0	--	--	--	--

Appendix C. Continued.

Depth interval (inches below land surface)		Water content of filter paper (percent dry weight)	Water content of soil sample excluding large particles (percent dry weight)	Chloride content of soil with particle sizes less than 2 millimeters (milligrams per kilogram dry soil)	Specific conductance of water extract for chloride determination (micromohs per centimeter)	Amount of sample with particle sizes less than 2 millimeters (percent dry weight)		Amount of sample (percent dry weight) in indicated size class (millimeter)					
Top (A)	Bottom (B)	(C)	(D)	(E)	(F)	Water-content sample (G)	Total sample (H)	Cobbles and boulders (>64) (I)	Gravel (2 to 64) (J)	Sand (0.062 to 2) (K)	Silt plus clay (<0.062) (L)	Silt (0.002 to 0.062) (M)	Clay (<0.002) (N)
						Area C02 Hole B15--Continued							
294	298	101.50	4.7	--	--	100	100	0	0	--	--	--	--
298	301	123.25	4.5	--	--	100	100	0	0	--	--	--	--
301	305	119.63	4.6	0.1	121	100	100	0	0	--	--	--	--
305	309	120.41	4.5	--	--	100	100	0	0	--	--	--	--
309	313	121.16	4.4	--	--	100	100	0	0	--	--	--	--
313	317	115.92	4.3	0.1	120	100	100	0	0	--	--	--	--
317	321	118.18	4.4	--	--	100	100	0	0	--	--	--	--
324	327	122.28	5.3	1.6	125	100	100	0	0	--	--	--	--
327	331	119.18	4.4	--	--	100	100	0	0	--	--	--	--
331	335	125.62	4.5	--	--	100	100	0	0	--	--	--	--
335	339	104.80	3.8	0.2	124	100	100	0	0	--	--	--	--
339	343	122.06	4.1	--	--	100	100	0	0	--	--	--	--
343	347	79.96	2.7	1.3	101	100	100	0	0	97.8	2.2	2.1	0.1
						Area C02 Hole B16							
1	4	10.27	1.3	2.5	140	100	100	0	0	76.0	24.0	23.3	0.7
4	8	22.11	2.3	--	--	100	100	0	0	--	--	--	--
8	12	26.00	2.7	--	--	100	100	0	0	--	--	--	--
12	16	26.62	3.0	3.7	85	100	100	0	0	--	--	--	--
16	20	33.12	2.7	--	--	100	100	0	0	--	--	--	--
20	24	31.40	2.7	--	--	100	100	0	0	--	--	--	--
24	25	32.46	2.5	--	--	100	100	0	0	--	--	--	--
25	29	34.00	2.2	1.5	128	100	100	0	0	--	--	--	--
29	33	37.27	2.7	--	--	100	100	0	0	--	--	--	--
33	37	37.62	2.4	--	--	100	100	0	0	--	--	--	--
37	41	37.05	2.3	1.3	114	100	100	0	0	--	--	--	--
58	62	35.70	2.3	1.6	132	100	100	0	0	99.8	0.2	--	--
62	66	53.03	2.4	--	--	100	100	0	0	--	--	--	--
66	70	53.80	2.4	--	--	100	100	0	0	--	--	--	--
80	84	42.79	2.6	--	--	100	100	0	0	--	--	--	--
84	88	63.10	2.6	--	--	100	100	0	0	--	--	--	--
88	92	71.89	3.0	--	--	100	100	0	0	--	--	--	--
92	96	59.01	2.4	1.5	112	100	100	0	0	--	--	--	--

Appendix C. Continued.

Depth interval (inches below land surface)		Water content of filter paper (percent dry weight)	Water content of soil sample excluding large particles (percent dry weight)	Chloride content of soil with particle sizes less than 2 millimeters (milligrams per kilogram dry soil)	Specific conductance of water extract for chloride determination (micromohs per centimeter)	Amount of sample with particle sizes less than 2 millimeters (percent dry weight)		Amount of sample (percent dry weight) in indicated size class (millimeter)					
Top (A)	Bottom (B)	(C)	(D)	(E)	(F)	Water-content sample (G)	Total sample (H)	Cobbles and boulders (>64) (I)	Gravel (2 to 64) (J)	Sand (0.062 to 2) (K)	Silt plus clay (<0.062) (L)	Silt (0.002 to 0.062) (M)	Clay (<0.002) (N)
					Area C02 Hole B16--Continued								
99	103	56.98	2.4	--	--	100	100	0	0	--	--	--	--
103	107	86.80	2.5	1.3	100	100	100	0	0	96.7	3.3	3.1	0.2
107	111	83.11	2.6	--	--	100	100	0	0	--	--	--	--
111	115	45.62	2.4	--	--	100	100	0	0	--	--	--	--
119	123	69.98	2.7	1.7	106	100	100	0	0	--	--	--	--
123	127	88.80	2.7	--	--	100	100	0	0	--	--	--	--
127	131	91.51	3.0	1.5	110	100	100	0	0	--	--	--	--
131	133	70.51	3.8	--	--	100	100	0	0	--	--	--	--
139	143	61.42	3.1	1.8	119	100	100	0	0	--	--	--	--
143	147	76.47	3.0	--	--	100	100	0	0	--	--	--	--
147	151	100.88	3.1	--	--	100	100	0	0	--	--	--	--
151	155	89.39	3.2	1.5	110	100	100	0	0	--	--	--	--
163	165	69.17	3.1	--	--	100	100	0	0	--	--	--	--
165	169	116.33	3.1	1.5	108	100	100	0	0	97.5	2.5	2.4	0.1
169	173	110.14	3.4	--	--	100	100	0	0	--	--	--	--
173	177	100.80	3.1	1.3	106	100	100	0	0	--	--	--	--
186	188	126.89	3.7	--	--	100	100	0	0	--	--	--	--
188	192	115.37	3.3	1.4	106	100	100	0	0	--	--	--	--
192	196	116.71	3.8	--	--	100	100	0	0	--	--	--	--
196	200	79.01	3.2	2.1	121	100	100	0	0	--	--	--	--
213	217	117.03	4.3	2.5	119	100	100	0	0	98.7	1.3	--	--
217	221	120.24	3.4	--	--	100	100	0	0	--	--	--	--
221	223	130.83	4.3	--	--	100	100	0	0	--	--	--	--
230	233	126.98	3.7	1.3	109	100	100	0	0	--	--	--	--
233	237	125.94	3.8	--	--	100	100	0	0	--	--	--	--
237	241	111.91	3.7	--	--	100	100	0	0	--	--	--	--
241	245	112.67	3.7	1.4	114	100	100	0	0	--	--	--	--
245	249	107.98	4.8	--	--	100	100	0	0	--	--	--	--
252	256	117.99	4.3	1.4	125	100	100	0	0	--	--	--	--
256	260	115.39	4.8	--	--	100	100	0	0	--	--	--	--
260	264	114.12	5.1	--	--	100	100	0	0	--	--	--	--
264	268	123.97	4.5	1.4	126	100	100	0	0	--	--	--	--
268	272	119.13	4.6	--	--	100	100	0	0	--	--	--	--

Appendix C. Continued.

Depth interval (inches below land surface)		Water content of filter paper (percent dry weight)	Water content of soil sample excluding large particles (percent dry weight)	Chloride content of soil with particle sizes less than 2 millimeters (milligrams per kilogram dry soil)	Specific conductance of water extract for chloride determination (micromohs per centimeter)	Amount of sample with particle sizes less than 2 millimeters (percent dry weight)		Amount of sample (percent dry weight) in indicated size class (millimeter)					
Top (A)	Bottom (B)	(C)	(D)	(E)	(F)	Water-content sample (G)	Total sample (H)	Cobbles and boulders (>64) (I)	Gravel (2 to 64) (J)	Sand (0.062 to 2) (K)	Silt plus clay (<0.062) (L)	Silt (0.002 to 0.062) (M)	Clay (<0.002) (N)
						Area C02 Hole B16--Continued							
272	276	123.44	4.7	--	--	100	100	0	0	--	--	--	--
276	280	119.59	4.9	1.3	124	100	100	0	0	--	--	--	--
280	284	125.24	4.7	--	--	100	100	0	0	--	--	--	--
284	288	121.89	4.7	--	--	100	100	0	0	--	--	--	--
288	292	118.90	5.0	1.7	130	100	100	0	0	99.7	0.3	--	--
293	296	137.60	4.7	--	--	100	100	0	0	--	--	--	--
296	300	114.11	4.6	--	--	100	100	0	0	--	--	--	--
300	304	126.98	4.7	1.4	122	100	100	0	0	--	--	--	--
304	308	124.94	4.5	--	--	100	100	0	0	--	--	--	--
308	312	121.22	4.4	--	--	100	100	0	0	--	--	--	--
312	316	106.36	4.6	1.6	140	100	100	0	0	--	--	--	--
318	321	116.18	4.7	--	--	100	100	0	0	--	--	--	--
321	325	124.31	5.0	--	--	100	100	0	0	--	--	--	--
321	325	124.31	5.0	--	--	100	100	0	0	--	--	--	--
325	329	125.94	4.5	1.6	125	100	100	0	0	--	--	--	--
329	333	122.22	5.0	--	--	100	100	0	0	--	--	--	--
333	337	120.68	4.7	--	--	100	100	0	0	--	--	--	--
339	343	132.88	4.0	1.7	128	100	100	0	0	--	--	--	--
343	347	131.57	3.6	--	--	100	100	0	0	--	--	--	--
347	351	135.29	2.8	1.0	72	100	100	0	0	99.5	0.5	--	--
351	353	132.24	2.5	--	--	100	100	0	0	--	--	--	--
						Area C02 Hole B19							
1	4	78.22	9.2	7.5	227	100	100	0	0	--	--	--	--
4	12	89.86	7.0	0.3	175	100	100	0	0	85	15	14	1.3
12	22	42.56	3.0	0.6	138	100	100	0	0	--	--	--	--
22	36	43.35	2.4	0.6	129	100	100	0	0	--	--	--	--
36	52	49.82	2.8	0.6	120	100	100	0	0	99.4	0.6	0.5	0.1
52	75	63.65	2.4	0.7	92	100	100	0	0	--	--	--	--
75	98	68.15	2.4	0.8	102	100	100	0	0	--	--	--	--
98	130	60.46	2.4	0.3	112	100	100	0	0	--	--	--	--
130	175	46.26	2.4	0.9	123	100	100	0	0	97.1	2.9	2.7	0.2
180	233	71.10	2.9	0.8	107	100	100	0	0	--	--	--	--

Appendix C. Continued.

Depth interval (inches below land surface)		Water content of filter paper (percent dry weight) (C)	Water content of soil sample excluding large particles (percent dry weight) (D)	Chloride content of soil with particle sizes less than 2 millimeters (milligrams per kilogram dry soil) (E)	Specific conductance of water extract for chloride determination (micromohs per centimeter) (F)	Amount of sample with particle sizes less than 2 millimeters (percent dry weight)		Amount of sample (percent dry weight) in indicated size class (millimeter)					
Top (A)	Bottom (B)					Water-content sample (G)	Total sample (H)	Cobbles and boulders (>64) (I)	Gravel (2 to 64) (J)	Sand (0.062 to 2) (K)	Silt plus clay (<0.062) (L)	Silt (0.002 to 0.062) (M)	Clay (<0.002) (N)
Area C02 Hole B19--Continued													
233	291	104.90	3.3	0.9	112	100	100	0	0	98.6	1.4	1.3	0.1
291	365	87.52	4.5	1.0	146	100	100	0	0	98.7	1.3	1.2	0.1
Area C03 Hole B17													
6 e	24	32.00	3.2	6.4	675	49	25	27	47	19	6.9	6.5	0.4
24	48	33.73	2.3	3.3	418	30	25	9	66	25 (a)	--	--	--
48	72	31.26	2.7	3.4	330	42	30	5	65	30 (a)	--	--	--
72	96	46.00	3.4	57	870	33	19	12	69	19 (a)	--	--	--
96	120	53.96	2.6	99	950	14	23	4	73	21	2.6	2.4	0.2
156	180	39.08	2.8	33	398	42	29	6	65	29 (a)	--	--	--
216	240	45.18	3.0	8.0	275	34	28	11	61	28 (a)	--	--	--
276	300	41.06	2.9	4.6	247	34	24	0	76	24 (a)	--	--	--
336	360	37.99	4.3	6.8	254	30	21	0	79	21 (a)	--	--	--
456	480	51.37	2.7	4.9	245	28	19	0	82	18 (a)	--	--	--
576	600	43.87	2.6	4.6	246	23	27	10	62	28 (a)	--	--	--
720	744	44.52	4.3	4.6	235	32	16	0	84	16 (a)	--	--	--
828	862	39.66	2.7	2.0	170	37	28	0	72	28 (a)	--	--	--
924	948	54.95	4.6	1.8	203	47	50	0	50	50 (a)	--	--	--
972	996	59.67	5.0	1.4	204	48	39	0	61	36	2.3	2.1	0.2
1,086	1,110	49.93	3.9	1.2	186	77	77	0	23	77 (a)	--	--	--
1,548	1,572	38.79	3.1	0.6	156	84	72	0	28	72	--	--	--
Area C03 Hole B18													
6 e	24	27.56	3.5	6.6	865	86	29	20	51	29 (a)	--	--	--
24	48	31.56	3.7	5.2	905	33	17	10	73	17 (a)	--	--	--
48	72	34.99	3.5	4.1	520	40	17	14	69	17 (a)	--	--	--
72	96	26.48	3.3	5.3	620	57	30	0	70	30 (a)	--	--	--
96	120	29.62	2.8	11	478	45	21	4	75	21 (a)	--	--	--
156	180	59.77	5.0	6.4	334	50	17	6	77	17 (a)	--	--	--
216	240	38.60	3.3	12	305	51	23	8	69	23 (a)	--	--	--
252	276	34.53	3.6	11	330	54	22	16	63	21 (a)	--	--	--
336	360	35.35	3.9	5.8	233	44	23	0	77	23 (a)	--	--	--
468	492	53.05	4.1	1.7	210	41	31	0	69	31 (a)	--	--	--

Depth interval (inches below land surface)		Water content of filter paper (percent dry weight)	Water content of soil sample excluding large particles (percent dry weight)	Chloride content of soil with particle sizes less than 2 millimeters (milligrams per kilogram dry soil)	Specific conductance of water extract for chloride determination (micromohs per centimeter)	Amount of sample with particle sizes less than 2 millimeters (percent dry weight)		Amount of sample (percent dry weight) in indicated size class (millimeter)					
Top (A)	Bottom (B)	(C)	(D)	(E)	(F)	Water-content sample (G)	Total sample (H)	Cobbles and boulders (>64) (I)	Gravel (2 to 64) (J)	Sand (0.062 to 2) (K)	Silt plus clay (<0.062) (L)	Silt (0.002 to 0.062) (M)	Clay (<0.002) (N)
					Area C03 Hole B18--Continued								
540	564	53.00	5.0	2.9	238	48	24	6	70	24 (a)	--	--	--
696	720	36.38	2.7	2.4	244	30	12	24	64	12 (a)	--	--	--
816	840	34.23	2.8	2.5	238	42	20	16	64	20 (a)	--	--	--
936	960	42.36	3.4	1.2	212	30	16	21	63	16 (a)	--	--	--
1,056	1,080	35.92	3.0	3.0	230	35	21	7	72	21 (a)	--	--	--
1,536	1,560	45.77	3.5	3.4	233	42	19	0	81	19 (a)	--	--	--
						Area C04 Hole B20							
2	12	8.44	1.0	0.3	86	97	96	0	4	96 (a)	--	--	--
12	24	20.12	2.2	0.3	85	97	95	0	5	74	21	20	0.7
24	48	39.87	4.1	1.9	308	93	54	10	36	40	14	14	0.5
48	72	31.83	3.6	13	695	60	30	6	64	30 (a)	--	--	--
72	96	24.05	2.2	130	3,680	46	25	14	61	20	4.6	4.3	0.3
96	120	23.04	2.5	160	4,650	42	27	8	65	27 (a)	--	--	--
120	180	35.22	4.8	120	693	22	24	0	76	21	2.7	2.4	0.3
180	240	45.61	4.9	58	490	34	32	0	68	32 (a)	--	--	--
240	300	43.44	4.7	24	234	77	57	0	43	57 (a)	--	--	--
300	360	40.12	4.4	16	260	63	70	0	30	70 (a)	--	--	--
360	480	41.96	7.8	5.0, 5.0 (b)	136, 149 (b)	80	77	2	23	58	19	18	1.2
480	600	34.89	3.5	0.6, 0.7 (b)	119, 125 (b)	92	90	0	0	90 (a)	--	--	--
600	720	32.46	3.9	2.9, 0.4 (b)	126, 114 (b)	98	89	0	11	89 (a)	--	--	--
720	780	37.63	2.9	4.0	129	92	83	3	14	83 (a)	--	--	--

Letter symbols in the following formulae represent values in the columns of the above table with corresponding letter headings:

Estimated soil-moisture potential, in meters of water, equals $-1.122\ (C/100)^{-3.683}$.

Water content of in-place soil, in percent by weight, equals D(H/G). To obtain water content in percent by volume, multiply water content in percent by weight by about 1.4 for soils from areas F01 and F02, and by about 1.7 for soils from areas C01, C02, C03, and C04.

Concentration of chloride in soil water, in milligrams per liter, equals E(G/D).

Chloride content of in-place soil, in milligrams per kilogram of dry soil, equals E(H/100).

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